

VIII CONGRESO IBERO – LATINO AMERICANO DE SEGURIDAD CONTRA INCENDIOS – CILASCI 8

Santander 8 – 10 Abril 2026

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associação luso-brasileira
para a segurança contra incêndio

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UNIVERSIDAD DE CANTABRIA
Dpto. de Transportes y Tecnología de Proyectos y Procesos
Avda. Los Castros, s/n
39005 Santander. Spain
Tf. + 34 942 201826. Fax. +34 942 202276; gidai@uncan.es ;
<http://grupos.uncan.es/GIDAI>

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Mariano Lázaro Daniel Alvear

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Preface

The Ibero-Latin American Fire Safety Congresses (CILASCI) are held biannually. They aim is to bring together researchers and experts from Portugal, Brazil, Spain, and other Latin American countries to disseminate their scientific and technical work in the field of fire safety, integrating the various stakeholders involved in this area of knowledge. CILASCI 8, on which this book is based, took place at University of Cantabria, in Santander, Spain, from April 8 to 10, 2026.

The first edition of the Ibero-Latin American Congress on Fire Safety, CILASCI 1, was held in Natal (Brazil) from March 10 to 12, 2011. The second congress, CILASCI 2, took place in Coimbra (Portugal) from May 29 to June 1, 2013. The third and fourth editions were held in South America: CILASCI 3 in Porto Alegre (Brazil) from November 3 to 6, 2015, and CILASCI 4 in Recife (Brazil) from October 9 to 11, 2017. CILASCI 5 returned to the Iberian Peninsula, being held in Porto (Portugal) from July 15 to 17, 2019. The sixth and seventh editions took place once again in South America, with CILASCI 6 in Belo Horizonte (Brazil) from June 22 to 24, 2022, and CILASCI 7 in São Paulo (Brazil) from November 6 to 8, 2024.

A total of 39 papers were selected for CILASCI 8, representing different countries: Argentina, Belgium, Brazil, Chile, France, Malaysia, Norway, Portugal, Slovenia, Spain, the United Kingdom, and the United States. The Invited Lectures - “Finite element model to determine the fire resistance of protected timber columns”, “Towards inclusive evacuation design through egressibility research”, “Fire safety engineering in the aftermath of the Grenfell Tower inquiry”, and “A multi-scale framework for assessing wildland-urban interface fire risk to support emergency planning: application to Barcelona communities” - were delivered by Prof. Paulo A.G. Piloto (Polytechnic Institute of Bragança, Portugal), Prof. Enrico Ronchi (Lund University, Sweden), Prof. José L. Torero (University College London, United Kingdom) and Prof. Elsa Pastor (Universitat Politècnica de Catalunya, Spain), respectively.

Finally, we wish to express our sincere appreciation to the Scientific Committee of the Congress for their work in the paper selection process and to the authors and speakers who dedicated their time and effort to share their experiences, methodologies, and scientific–technical advances in fire safety.

On the behalf of the Organizing Committee

Prof. Mariano Lázaro Urrutia

Prof. Daniel Alvear Portilla

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Prólogo

Los Congresos Ibero-Latinoamericanos de Seguridad contra Incendios (CILASCI) se celebran cada dos años. Su objetivo es reunir a investigadores y expertos de Portugal, Brasil, España y otros países de América Latina, con el fin de difundir sus trabajos científicos y técnicos en el ámbito de la seguridad contra incendios, integrando a los distintos actores involucrados en esta área del conocimiento. CILASCI 8, en el que se basa este libro, tuvo lugar en la Universidad de Cantabria, en Santander (España), del 8 al 10 de abril de 2026.

La primera edición del Congreso Ibero-Latinoamericano de Seguridad contra Incendios, CILASCI 1, se celebró en Natal (Brasil) del 10 al 12 de marzo de 2011. El segundo congreso, CILASCI 2, tuvo lugar en Coímbra (Portugal) del 29 de mayo al 1 de junio de 2013. La tercera y cuarta ediciones se realizaron en Sudamérica: CILASCI 3 en Porto Alegre (Brasil) del 3 al 6 de noviembre de 2015, y CILASCI 4 en Recife (Brasil) del 9 al 11 de octubre de 2017. CILASCI 5 regresó a la península ibérica, celebrándose en Oporto (Portugal) del 15 al 17 de julio de 2019. La sexta y séptima ediciones se llevaron a cabo nuevamente en Sudamérica: CILASCI 6 en Belo Horizonte (Brasil) del 22 al 24 de junio de 2022, y CILASCI 7 en São Paulo (Brasil) del 6 al 8 de noviembre de 2024.

En CILASCI 8 se seleccionaron un total de 39 trabajos procedentes de distintos países: Argentina, Bélgica, Brasil, Chile, Francia, Malasia, Noruega, Portugal, Eslovenia, España, Reino Unido y Estados Unidos. Las Conferencias Invitadas —“Finite element model to determine the fire resistance of protected timber columns”, “Towards inclusive evacuation design through egressibility research”, “Fire safety engineering in the aftermath of the Grenfell Tower inquiry”, y “A multi-scale framework for assessing wildland-urban interface fire risk to support emergency planning: application to Barcelona communities”— fueron impartidas por el Prof. Paulo A.G. Piloto (Instituto Politécnico de Bragança, Portugal), el Prof. Enrico Ronchi (Universidad de Lund, Suecia), el Prof. José L. Torero (University College London, Reino Unido) y la Prof. Elsa Pastor (Universitat Politècnica de Catalunya, España), respectivamente.

Finalmente, deseamos expresar nuestro más sincero agradecimiento al Comité Científico del Congreso por su labor en el proceso de selección de los trabajos, así como a los autores y ponentes que dedicaron su tiempo y esfuerzo para compartir sus experiencias, metodologías y avances científico-técnicos en el ámbito de la seguridad contra incendios.

En nombre del Comité Organizador

Prof. Mariano Lázaro Urrutia

Prof. Daniel Alvear Portilla

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Prefácio

Os Congressos Ibero-Latino-Americanos de Segurança contra Incêndios (CILASCI) são realizados bienalmente. O seu objetivo é reunir pesquisadores e especialistas de Portugal, Brasil, Espanha e de outros países da América Latina, com o propósito de divulgar seus trabalhos científicos e técnicos na área de segurança contra incêndios, integrando os diversos atores envolvidos neste campo do conhecimento. O CILASCI 8, no qual este livro se baseia, ocorreu na Universidade da Cantábria, em Santander (Espanha), de 8 a 10 de abril de 2026.

A primeira edição do Congresso Ibero-Latino-Americano de Segurança contra Incêndios, CILASCI 1, foi realizada em Natal (Brasil), de 10 a 12 de março de 2011. O segundo congresso, CILASCI 2, teve lugar em Coimbra (Portugal), de 29 de maio a 1º de junho de 2013. A terceira e a quarta edições foram realizadas na América do Sul: o CILASCI 3 em Porto Alegre (Brasil), de 3 a 6 de novembro de 2015, e o CILASCI 4 em Recife (Brasil), de 9 a 11 de outubro de 2017. O CILASCI 5 retornou à Península Ibérica, sendo realizado na cidade do Porto (Portugal), de 15 a 17 de julho de 2019. A sexta e a sétima edições ocorreram novamente na América do Sul: o CILASCI 6 em Belo Horizonte (Brasil), de 22 a 24 de junho de 2022, e o CILASCI 7 em São Paulo (Brasil), de 6 a 8 de novembro de 2024.

No CILASCI 8 foram selecionados um total de 39 trabalhos provenientes de diferentes países: Argentina, Bélgica, Brasil, Chile, França, Malásia, Noruega, Portugal, Eslovênia, Espanha, Reino Unido e Estados Unidos. As Palestras Convidadas — “Finite element model to determine the fire resistance of protected timber columns”, “Towards inclusive evacuation design through egressibility research”, “Fire safety engineering in the aftermath of the Grenfell Tower inquiry”, y “A multi-scale framework for assessing wildland-urban interface fire risk to support emergency planning: application to Barcelona communities” — foram apresentadas pelos Prof. Paulo A.G. Piloto (Instituto Politécnico de Bragança, Portugal), Prof. Enrico Ronchi (Universidade de Lund, Suécia), Prof. José L. Torero (University College London, Reino Unido) e Prof. Elsa Pastor (Universitat Politècnica de Catalunya, Espanha), respectivamente.

Por fim, desejamos expressar o nosso sincero agradecimento ao Comitê Científico do Congresso pelo trabalho desenvolvido no processo de seleção dos artigos e aos autores e palestrantes que dedicaram seu tempo e esforço para compartilhar suas experiências, metodologias e avanços científico-técnicos no campo da segurança contra incêndios.

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Keynote lectures
Conferencias Magistrales
Palestras principais

FINITE ELEMENT MODEL TO DETERMINE THE FIRE RESISTANCE OF PROTECTED TIMBER COLUMNS



Paulo A.G. Piloto*
Professor
IPB, Bragança
Portugal

Keywords: Fire, Timber, columns, Gypsum protection.

1. INTRODUCTION

Timber is a sustainable and renewable building material increasingly popular in modern architecture due to its aesthetic appeal, low environmental footprint, and structural ability. Glued-laminated timber (GLT) is commonly used for columns and beams in mid to high-rise buildings due to its strength and spanning ability. However, timber's combustibility raises concerns about fire safety, especially for load-bearing structural components. One effective technique for increasing the fire performance of GLT columns is by applying protective gypsum cladding, which acts as a thermal barrier, slowing the temperature rise in timber and delaying structural degradation.

The experimental determination of fire resistance for load-bearing columns is conducted according to established testing protocols. This procedure encompasses specimen preparation, furnace conditions, performance monitoring, and evaluation of failure criteria. Fire resistance testing of columns should comply with EN 1363-1 [1], which establishes fundamental testing principles including furnace temperature control following a standard temperature-time curve, pressure conditions maintained at specified levels, and comprehensive instrumentation requirements. For vertical load-bearing elements specifically, EN 1365-4 [2] provides detailed specifications for column testing procedures, including specimen dimensions, loading configurations, support conditions, and measurement techniques. Failure of load-bearing capacity

* Corresponding author— GICoS, Instituto Politécnico de Bragança. Campus Santa Apolónia, 5300-253 Bragança (Portugal).

Telef.: +351 273 303157, E-mail: ppiloto@ipb.pt

occurs when the deflection rate exceeds specified limits or when the maximum deflection becomes excessive. Following EN 13501-2 [3], fire resistance is classified based on test results. The classification system includes R15, R20, R30, R45, R60, R90, R120, R180, R240 and R360, indicating the time (in minutes) the column maintains the ability to sustain the load.

The fire resistance of protected timber columns can be determined using simplified design methods based on the European Charring Model (ECM), as specified in EN1995-1-2 [4] and prEN1995-1-2 [5]. However, the Finite Element (FE) models provide enhanced insight into the thermal and mechanical behaviour of protected timber columns under fire exposure. This study presents a full three-dimensional solid finite element model validated against experimental tests on protected GLT columns. The numerical model accounts for isotropic and orthotropic material behaviour, temperature-dependent thermal and mechanical properties, and GMNIA modelling techniques (Geometrically and Materially Non-linear Imperfection Analysis). The FE model is used to simulate the thermal response, charring progression, and structural stability of protected timber columns during fire exposure, with particular focus on specimen SP1 as the primary validation reference.

Several fire resistance tests have been conducted on timber columns. Ali and Kavanagh in 2005 [6], developed six tests on columns under high temperatures. The columns failed due to global flexural buckling and did not experience any expansion. The fire resistance decreased with load level and slenderness, as expected. A comparison of experimental results with the simplified Effective Cross Section Method (ECSM), showed a reasonable agreement, being the EN1995-1-2 [4] on the safe side by an average safety factor of 38.7%. In 2021, Gernay [7] investigated the resistance of timber columns to full burnout using finite element modelling. Gernay introduced the concept of burnout resistance of timber columns, following a natural fire curve (parametric) to determine the equivalent failure time of the timber column in comparison to ISO834. The results show that burnout resistance ranges from 20% to 50% of the standard fire resistance. Critical findings demonstrate a significant susceptibility to failure during cooling phases, resulting from delayed heating and property degradation at low temperatures. The study reveals important challenges for mass timber construction safety in tall buildings, highlighting the gap between standard fire resistance ratings and actual performance during decay phases of realistic fires. Gernay *et al.* in 2023 [8], developed full-scale furnace tests on loaded glulam columns measuring the structural response during heating and cooling phases. Identical 280×280mm columns failed under various heating durations. Two columns exposed to ISO 834 heating failed at 55-58 minutes. Two columns with 15-minute heating followed by cooling failed during the cooling phase after 98-153 minutes. Two columns with 10-minute heating survived. Thermocouples recorded sustained temperature increases hours post-heating. Results highlighted the critical need for investigating timber fire safety beyond standard heating phases. In 2025, Zhu *et al.* [9] conducted an experimental and numerical investigation to examine the compressive performance of GLB (Glued Laminated Bamboo) columns under ISO 834 standard fire exposure. Results show the fire resistance decreases with increasing slenderness and load ratio for axial compression, with a slight decline for eccentric compression. Failure mode was dominated by tensile fibre rupture. Thermo-mechanical coupling analysis accurately simulates temperature distribution and mechanical behaviour with charring depth and fire resistance errors below 10%. The mechanical and thermal properties were considered orthotropic with slight modifications in comparison to EN1995-1-2 [4]. This study provides essential references for designing and fireproofing

engineered bamboo structures under complex loading conditions. More recently, Piloto *et al.* [10] investigated the fire resistance of gypsum-protected GLT columns, examining the effects of geometry, load level, and cladding configuration. European Charring Model (ECM) and effective cross-section design methods (ECSM) combined with three experimental tests and a full 3D computational ANSYS modelling. Results show under 36% load level, doubling protection layer increases fire resistance up to 95%. Upgrading GL24h to GL28h increases fire resistance 2-12% depending on slenderness. Increasing load from 6% to 36% reduces fire resistance up to 47%.

Several computational models have been used to evaluate the fire resistance of timber columns and frames. In 2023, Huang and Wang [11] presented an experimental and numerical investigation of the progressive collapse in two-story glulam frames when middle columns were exposed to ISO834 fire. Experimental tests indicate column failure at 16.8 minutes, followed by frame collapse at 17.17 minutes. The connections between steel and wood are heated rapidly under fire, and these regions become a weak point. This observation justifies the use of fire protection on glulam timber structures, thereby enhancing their fire resistance. The GLT frame structure can remain stable for a long time after the failure of the middle column due to the catenary action of the beams. The thermal-mechanical sequential coupling analysis using ABAQUS accurately reproduced temperature distributions and deformation. Numerical predictions agree well with experimental observations within acceptable margins. More recently, Ma *et al.* [12] investigated the timber column fire resistance through finite element analysis with a focus on stress-strain relationships, using linear elastic in tension and elastic-plastic in compression, assuming damage of material (stress drops to zero). A nonlinear fibre-based beam element model with temperature-dependent properties was applied to 52 standard fire tests on glulam columns. Bayesian optimisation examines strength reduction factors and plastic limit strain. Results show EN 1995-1-2 [4] reduction factors underestimate fire resistance. The study supports the development of improved numerical methods and guidance on material properties for timber structure fire assessment standards. In 2025, Han and Tesfamariam [13] presented the equivalent section temperature (EST) method for timber columns exposed to fire, reducing computational costs of sequential thermal-structural analysis. The EST uses a single temperature value providing the same compression strength or bending stiffness as the original temperature field. The numerical models were validated against large test datasets. Reliability analysis using Polynomial Chaos Kriging evaluates the probability of timber column failure under fire conditions with random thermal and structural variables. Different reliability assessment methods were applied. This investigation supports the development of improved numerical modelling guidance for timber structure fire design standards.

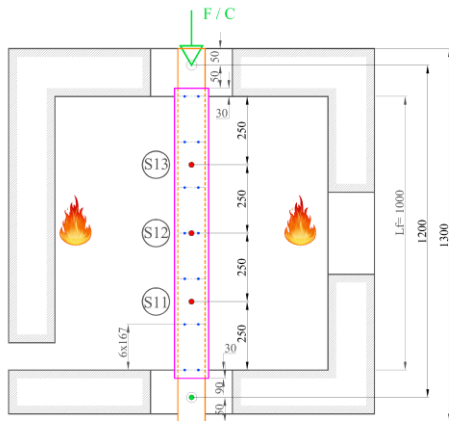
This manuscript presents the 3D numerical model used for simulating GLT-protected columns, utilising gypsum. This simulation model was validated against experimental results, verified against simple calculation methods, and a parametric analysis is also presented. The computational model included a four-step analysis procedure.

2. FINITE ELEMENT MODEL

The finite element model is a full three-dimensional solid finite element model composed of four sequential analysis stages. The Analysis 1 (Elastic Buckling Analysis) determines the elastic

buckling load (F_{cr}) and the first mode of instability, which is used to introduce geometric imperfection into subsequent analyses. The Block Lanczos extraction method is used to solve this eigenvalue problem. For specimen SP1, the elastic buckling load was calculated as $F_{cr} = 481\,393$ N, for the case of a simply supported GLT column with a length of 1.2 m between pin supports and a cross section made of 80×100 mm² with GL24h material grade [14]. The analysis 2 (Geometrically and Materially Non-linear Imperfection Analysis (GMNIA)) is applied at room temperature to predict the load-bearing capacity of the timber column at ambient temperature. The geometric imperfection is introduced using the first buckling mode scaled to an initial maximum deviation from straightness of $L/500$ [15]. The analysis is incremental in force ($\Delta F = 5\,000$ N with adaptive reduction to 0.1 N) and iterative, using the Newton-Raphson method. Convergence is controlled by displacement with a tolerance of 10^{-3} and a reference value of 1 m. For specimen SP1, the load-bearing capacity was determined as 172 380 N. The analysis 3: (Transient Nonlinear Thermal Analysis (TNA)) determines the temperature field within the column cross-section during fire exposure. The heat source is modelled as the ISO834 standard fire curve applied to four exposed surfaces (L_f in Fig. 1a)). Thermal properties of timber, gypsum, and steel connections are temperature-dependent. The analysis is incremental in time ($\Delta t = 60$ s with adaptive reduction to 1 s) and iterative. Convergence is based on heat flow calculation with tolerance of 10^{-3} and reference value of 10^{-6} W. The analysis 4 considers the mechanical load (load level) and the thermal effect (Thermo-Mechanical Analysis) using GMNIA. This coupled analysis includes the effects of mechanical load and fire exposure to determine fire resistance. One percentage of load bearing capacity determined from analysis 2 is applied (load level), and the temperature distribution from analysis 3 drives the reduction of material properties. The analysis is incremental in time ($\Delta t = 10$ s with adaptive reduction to 0.00001 s) and iterative using the same displacement control of analysis 2. The fire resistance is determined as the time at which the column can no longer sustain the applied load (usually an asymptotic behaviour for the contraction displacement over time).

Fig. 1 presents the experimental setup used for testing GLT columns under fire, which will also be used for validation. A dummy short column for the installation of internal thermocouples accompanies the main column. Fig. 1 also shows the displacement transducers and load transducer applied on the top support of the GLT column. Both supports are pinned-pinned, using a steel rod to transfer the load from the top to the bottom (reaction). The length exposed to fire is $L_f = 1.0$ m, and the length between supports is 1.2 m. The total length of the GLT column is 1.3 m. The length between screws is 162 mm. Three thermocouples are applied to the external surface of the GLT column (S11, S12 and S13), while height thermocouples are applied to the dummy to represent the temperature in different points of the cross section (S1 to S8).



a) Sections used for thermocouples and screws.



b) Position of the timber column, including dummy.



c) Front view from hydraulics and vertical contraction sensors.



d) Top support.



e) Bottom support.

Figure 1: Model used for testing protected GLT columns under fire, including dummy.

2.1 Thermal and mechanical material properties

The thermal properties are temperature-dependent for all the materials involved in the thermal simulations (timber, Gypsum plasterboard, and steel) and were considered as isotropic. Fig. 2 presents the main thermal properties for all the materials involved, with the exception of the emissivity of the radiation-exposed material (gypsum, $\epsilon = 0.8$).

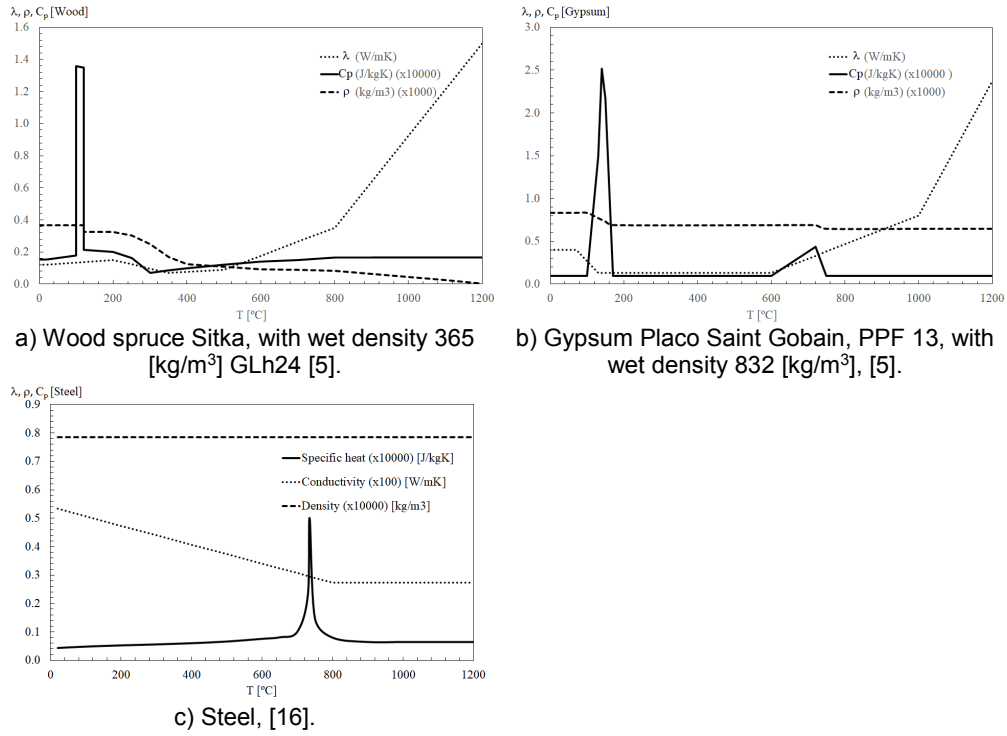


Figure 2: Thermal properties of materials.

Other authors are using orthotropic thermal properties for wood species, differentiating only the thermal conductivity in the three main directions in space [9]. This should be tested and validated with experimental results. Charring is implicitly considered through effective properties [12]. Eurocode 5 provides limited guidance for advanced calculation methods, excluding stress-strain models, but includes effective temperature-dependent thermal and mechanical properties calibrated for standard fire exposure [12].

The mechanical properties of wood are temperature- and fibre-dependent. Wood is an orthotropic material due to the way the natural growth pattern and cellular structure of the tree. The wood model considers the different behaviour of the material in the direction of the fibres, the radial direction, and the tangential direction. The strength and stiffness of wood are considerably higher in the longitudinal direction than in the other orthogonal directions. The generalised Hooke's law for the orthotropic material may be considered, as shown in Table 1.

Table 1: Elastic properties for wood species Spruce Sitka [17].

	20 °C	100 °C	300 °C
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EX (MPa)	11500	4025	115
EY (MPa)	897	313	8
EZ (MPa)	494	173	4
ν_{XY}	0.372	0.372	0.372
ν_{YZ}	0.435	0.435	0.435
ν_{XZ}	0.467	0.467	0.467
GXY (MPa)	736	257	7
GYZ (MPa)	34	12	0.3
GXZ (MPa)	701	245	7

This material model considers the reduction coefficient for elevated temperatures, assuming 1% of the room temperature values for residual strength and stiffness at 300 °C and temperatures above. Moreover, according to prEN1995-1-2 [5], it is possible to conclude that the compressive strength of wood in the direction parallel to the grain (direction x) is linearly reduced with increasing temperature. The modulus of elasticity (EX, EY, EZ) is also affected by the increase in temperature, with the application of reduction factors between 100 and 300 °C, as shown in Fig. 3.

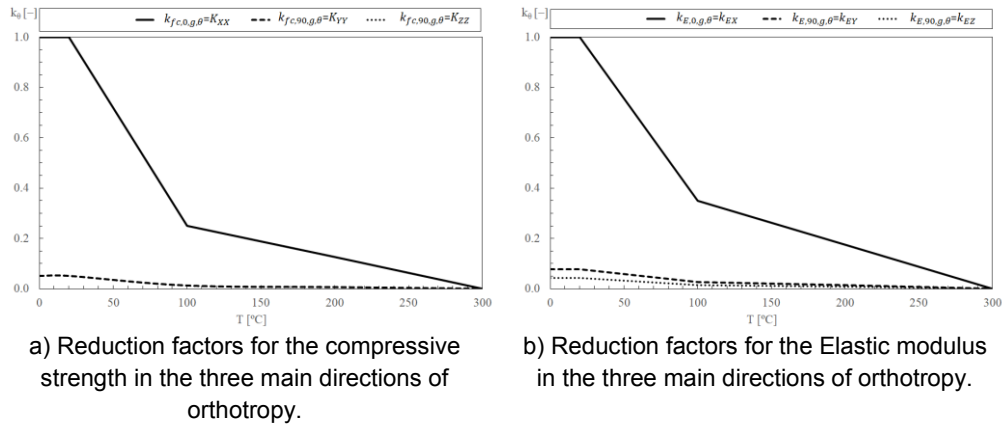


Figure 3: Temperature-dependent mechanical properties for wood species.

Poisson's coefficients ($\nu_{XY}, \nu_{YZ}, \nu_{XZ}$) are considered constant with increasing temperature, due to the inexistence of any correction factors for this property [4] [5]. The transverse elastic modulus (GXY, GYZ, GXZ) also undergoes a reduction with increasing temperature, and the same reduction coefficients of the modulus of elasticity are used, since both elastic properties of wood are related through Poisson's coefficients.

The failure of wood can be presented in several ways, such as fibre breakage, micro-cracking of the matrix, detachment of fibres or delamination. To characterise this effect, the Hill criterion is adopted [18]. This criterion is based on von Mises's theory and adapted for orthotropic materials. Hill's criterion considers the interaction between the stress in the failure mechanism and depends on the orientation of the stress with respect to the orthotropic axis of the material. This criterion allows the determination of the elastic and elastoplastic zones in the stress-strain relationship of

the wood. The characteristic parameters of the orthotropic material, defined for this criterion, are the R_{ij} yield rates, which are established as a function of the limit stress in the main directions of the material. Assuming the wood does not have the plastic capacity, the elastic-plastic regime is considered for the constitutive law in this investigation, to ensure the material remains within the elastic limit. The compressive strength $f_{xx}^y = f_{c,0,g,k}$ was experimentally measured at room temperature (26 MPa), whereas the standard EN 14080 [14] establishes a minimum value of 24 MPa. Table 2 gives the yielding rates used for each orthogonal direction and temperature level.

Table 2: Strength limit in tension and Hill coefficients for softwood Spruce Sitka [19].

	20 °C	100 °C	300 °C
f^y (MPa)	24	6	0.24
$R_{xx} = f_{xx}^y / f^y$	1	1	1
$R_{yy} = f_{yy}^y / f^y$	0.052	0.052	0.052
$R_{zz} = f_{zz}^y / f^y$	0.052	0.052	0.052
$R_{xy} = f_{xy}^y / (f^y / \sqrt{3})$	0.405	0.405	0.179
$R_{yz} = f_{yz}^y / (f^y / \sqrt{3})$	0.405	0.405	0.179
$R_{xz} = f_{xz}^y / (f^y / \sqrt{3})$	0.405	0.405	0.179

The mechanical properties used for steel are considered isotropic, and a linear elastic model has been selected ($E=210$ GPa, $\nu=0.3$), based on the reduced stress level introduced to this small element at the bottom and top supports (steel rods).

2.2 Solid finite elements

Two main types of finite elements were used. For analyses 1, 2 and 4, the eight-node solid finite element (SOLID185) was selected. This element has 8 nodes, each with three degrees of freedom (three translations in each of the three spatial directions). The element uses linear interpolating functions and an enhanced strain formulation for the integration method, preventing shear locking in bending-dominated problems and volumetric locking in nearly incompressible cases. The mesh only includes hexahedral shape finite elements. For analysis 3, the eight-node solid finite element (SOLID70) was selected for the thermal analysis. This element has 8 nodes, each with one degree of freedom (temperature). The element uses linear interpolating functions and the full Gauss integration method. The mesh only includes hexahedral shape finite elements. Analysis 4 utilised the same mesh as Analysis 2, incorporating the transient results from Analysis 3.

2.3 Numerical Validation and verification

The verification of analysis 1 achieved a relative difference of 4% for the case of GL24h, when using the cross-sectional area of 80x100 mm² and the length of 1.2 m. The bigger difference (5.9%) was determined for the case of GL24h, with a cross-sectional area of 140x160 mm² and a length of 2.4 m and is mainly due to the orthotropic behaviour. The comparison of the results was also determined for other cross-sections, lengths and material grades.

The verification of analysis 2 for the load-bearing result achieved a relative difference of 5% for the case of GL24h, with a cross-sectional area of 80x100 mm² and a length of 1.2 m. The bigger difference (8%) was determined for the case of GL24h, with a cross-sectional area of 140x160 mm² and a length of 2.4 m. The comparison of the results was also determined for other cross-sections, lengths and material grades.

The validation of analysis 3 for the temperature results was determined for the predicted temperatures inside the cross-section (dummy) and for the temperature predicted in the external surface of the timber element (below the gypsum protection). The validation was determined by the calculation of the Root Mean Square Error (RMSE), using a time increment of 2.5 min. The maximum RMSE was determined for the dummy SP1 at the position S4 with 84 °C. The maximum RMSE for the temperature predictions on the external surface of the timber element (specimen SP1) was 36°C for the position S11. Fig. 4 shows the temperature evolution during the test of the specimen SP1 and respective dummy.

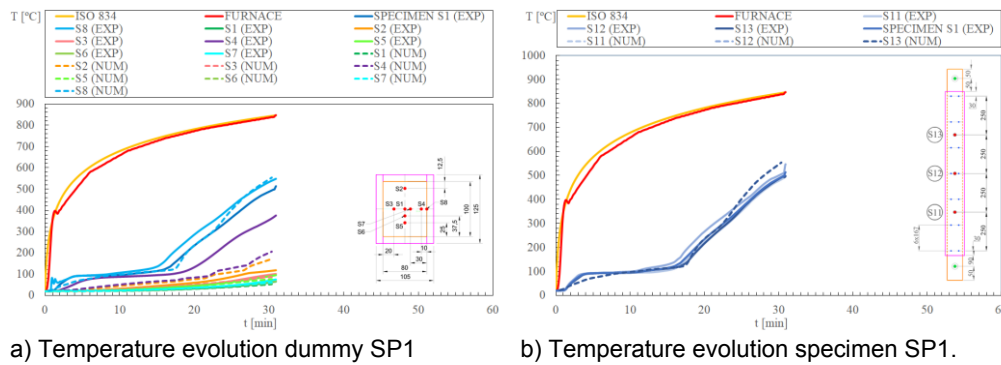


Figure 4: Temperature evolution during the fire test of the specimen SP1.

The validation of analysis 4 to determine the fire performance was made by predicting the relative difference for the fire resistance time and the calculation of the RMSE for the axial contraction displacement for each specimen. The relative difference is presented for specimens SP1, which had flexural buckling as failure mode. The relative difference for the fire resistance was 0%. The comparison of the contraction axial displacement gave an RMSE of 0.55 mm for the specimen SP1, using the same time increment of 2.5 min. These values are almost below the required precision for the measuring equipment regarding displacement (± 0.5 mm). Fig. 5 shows the comparison between the numerical and the experimental measurements.

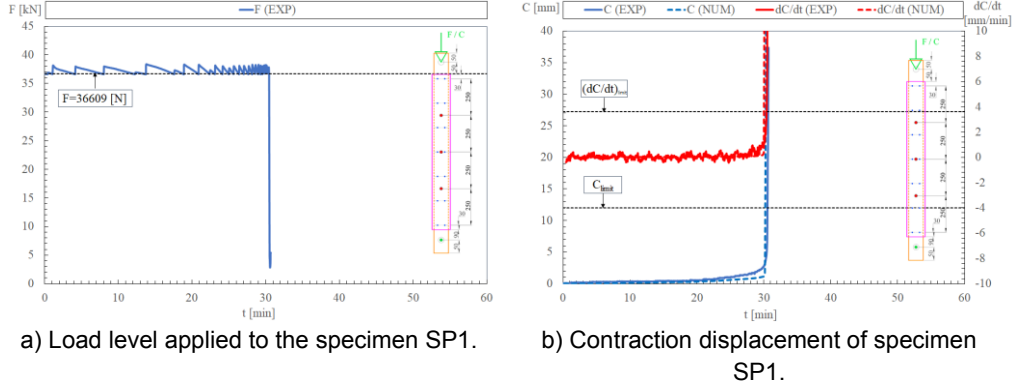


Figure 5: Load and displacement during the fire resistance test of the specimen SP1.

Displacement and load were measured during the experimental tests. The load was applied 10 min prior to the start of the fire and was stable in the range of +5%, with respect to the target value, respectively to specimens SP1, with the exception at the end of the test, when the hydraulics had difficulties keeping the load level due to the high level of the rate of displacement. Fig. 5 shows the load level for the fire test and the vertical contraction displacement over time (depicted as positive), assuming zero displacement at the beginning of the heating phase of the fire test. The test ended with a sharp increase in the vertical contraction displacement rate. The criterion that defined the fire resistance was the displacement rate; however, the limiting vertical contraction was very close, as shown in Table 3. The fire resistance is defined in terms of completed minutes, and a comparison is presented between experimental results (EXP) and numerical results (NUM).

Table 3: Fire resistance (t_{fi}). Experimental (EXP) results according to EN1363-1 [1] or the 2025 version of ISO834 [20] and numerical results (NUM).

Specimen	Load [N]	Layers/ thickness [mm]	$C_{limit} = h/100 = (3h/1000)$ (EXP) [min]	$(dC/dt)_{limit} = (3h/1000)$ (EXP) [min]	t_{fi} (EXP) [min]	$C_{limit} = h/100 = (3h/1000)$ (NUM) [min]	$(dC/dt)_{limit}$ (NUM) [min]	t_{fi} (NUM) [min]
SP1	36609	1/12.5	30.52	30.39	30	30.20	30.17	30

The failure mode was identified by flexural buckling along the strong axis due to the restraining effect of both supports.

2.4 Numerical results

Fig. 6 represents the finite element model used for each analysis type. The mesh remains unchanged between simulations, except in analysis 3, where the fire protection material is introduced. The gypsum plates are used solely for fire protection and contribute directly to the thermal simulation (analysis 3) and indirectly to the thermo-mechanical simulation (analysis 4). Fig. 6 shows the mesh used for each simulation process and presents some important results.

The average element size is 5 mm and the joints between plates were not addressed. Fig. 6 a) presents the first mode of instability associated with a critical load of 481 kN. Figure 2 b) represents the von Mises stress for the last equilibrium position, corresponding to the load bearing capacity of 172 kN. Fig. 6 c) illustrates the mesh and temperature field after 30 min. It can be noted that the protection effect of a 12.5 mm gypsum layer, keeping the residual area below 300 °C with a dimension of 60% of the original cross-section for a time of 30 min. Fig. 6 d) shows the ultimate position of equilibrium representing the total mechanical strain and the residual finite elements with temperature below 300°C, corresponding to the fire resistance time.

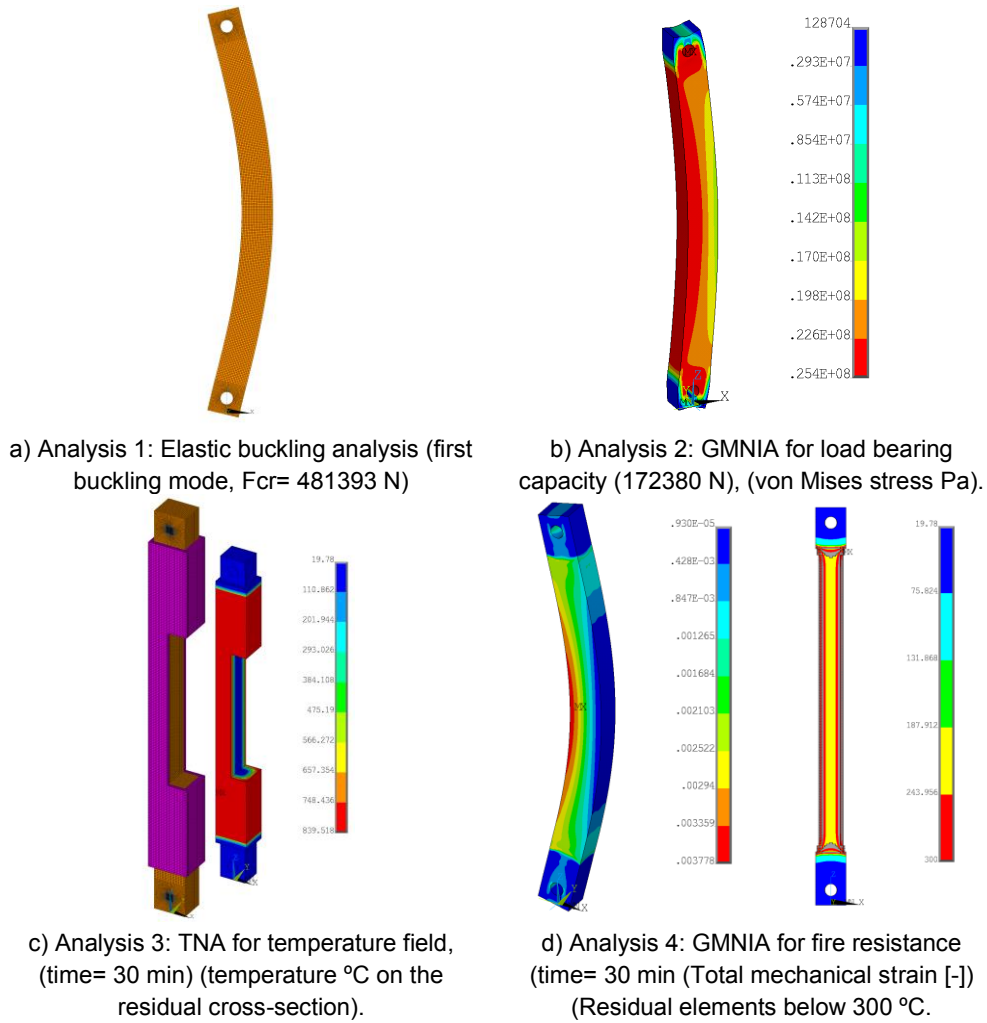
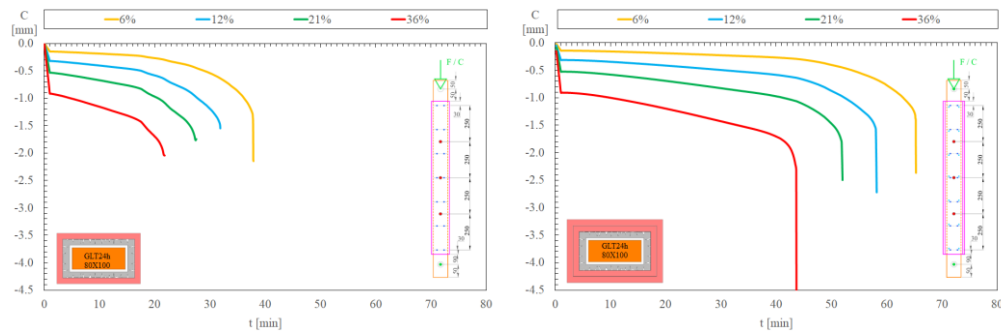


Figure 6: Numerical results during simulations for the case of specimen SP1.

2.5 Parametric study

The numerical results were determined for the case of single protection (1/12.5) and double protection (2/12.5), using different load levels (6, 12, 21 and 36%). The contraction displacement is presented for all simulations, showing the complete displacement from the start of the applied load. It is worth noting that the previous graphs presented for the axial contraction displacement, “as positive”, started with the axial contraction measured from the commencement of heating. In fact, according to EN1363-1 [18], and for vertical load-bearing elements, axial deflection should be expressed negatively whenever there is no thermal expansion, which is the case herein. The results presented in Fig. 7 are depicted from the starting of the mechanical load. There is an initial increase in load during the first 60 seconds, reflected in the initial increase in vertical contraction, to enhance solution convergence.



a) Case of single protection (P1).

b) Case of double protection (P2).

Figure 7: Vertical axial contraction of timber column GL24h with different fire protection levels and load levels.

The limits for the vertical contraction and the rate of vertical contractions may not be achieved due to the criterion established for the equilibrium. This numerical equilibrium depends on the load increments and the criteria used to find the equilibrium position. Table 4 presents the numerical results for the fire resistance when varying the load level and the protection level (P1 and P2).

Table 4: Fire resistance (t_{fi}) depending on the load level and protection level.

Cross-section [mm x mm]	Wood grade	Column Length [m]	Protection layer [#/mm]	$N_{b,Rd}$	$N_{b,Rd}$	t_{fi}			
				ANSYS	EN1995-1-1	ANSYS			
				[N]	[N]	[min]			
						Load level			
						6%	12%	21%	36%
80x100	GL24h	1.2	1/12.5	172380	180871	40	35	30	24
80x100	GL24h	1.2	2/12.5	172380	180871	70	63	56	47

The fire resistance decreases with the load level. Doubling the protection level from single protection to double protection layers, there is an increase in the fire resistance that depends on the load level. The increase changes from 70% to 95%, with the increase of the load level from 6% to 36%.

3. CONCLUSIONS

This investigation presents an important study on the fire resistance of protected glued-laminated timber (GLT) columns, focusing on the effects of geometry, load level, and gypsum-based cladding protection. The combination of experimental tests (limited to one cross-section, two load levels, and two protection levels), the use of 3D finite element modelling, has led to several key conclusions.

1- Fire Protection effect: The application of gypsum plasterboard cladding significantly improves the fire resistance of GLT columns, acting as a thermal barrier that delays temperature rise and charring of the timber. Doubling the gypsum protection layer thickness notably increases fire resistance by approximately 70% to 95%, with the increase of the load level from 6% to 36%. This confirms gypsum cladding as an effective fire protection system for timber columns.

2- Load Level effect: The fire resistance of timber columns decreases as the applied load level increases. The study quantified this reduction, showing that increasing the load from 6% to 36% of the ultimate capacity reduces fire resistance by nearly 47.2%. This emphasises the importance of considering load level in fire design assessments.

3- Numerical Modelling Verification and Validation: The developed full 3D solid finite element model, incorporating orthotropic, temperature-dependent material properties and nonlinear thermo-mechanical behaviour, accurately predicted temperature evolution, displacement, and char depth. The model showed good agreement with experimental results, with relative differences in critical parameters generally below 18%, validating its use for fire performance prediction of timber columns.

4- Failure Modes and Protection Integrity: The study observed that the failure modes under fire include flexural buckling. Maintaining the integrity of adhesive bonds during fire exposure is essential, as it impacts charring rates and load-bearing capacity. The choice of adhesive and its fire performance also affects the overall fire resistance of GLT columns.

The validated and verified 3D finite element model provides a robust computational model for detailed fire safety assessment, bridging the gap between experimental data and design standards. Future design codes should incorporate these findings to improve safety and optimise the use of timber in sustainable construction.

4. ACKNOWLEDGMENTS

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TOWARDS INCLUSIVE EVACUATION DESIGN THROUGH EGRESSIBILITY RESEARCH



Enrico Ronchi
Associate Professor
Lund University
Sweden

Keywords: Egressibility, evacuation, fire safety, accessibility, egress

1. INTRODUCTION

The adoption of the United Nations (UN) Convention on the Rights of Persons with Disabilities in 2006 marked a fundamental shift in the global recognition of the rights of persons with disabilities. The Convention establishes the obligation of States Parties to undertake “*all necessary measures to ensure the protection and safety of persons with disabilities in situations of risk, including situations of armed conflict, humanitarian emergencies and the occurrence of natural disasters*” [1,2]. Despite this clear mandate, the design of buildings and emergency procedures continues to be largely based on the needs and capabilities of healthy adult populations. Accessibility provisions are typically introduced as ad hoc solutions, such as areas of refuge [3,4], evacuation elevators for people with reduced mobility [5,6], or dedicated alarm systems for individuals with hearing impairments [7]. This approach has proven inadequate. Evidence from a wide range of fire disasters (e.g. the recent Grenfell fire disaster [8]) consistently shows that persons with disabilities are disproportionately affected and frequently experience the highest fatality rates. The persistent over-representation of persons with disabilities among disaster casualties highlights a structural failure in how evacuation safety is conceptualised and implemented. In other words, evacuation design is not inclusive today.

Over recent decades, evacuation research has advanced significantly, moving beyond the outdated notion of panic as the dominant explanation of human behaviour in fire emergencies [9]. Research focuses today on understanding rational decision-making processes and has adopted different theoretical and modelling approaches, including utility-based choice models

[10,11], affordance theory [12], and psychological frameworks [13–15]. These approaches have enhanced our knowledge of human behaviour during fire evacuation and improved the predictive capabilities of simulation tools. However, their application has largely been restricted to homogeneous populations of healthy adults.

Current evacuation models rarely represent disability beyond reduced mobility [16,17], and there is a notable absence of empirical data and modelling frameworks tailored to individuals who are blind, deaf or have cognitive limitations [18]. As evacuation safety increasingly relies on performance-based design supported by computational simulations, the limitations of existing models become more critical. The demographic transformation towards an ageing global population further intensifies this challenge, as ageing is often associated with declines in sensory, cognitive and motor abilities [19]. These abilities can be conceptualised as components of functional capacity, while their reduction constitutes functional limitations.

Addressing the gap between inclusive evacuation design and current modelling practice adopted in performance-based design requires a fundamental shift in perspective. Rather than adapting existing evacuation systems to diverse users, there is a need to reconceptualise emergency egress in terms of functional diversity. The use of the concept of egressibility, intended as accessibility to means of evacuation [20], represents a crucial step in this direction, aiming to advance evacuation research towards models and design principles capable of accounting for heterogeneous populations and diverse functional capacities.

2. MODELS OF DISABILITY APPLIED TO EGRESSIBILITY

Understanding the concept of egressibility requires stepping back to examine how disability has been interpreted across different conceptual models. This involves considering the historical development of disability rights advocacy and clarifying the key terminology associated with accessibility and functional limitations.

2.1 Models of disability

The International Classification of Functioning, Disability and Health (ICF) developed by the World Health Organization [21] defines disability as a wider term which represents “*problems an individual may experience in involvement in life situations*”. Based on ICF [21], an impairment is defined as “*loss or abnormality in body structure or physiological function (including mental functions)*”.

Egressibility can therefore be interpreted as the capacity of the built environment and its associated systems to enable accessible evacuation for everyone, i.e. considering people with diverse functional capacities [20]. This concept is inherently shaped by underlying assumptions about disability. Different models of disability can indeed lead to fundamentally different approaches to evacuation design and associated regulatory implications.

A particularly relevant framework for egressibility is the biopsychosocial model of disability [22,23]. This integrative perspective recognises that disability arises from the dynamic

interaction between health conditions, individual functioning and contextual factors. Within this framework, disability is described across three connected domains: body functions and structures (e.g. sensory, cognitive and motor functions), activities (e.g. walking, communicating, perceiving information), and participation (involvement in life situations). These domains are influenced by environmental factors (such as architectural layout, egress components, alarm and communication systems, organisational procedures and societal attitudes) and personal factors (such as prior experience with fire scenarios, familiarity with egress systems) [24].

To appreciate the significance of this approach, it is useful to contrast it with earlier models of disability. The medical model [25], which historically dominated policy and practice, conceptualises disability as a deficit located within the individual and caused by an underlying impairment. Within this framework, evacuation challenges are addressed primarily through treatment, rehabilitation or compensatory technologies. In fire safety, this has translated into add-on or specialised solutions aimed at ‘fixing’ or compensating for impairments, such as assistive evacuation devices or dedicated equipment [26,27]. While such measures may be beneficial, the medical model implicitly frames the individual as the problem and does not fundamentally question whether the environment itself produces disabling conditions.

The social model of disability reframed disability as the result of social, environmental and attitudinal barriers [28]. From this perspective, individuals are disabled not by their impairments per se, but by inaccessible buildings, inflexible procedures and discriminatory assumptions. Applied to emergency egress, this model shifts attention towards step-free routes, inclusive alarm systems, clear communication strategies and organisational preparedness. The social model has had a profound influence on accessibility and inclusive design by emphasising the responsibility of society to remove barriers. However, it does not yet fully account for the complex interplay between health conditions, functional capacities and situational demands encountered during emergencies.

2.2 Egressibility

Egressibility represents a conceptual progression from traditional evacuation research and practice towards a performance-based, function-oriented understanding of safety that explicitly accounts for population heterogeneity. Performance-based design is therefore extended beyond the scale of the building as a whole to include the design and evaluation of individual egress components, systems and procedures. These elements should not merely accommodate specific groups retrospectively, but be conceived and assessed from the beginning to function effectively for all users, irrespective of functional capacity.

In this context, egressibility research has started investigating how to define heterogeneous populations beyond simple characteristics which are typically investigated in evacuation research (e.g. age and gender). This means that functional capacity should be investigated in a much more refined manner, borrowing knowledge from the medical and health science field which has already landed in the world of accessibility research [29]. Resulting key functional limitations that can be used to characterise people in the context of egressibility research and practice are presented in Table 1. This table introduces the categories of functions that have

been included in a self-assessment questionnaire designed for egressibility research [30]. This self-assessment questionnaire has already been successfully adopted in the context of qualitative egressibility studies [30] and is currently being adopted for quantitative research.

Table 1: Categories of functional limitations for egressibility research and practice [30].

Category
Seeing
Hearing
Mobility – Head
Mobility – Spinal column and/or lower extremities
Dependency on mobility aids
Dependency on wheelchair
Balance
Stamina
Coordination
Mobility – Upper extremities
Fine hand use
Smell

The use of the aforementioned ICF [21] perspective is central to egressibility. Functional limitations only translate into evacuation disadvantage when environmental or organisational conditions fail to accommodate them. For example, reduced mobility becomes disabling in the presence of stairs without alternatives; visual impairments become disabling when wayfinding relies exclusively on visual signage; cognitive limitations become disabling when evacuation procedures are overly complex or ambiguous.

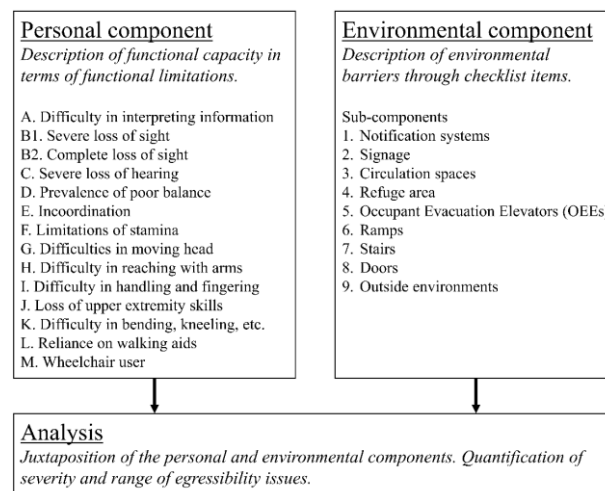


Figure 1: Egressibility through the biopsychosocial model of disability (figure from [20]).

Egressibility therefore depends not solely on individual characteristics, nor solely on environmental design, but on their interaction. This practically means that it is necessary to

perform an analysis between the functional capacity of individuals (the so-called personal component) with the environmental barriers present (so called environmental component). These concepts have been used in development of the Egress Enabler [31], a tool designed to assess egressibility of public buildings. Figure 1 presents a description of factors considered in the personal and environmental components and the analysis that can be performed to assess egressibility [31].

3. METHODS FOR EGRESSIBILITY RESEARCH

Egressibility research builds on a range of methods which are based on evacuation studies [32] while also incorporating approaches specifically designed to understand the interaction between functional limitations and emergency egress systems. Each of these methods present specific strengths and weaknesses for the scopes of egressibility research. In particular, several challenges are associated with ethics and privacy, especially given the people being investigated. Table 2 presents a summary of the methods for egressibility research along with examples of approaches which are discussed in this section.

Table 2: Summary of research methods, along with examples of approaches and relevant to egressibility.

Method	Examples of approaches	Relevance to egressibility
Incident analysis	Literature, reports, media, social media	Understand evacuation responses of different groups
Qualitative studies	Interviews, focus groups, workshops	Ground egress design in lived experience of functional limitations
Behavioural intention studies	Experimental scenarios	Examine how environmental, personal and procedural factors influence evacuation decisions
Experimental investigations	Physical lab experiments	Test cause-effects relationships for different groups
	VR experiments	Safely study complex evacuation contexts for specific type of individuals. Provide multi-sensory stimuli and collect physiological responses
	Drills	Observe evacuation behaviour (possibly of heterogenous populations) at full scale
Evacuation modelling	Agent-based modelling	Test evacuation procedures involving people with functional limitations and simulate people with mobility limitations
	Data-driven modelling	Understand evacuation behaviour and decision patterns for different individuals and groups

Recent research has discussed that a key gap in evacuation research, the lack of knowledge related to people with cognitive limitations, is mostly linked to the difficulties in collecting data on

this specific group due to ethical constraints [33]. In fact, people affected by cognitive limitations may not be able to provide informed consent, meaning that their evacuation behaviour may need to be investigated only through observations from real world events or through their caregivers. Ethical issues associated with evacuation research with people with functional limitations have indeed been highlighted in several studies, e.g., [34,35]. Additionally, careful consideration is needed to avoid reinforcing stereotypes or inadvertently exposing participants to situations that may highlight vulnerabilities, ensuring that the research respects dignity and equality while still generating meaningful insights into egressibility.

3.1. Analysis of real-world incidents

Analysing past evacuation events provides critical insights into human behaviour in emergencies. Reviews of real-world events rely on diverse sources such as official incident reports [9], news media [36], video footage [37], and social media data [38]. Each source offers complementary perspectives, including official valid knowledge base to on-the-ground reactions and public perceptions. A key focus in egressibility research is on how functional limitations influenced evacuation outcomes. By examining patterns in decision-making across different populations, this analysis helps identifying environmental, organisational, and social factors that can facilitate or negatively affect safe egress for different populations.

3.2. Qualitative studies

Qualitative methods provide in-depth understanding of how individuals with functional limitations perceive, interpret, and respond to evacuation scenarios [30]. These methods include semi-structured interviews, focus groups, participatory workshops, and other exploratory approaches that allow participants to describe their experiences and concerns in their own terms. Participants are typically recruited through organisations representing specific groups, such as people with visual, mobility or hearing limitations, pensioner organisations or people affected by particular conditions. Data are analysed using qualitative techniques to identify recurring patterns and shared meanings related to evacuation barriers, coping strategies, trust in systems, and perceptions of safety. Qualitative studies are particularly important in egressibility research because they reveal aspects of evacuation that are not easily captured through observation, experiments or simulation studies, such as perceived autonomy, reliance on others, communication challenges, and emotional responses. These insights help ensure that the design of egress systems is grounded in lived experience rather than assumptions about capability.

3.3. Behavioural intention/vignette studies

Behavioural intention studies (also called vignette studies) allow participants to engage with hypothetical evacuation scenarios in a controlled and standardised manner [39,40]. Vignettes can allow to manipulate several characteristics of the evacuation scenarios, such as the evolution of the fire threat, available information, environmental features, accessibility of evacuation routes, interaction with others, etc. By systematically altering these factors, researchers can observe patterns in decision-making and behavioural intentions among individuals with different functional limitations. Vignettes are particularly useful for collecting data

from large and diverse samples, including people with functional limitations. They also allow exploration of scenarios that are difficult or unsafe to study in real life. The structured nature of vignette designs makes them well suited for identifying how specific environmental or procedural changes influence evacuation behaviour.

3.4. Experimental investigations

Experimental methods remain central to understanding evacuation behaviour under controlled conditions. These methods can be divided into three main categories, namely 1) Physical laboratory experiments, 2) virtual reality experiments and 3) evacuation drills.

Controlled physical laboratory experiments allow precise measurement of movement, perception, reaction time, and decision-making. Participants with diverse functional abilities can be included to evaluate multiple factors affecting evacuation performance. Physical laboratory experiments have been conducted in the past in particular for the specific case of heterogeneous crowds including people with mobility limitations [41].

Virtual Reality (VR) experiments [32,42,43] have gained significant attention in the evacuation research community in recent years, as they provide a safe and immersive platform for studying evacuation in complex or high-risk scenarios. In the context of egressibility, multi-sensory VR environments can allow providing multiple types of stimuli, meaning that inclusive VR experiments can be designed so that they can be deployed with diverse populations, including people with functional limitations. Visual [42,44], auditory [45], haptic [46], and even olfactory cues [47] enable the investigation of how individuals with different functional capacities respond to environmental stimuli in relation to different egress scenarios. In addition, recent research efforts have started investigating the combined use of multi-sensorial stimuli along with physiological measurements of body response. This can include a wide range of data, such as Electroencephalography [48], eye tracking [49,50], and galvanic skin response [51].

Evacuation drills [52] can provide empirical data on pre-evacuation and movement behaviour. Their use in egressibility research requires careful ethical evaluation as they can be physically and psychologically challenging, particularly for participants with functional limitations. The level of knowledge about the drill (announced, unannounced or semi-announced) would affect to which extent participation is voluntary [53]. This means that researchers should carefully evaluate the trade-offs between benefits and risks, specifically for people with functional limitations.

3.5. Evacuation modelling

Computational modelling is an established method in evacuation research. Its applicability to egressibility has so far mostly focused on the use of agent-based models for the simulation of people with mobility limitations and assisted evacuation procedures [54,55]. Existing evacuation models can represent heterogeneous populations by incorporating differences in mobility, pre-evacuation response, and decision-making strategies. Nevertheless, their applicability to populations with functional limitations different than people with mobility impairments is currently fairly limited.

Alongside traditional evacuation simulation, egressibility should benefit from newer approaches based on data-driven modelling. Such approaches can use large datasets collected via different methods to discover relationships between the specific characteristics of a population and their evacuation decisions. Large and diverse datasets are essential for calibrating models so that they accurately reflect the behaviour of heterogeneous populations. Machine learning approaches can detect complex patterns and interactions that may not be visible through conventional statistical methods. However, careful attention is required to ensure that models are transparent (e.g. following principles of ethical AI) and do not introduce bias through uneven representation of functional groups. A potentially interesting approach would be to use data-driven methods for the analysis of virtual reality experimental data, i.e., linking physiological response data with evacuation decisions. This field is currently largely unexplored but has great potential to inform inclusive evacuation design.

4. DISCUSSION AND CONCLUSIONS

The persistent over-representation of people with disabilities among disaster fatalities highlights the inadequacy of current evacuation design and safety practices. Traditional approaches, which adapt systems designed for healthy adults with add-on solutions for “special cases”, fail to accommodate the full spectrum of functional limitations. This paper advocates for the adoption of the biopsychosocial model and the ICF framework as a conceptual foundation for egressibility, emphasising that disability arises from the interaction between individual functional capacities and environmental barriers.

Egressibility represents a shift from designing for an average population towards performance-based, function-oriented safety. By systematically considering sensory, cognitive, and motor capacities in relation to egress components and organisational procedures, evacuation design can move beyond retrospective adaptations to inclusive design. This approach enables the identification of barriers that are not apparent when focusing solely on impairments, and highlights the importance of environmental and procedural factors in enabling safe evacuation for all.

A range of research methods applicable to egressibility have been reviewed, highlighting their ability to provide complementary insights into human behaviour in fire. Ultimately, advancing egressibility requires not only methodological innovation but also ethical and regulatory commitment. Inclusive evacuation design is both a practical necessity and a human-rights obligation, ensuring that emergency safety measures protect all individuals regardless of functional capacity. Egressibility offers a pathway to achieving this goal, bridging the gap between regulatory frameworks, research, and design practice.

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FIRE SAFETY ENGINEERING IN THE AFTERMATH OF THE GRENFELL TOWER INQUIRY



José L. Torero*
Professor
University College London
United Kingdom

Keywords: Fire, External Wall Systems, Design, Engineering.

1. INTRODUCTION

Fire Safety Engineering, as a Professional Discipline, has not been the subject of extensive studies [1]. In contrast with other disciplines such as Civil, Mechanical or Chemical Engineering, where there are entire journals dedicated to professional issues and higher education [2-4], the body of literature is very limited. Furthermore, academic presence in this field is very small and higher-education offerings have mostly evolved out of a single educational framework that emerged in the 1980's [5] to 1990's [6]. Only in the UK, there are more than fifty Chemical Engineering undergraduate offerings with more than a hundred post graduate courses. In Civil and Mechanical Engineering there are more than one hundred undergraduate offerings and an even greater number of post-graduate programmes. In contrast, the number of offerings in Fire Safety Engineering is negligible. A comprehensive review of these programmes can be found in the Warren Centre Report on Education [7].

The construction of a pedagogical foundation to the discipline has only been attempted in the last 10 years [8,9] and its application and evolution has been slow. Nevertheless, the existing pedagogical framework is based on solid theoretical underpinnings [10], appropriate consultation [11] and experiential assessment, hence should be considered as a solid starting point for the establishment of an adequate higher educational pathway that delivers graduates that possess the knowledge and attributes necessary to undertake additional development through properly supervised professional experience.

* José L. Torero — CEGE, University College London, Gower Street, London, WC1E 6BT, United Kingdom.

Telef.: +44 207 679 2756, E-mail: j.torero@ucl.ac.uk

The delivery of a competent engineer that has acquired the knowledge, attributes and experience necessary to be Registered is a two-part process [7], the first part being completion of an appropriate higher education degree and the second, the acquisition of sufficient and appropriately supervised experience. Here, the focus will be the Registered Fire Safety Engineer that will be referred to simply as the Fire Safety Engineer.

Figure 1 shows the professional competency ladder commonly referred to when discussing professional requirements for registration [12]. Each stage of the process is of relevance to professional registration, and all stages are related. Hence, it is generally not possible to separate or omit any of the stages. The initial stage (bottom of the ladder) corresponds to the “entry requirements.” The entry requirements for higher education are guaranteed through a selection process that evaluates the content of the secondary education attainment as well as the performance of the applicants [13]. Not all applicants will have acquired the necessary knowledge and attributes to a sufficient extent to enter engineering higher education. University will evaluate the subjects studied, the level of attainment as well as the individuals understanding, attitudes and motivation towards the discipline to which they are applying. Without these entry requirements there is no guarantee that the necessary knowledge and academic maturity thresholds required to enable the further acquisition of skills and attributes can be achieved [14]. Universities have for centuries studied the relationship between entry requirements and progression and success of students. While there is no perfect correlation between these and the discussion is never closed, what is clear is that a strong relationship exists between entry requirements and progression and success.

Students entering higher education in engineering are expected to follow an undergraduate programme. The undergraduate programmes provide foundational knowledge as well as discipline specific knowledge. The foundational knowledge corresponds to the first step of the ladder, and this generally involves the understanding of the principles that support discipline specific knowledge. Discipline specific knowledge will correspond to the second step.

Multiple pedagogical approaches exist towards the acquisition of knowledge, but there is consensus that modern engineering higher education relies on Problem Based Learning (PBL) [15]. It has been shown that the disciplinary context enables the necessary intrinsic motivation that is essential for the students, not only to cement their knowledge, but also to acquire the necessary attributes that enable them to be industry ready [16]. Accreditation bodies such as the Joint Board of Moderators (JBM) provide guidelines on these matters [17]. This guidance is linked to both higher education programme accreditation and individual registration [18] and defines the many attributes expected from engineers in the AHEP-4 document [19]. Similar systems exist in many countries as well as internationally agreed frameworks such as the Washington or Sydney Accords [20,21].

Table 1 represents typical descriptions of the attributes expected from engineering graduates. The attributes presented in the table are of very general nature and tend to be followed by more detailed attributes. Nevertheless, these attributes will touch on issues such as creative thinking, organization, handling of complexity, lifelong learning, consequences, etc. and therefore will remain general in nature. It is only when specific disciplines are discussed that some specificity is provided.

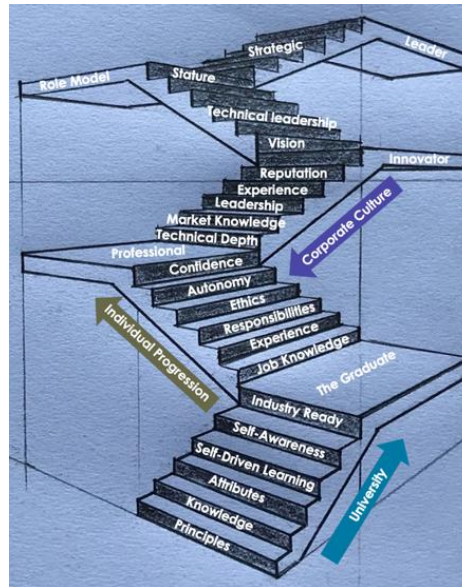


Figure 1: The Professional Competency Ladder

In the case of Civil Engineering, the Joint Board of Moderators describes the graduate attributes in more specific terms. What is expected from a graduate follows statements like: *“Demonstrate, through design work, projects, coursework and/or examinations, a strong awareness of, and commitment to, the principles of regenerative design, intervention which has societal benefit, and sustainable development”* or *“Identify an appropriate range of construction technologies for the project they are working on [17].”* Furthermore, professional skills requirements such as planning, communication, teamwork, client and stakeholder interaction, ethical behaviour and an understanding of the brief, including the functional, social and economic objectives.

Fire Safety Engineering currently lacks a formal definition of such specific attributes. Different studies have aimed to produce these attributes but there is no formal recognition associated to any of these studies [7]. It is consistent among engineering disciplines that the entry point for certification is an accredited Master’s level course, whether it is through an integrated programme, such as a MEng, or through a BEng followed by an MSc. It is clearly stated that to enter an MEng or MSc, you need to have a BEng from an accredited institution with a minimum level of attainment [18]. An alternative pathway is through qualification or apprenticeship at the appropriate level that has been approved or accredited in line with AAQA, [22] for example.

The graduate that meets the exit requirements of an accredited institution of higher education is considered to be industry ready. Graduates who are industry ready have attained a threshold of learning and personal development that enables them to exercise the profession under supervision of a certified professional. The second set of steps follows the graduate as they acquire knowledge and experience through supervised practice. Acquisition of responsibilities and confronting ethical dilemmas will further enable them to attain the level of confidence and

autonomy that frees them from supervised practice. It is at this point where professional certification and/or registration can be achieved.

Professional development is recognized as a lifelong process, where experience, increased responsibilities and the solution of new problems allow the professional to innovate, become a role model and eventually take positions of leadership. It is the innovators, role models and leaders that mould the corporate culture that is transmitted to the graduates in their path towards professionalization. What is described here is consistent among engineering disciplines and is applicable to the Fire Safety Engineer.

Table 1: Comparison of the general engineering graduate attributes presented by the Sydney Accord [21]. These general attributes are followed by more detailed attributes (WK1-WK4, SK1-SK4, DK1-DK4) that are applicable to all engineering disciplines. Each discipline will then define even more specific attributes.

... for Washington Accord Graduate	... for Sydney Accord Graduate	... for Dublin Accord Graduate
Apply knowledge of mathematics, science, engineering fundamentals and an engineering specialization as specified in WK1-WK4 respectively to the solution of complex engineering problems.	Apply knowledge of mathematics, science, engineering fundamentals and an engineering specialization as specified in SK1-SK4 respectively to defined and applied engineering procedures, processes, systems or methodologies.	Apply knowledge of mathematics, science, engineering fundamentals and an engineering specialization as specified in DK1-DK4 respectively to wide practical procedures and practices.

2. DEFINING FIRE SAFETY ENGINEERING AND ITS RELATIONSHIP WITH THE FIRE SAFETY ENGINEER

The definition of what a profession is and who are the professionals who belong to a professional body is difficult. There is no universal approach towards defining the profession. Many times, the expectations on the professional serve to define the profession, but in other case is the profession and its activities that define the professional. While the relationship between the profession and the professional is difficult to break, professional organizations are constantly revisiting how they define the professional context.

The Institution of Structural Engineers focuses on the professional and defines a Structural Engineer as: *“Structural engineers are highly skilled, creative professionals who design the strength and stability of our buildings and bridges. Structural engineers help create record-breaking structures, beautiful structures, useful structures and sometimes just cool structures - anything from bridges, rollercoasters and skyscrapers to hospitals, homes and public artworks. They work as part of a team alongside architects, builders and other engineers. They make sure the building works well in practice, depending on what it is used for: for example, a dance floor shouldn’t vibrate too much when people jump up and down on it. Structural engineers design buildings so they’re strong enough to support the loads on them (like people and equipment) and stable against elements like wind. They usually design buildings to last for fifty years, and bridges for over a century, so their structures are used and enjoyed by thousands, or even millions of people. Structural engineers make sure all our buildings and infrastructure are safe to use. For instance, they study how to stop buildings from falling down during earthquakes,*

hurricanes, and other natural disasters. Structural engineers use many skills to solve problems – from basic maths to cutting-edge technology. They work to design sustainable structures: that is buildings that are larger and longer, but use less material and require less maintenance.”[22]

A very similar approach is used by the Royal Institution of British Architects that defines Architecture through the actions of the Architect: *“Architects are highly skilled and professionally trained to turn your aspirations into reality. They will guide you through the design, planning and construction process whether you are constructing a new building or adapting an existing property. Architects apply impartial and creative thinking to projects large and small. They add value, whether from maximising light and space, adding functionality, or achieving the best return on your investment [23].”*

In contrast, the Institution of Chemical Engineers defines the profession of Chemical Engineering and not the professional. The definition focuses on the activity and its underpinning principles: *“Chemical engineering is the ‘engineering of chemistry’. At its simplest, chemical engineering is the science of transformation, converting one thing to another. Chemical engineers change raw materials into useful, everyday consumer products, focusing on safety, efficiency, and sustainability as their key priorities.”*

In a similar manner, the Institution of Civil Engineers chooses to define the profession of Civil Engineering and only highlight the quality of creativity on the professional. In this case, nevertheless, the focus is not on the activity but on the product: *“Civil engineering centres around the design, construction and maintenance of infrastructure, from bridges to flood defences, wind turbines to tunnels, and more. Civil engineers are creative problem solvers. They work in harmony with the natural environment to keep towns and cities running and to build a more sustainable world.[24]*

In the case of Mechanical Engineering, the Institution of Mechanical Engineers defines Mechanical Engineering through the skills associated to the profession emphasizing the breadth of application: *“Mechanical Engineering encompasses the teaching, practice, leadership, and application of engineering and scientific principles. It delivers and optimises safe, sustainable solutions for the design, construction, production, and operation of systems, devices, machines, structures, and processes. Mechanical Engineering is broad and diverse and frequently involves working in multi-disciplinary teams where mechanical engineering is integral, but not necessarily the primary discipline. Mechanical engineering requires practicing sustainability, integrity, ethics, diversity, and inclusion. It can include functional and management roles, which require an understanding of commercial implications and compliance with legal requirements.[25]”*

The Institution of Fire Engineers follows the same patterns described above when defining Fire Engineering or Fire Engineers. An initial statement points towards what is necessary to “demonstrate” Fire Engineering. IFE states: *“Fire engineering can be demonstrated through the use of scientific and engineering principles, standards and professional judgement[26]”*

The object of the demonstration is then made clear as being the *“protection of people, property and the environment from the adverse effects of fire.”* This is followed by a second statement that establishes that: *“Fire engineers are those who are qualified, competent and skilled in the*

practice of fire engineering.” It can therefore be inferred that those who are qualified, competent and skilled in the practice of fire engineering are those who are qualified, competent and skilled in the demonstration of how people, property and the environment are protected. The statement that follows dictates that Fire Engineers: *“cover a huge range of jobs and come from all different backgrounds.”* Nevertheless, what they all have in common is that they must be qualified, competent and skilled in demonstrating how people, property and the environment are protected. Following the Grenfell Tower Inquiry, Phase II, report [27] the demonstration of how people, property and the environment are protected is the Fire Safety Strategy. Finally, it is stated that *“Fire engineers work closely with many other professions such as architects, designers, lawyers, scientists and other engineers”* which sets a broad context of professional interactions.

Given the above statements, here the definition of Fire Safety Engineering and the Fire Safety Engineer adopts the approach proposed by the Warren Centre, where the object of the Fire Safety Engineer’s work is the Fire Safety Strategy:

“A Fire Safety Engineer should be able to design a robustly defensible fire strategy accounting for all components which that strategy is composed of [7].

The development of the Fire Safety Strategy should be based on *“an ability to apply science and engineering principles,”* thus defining the skills of the Fire Safety Engineer. This simple definition is aligned with the definitions proposed by other disciplines but also is consistent with that proposed by the Institution of Fire Engineers. The necessary next step is then to define what a Fire Safety Strategy is.

3. DEFINING THE FIRE SAFETY STRATEGY

Fire is a physical phenomenon that can occur at any point in the life of any particular space (eg. Building, infrastructure, natural environment, etc.) and that once it is initiated it evolves in space and time and has the potential to negatively affect people and property. For the purposes of this document the space will be a building, but the concepts apply to any space where the evolution of a fire event needs to be controlled.

It is expected that a fire will be initiated during the life of the building, and hence all buildings have provisions to mitigate the impact of a fire. Once the fire is initiated, whenever it occurs, the provisions for fire safety should control the evolution of the event in a manner that the consequences or outcome is socially acceptable. Fire Safety Engineering is therefore governed by two characteristic times, the life of the relevant building (i.e. cradle to grave) and the duration of the fire event.

Explicit performance objectives need to be agreed by all stakeholders and must address both characteristic times. These performance objectives represent, through all stakeholders, what society deems as an acceptable outcome and must include the needs of all people including those most vulnerable.

In what concerns the characteristic time associated to the life of the building, fire safety needs to always be guaranteed and hence it pertains the design process, construction, the operational period and the decommissioning of the building. Construction, refurbishment, retrofit, demolition, and use can all transform buildings and, as a result, the provisions for fire safety may evolve—meaning they are not always static. Fire safety is also influenced by the maintenance of all relevant provisions through the lifetime of the building.

The provisions for fire safety will remain inactive through the lifetime of the building and will only be active during a fire event. This allows for the possibility of implementation of a poor set of provisions in an unnoticed manner and whose flaws will only be evident during the event. Furthermore, it can also allow for the unnoticed deterioration of the fire safety provisions through the life of the building. As a result, appropriate methods by which the adequacy of the provisions are assessed through the life of the space are of critical importance.

The characteristic time associated to a fire event is when all provisions need to respond appropriately. The response of the fire safety provisions to a fire initiation event is a coordinated interaction of all these components in a manner that the evolution in time of the fire event is controlled to deliver an acceptable outcome. The acceptable outcome is delivered the building as a whole so the way the provisions are coordinated is as important as the performance of the individual provisions. The narrative that describes the individual provisions and the coordinated response as a function of time is referred to as the Fire Safety Strategy. The Fire Safety Strategy defines the acceptable performance of the building during the characteristic time of the fire event.

The Fire Safety Strategy will include the individual description of all features of the building that will be either affected by a fire or play a role in managing a fire, including the fire brigade intervention. It will provide a narrative that describes the interaction and sequence of intervention of each provision including any interactions, dependencies and conflicts. It will describe redundancies and measures of robustness as well as establishing the key assumptions enabling the Fire Safety Strategy. Management and maintenance issues important for the correct delivery of the Fire Safety Strategy will be included together with a mapping of all aspects of the strategy that need to be inspected to enable an assessment of the potential performance of the Fire Safety Strategy at each moment in time during the life of the building. Given the relative importance of each component, the sequence of assessment of each individual component might require more or less regular inspections. This sequence of assessment and inspection should also be part of the Fire Safety Strategy. It is important to note, that while more robust or less critical components might require inspections at less regular intervals, the performance assessment will always pertain the integrity of the building and its Fire Safety Strategy. As an example, heavily redundant compartmentation that might experience small changes might require less regular inspections than detection or suppression systems, therefore, when assessing the performance of the Fire Safety Strategy it can be assumed that the compartmentation remains unchanged without an inspection.

The narrative must be accompanied by an explicit demonstration of performance that establishes the potential outcomes of a fire event. These outcomes must be expressed as a function of time and be contrasted with the fire safety objectives accepted by all stakeholders.

The Fire Safety Strategy without the demonstration of performance will be named the conceptual Fire Safety Strategy. As it will be discussed later in more detail, it might be convenient to create this separation to better define the roles and responsibilities of the Fire Safety Engineer and that of the Designer.

It is important to note that the above descriptions are not consistent with current approaches to a Fire Safety Strategy, nevertheless, they are consistent with the definition of the Fire Safety Strategy suggested by paragraph 113.15 of the Phase II report of the Grenfell Tower Inquiry [27]:

“A fire safety strategy for a building should describe its structure and the various fire protection systems it contains and set out how they work together to ensure the safety of the occupants in the event of a fire.”

Furthermore, the Fire Safety Strategy is a term that has been used often over the past 30 plus years, despite the absence of a formal definition having been put forward. Early uses of the term Fire Safety Strategy or Fire Strategy reflect important evolutionary steps in developing consistent approaches to fire safety engineering. An early mention of a fire strategy (but not the earliest) in the scientific literature relates to the development of a fire protection strategy for an airport [28]. The underlying intention was to specify the internal layout of the terminal such that any resulting fire could never overcome the provisions that were in place within the building. The document does not consider the evolution of the fire event in time. The first example of the concept resembling the present description appeared in literature in 2002, in an article promoting design for fire safety based on safety goals and graphically introducing the concept of a narrative [29]. However, the term Fire Safety Strategy itself was not actually introduced until 2011 as part of the description of the knowledge required to design a Fire Safety Strategy for tall buildings [30]. Other examples of the use of the term appeared in 2013 [31,32]. However, it was not until the recent Warren Centre work on Fire Safety Engineering [33], and the publications which followed [34], that an explicit definition was put forward. This definition is similar to that adopted in the draft Australian Society for Fire Safety Practice Guide on Holistic Fire Safety Engineering [35]. However critically, this definition omitted the narrative component, which was re-emphasised in the reporting from the Grenfell Tower enquiry [27]. This evolution of the concept of goals-based design into the definition given above represents a natural evolution of the thought process which must underpin fire safety engineering, and the outcome to the design process which delivers not only the information needed for other stakeholders in construction projects but also the expected fire safety outcomes to society.

Figure 2 shows a schematic of the core of a Fire Safety Strategy for a high-rise building. This example serves to illustrate the different fire safety provisions, their sequence of intervention and the different relationships between provisions. A time sequence is also presented as an example of the results of an explicit performance assessment. Calculations, inputs and assumptions leading to all these times should be clearly presented in the Fire Safety Strategy documentation.

The example does not intend to represent a model of how a Fire Safety Strategy should be presented or constructed. This diagram is simply introduced here to illustrate the multiplicity of

aspects that a Fire Safety Strategy needs to consider. The different provisions are structured following the sequence of their intervention, the areas where provisions that provide redundancy are presented including the Fire Brigades, who, in this case appear as a redundancy to the building performance. The schematic highlights dependencies and potential conflicts as well as indicating areas where performance assessment methods (i.e. structural fire resistance) bring robustness to the design. Building management provisions are not embedded in the flow chart but they will be described in the accompanying narrative, so will be all maintenance provisions required for all elements of the Fire Safety Strategy together with schedules for inspection and key components that enable an assessment.

It is important to note that today, the terminology Fire Risk Assessment is commonly used to amalgamate the inspection and performance assessment aspects of the Fire Safety Strategy. Furthermore, commonly used methodologies like PAS9980 [36] attempt a Fire Risk Assessment without consideration of the Fire Safety Strategy. Such an approach represents more of an inspection report with a subsequent “expert opinion” than a proper performance assessment. An assessment can only be conducted in the context of a Fire Safety Strategy and considering the explicit performance expected of the building as a whole.

The ultimate objective of all fire related aspects of the design process is to deliver a Fire Safety Strategy. This incorporates all aspects related to the provisions for fire safety but also addresses management, maintenance, inspection (elements, process and schedule) and performance assessment through the life of the building. Fire Safety Engineering represents the delivery of the Fire Safety Strategy, and it is the Fire Safety Strategy that defines what a competent Fire Safety Engineer should be capable of delivering.

4. CONCLUSIONS

The Fire Safety Engineer has been redefined as the professional that stewards the Fire Safety Strategy. Part of the role of the Fire Safety Engineer is to interact with other professionals in the delivery of such a strategy, nevertheless, it is the Fire safety Engineer who is responsible for the adequacy of the strategy.

5. ACKNOWLEDGMENTS

The author is indebted to Michael Woodrow and David Lange for many discussions on this matter. Much of what is written here are their ideas.

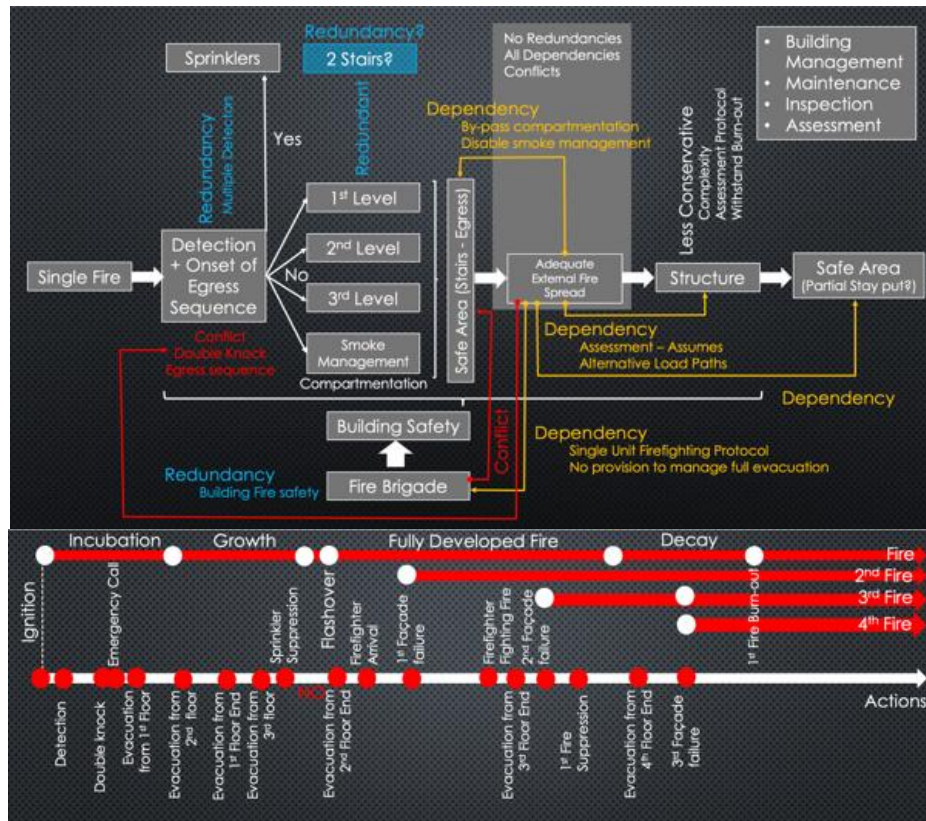


Figure 2: Schematic of the different aspects covered by a Fire Safety Strategy

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A MULTI-SCALE FRAMEWORK FOR ASSESSING WILDLAND-URBAN INTERFACE FIRE RISK TO SUPPORT EMERGENCY PLANNING: APPLICATION TO BARCELONA COMMUNITIES

Elsa Pastor*, Haseeb Kazmi, Adrià Barreiro, Pascale Vacca

Centre for Technological Risk Studies (CERTEC), Department of Chemical Engineering,
Universitat Politècnica de Catalunya

Keywords: wildfire simulations, community vulnerability analysis, performance-based design,
design fire scenarios

1. INTRODUCTION

Wildland–Urban Interface (WUI) fires are increasingly recognised as one of the most complex fire safety challenges of the 21st century. Their growing frequency and severity are driven by climate change, prolonged fire seasons, land-use transformation, rural abandonment, and the expansion of residential areas into fire-prone landscapes. Mediterranean regions are particularly exposed to these processes and the 2025 fire season in Europe illustrates the scale of the problem: the EU season closed with ~1,034,552 ha burned according to the Joint Research Centre's EFFIS-based assessment. In Spain, EFFIS reported ~393,079 ha burned in 2025, placing the country among the most affected in the EU and reinforcing the urgency of WUI-focused preparedness and operational planning. Within Spain, Catalonia experienced severe impacts during the season; for example, a major wildfire in Tarragona province led authorities to impose lockdown measures affecting more than 18,000 people while thousands of hectares burned under strong winds and extreme conditions.

These trends are particularly concerning for metropolitan areas located in direct contact with large forested massifs, where high population density, complex urban morphology, and constrained access routes coexist with continuous wildland fuels. In such environments, wildfire becomes not only an environmental hazard but a significant urban safety and civil protection challenge, where evacuation feasibility, confinement strategies, and protection of vulnerable populations pose critical operational difficulties for emergency services.

Fire services and civil protection authorities are increasingly required to move from a reactive posture to an anticipatory, risk-informed approach to WUI fire management. This involves not only forecasting potential wildfire behaviour under extreme meteorological and fuel conditions, but also understanding how fire propagates through communities, how residents and the built environment respond under time pressure, and how operational constraints such as access or safe refuge options shape emergency outcomes. In practice, this demands tools that allow authorities to explore credible fire scenarios in advance, identify vulnerable neighbourhoods,

* Corresponding author — Centre for Technological Risk Studies (CERTEC), Department of Chemical Engineering, Universitat Politècnica de Catalunya. C.
Eduard Maristany, 16, 08019 Barcelona (Spain)
Telef.: +34 934011090, E-mail: elsa.pastor@upc.edu

pre-define evacuation or confinement strategies, and allocate resources according to expected impact rather than historical experience. Such a shift towards anticipatory planning is consistent with recent calls in wildfire risk science [1–3] and European policies [4–7] to strengthen community resilience through improved understanding of exposure and vulnerability.

This need for integrated planning reflects the intrinsically multi-scale nature of WUI fire risk, where interacting processes occur at the landscape, settlement, and homeowner levels [8]. Each scale is associated with different yet complementary management actions, from fuel and suppression planning at landscape level, to community protection measures at settlement level, and mitigation of structure vulnerability in the immediate surroundings of buildings. However, despite advances in wildfire modelling and fire safety engineering, current assessment approaches often remain fragmented across these scales. Fire spread simulations, evacuation / confinement analyses, and building exposure studies are frequently developed independently, limiting their ability to inform operational planning in a coherent manner. This separation reduces the practical usefulness of scientific tools for decision-making and highlights the need for frameworks that explicitly link fire dynamics, community vulnerability, and building exposure within a unified approach [9,10].

The objective of this paper is to develop and demonstrate an integrated multi-scale WUI risk assessment framework for WUI communities in metropolitan areas that directly supports pre-incident planning by fire services and civil protection authorities. The proposed framework seeks to bridge the gap between wildfire behaviour modelling, fire safety engineering, and community vulnerability analysis by connecting modelling and assessment at three interconnected scales: the property scale, the community scale, and the landscape scale. The paper is structured as follows: the next section presents the overall framework and describes the methods used to analyse wildfire hazard at landscape scale, community vulnerability in terms of evacuation and confinement capacity, and building-level exposure, and explains how these elements are combined into decision-support outputs for first responders. This is followed by a case study illustrating the preliminary results of the application of the framework to a real WUI community within the municipality of Barcelona (Spain). Finally, the conclusions summarise the main findings and discuss the scalability and transferability of the proposed approach to other metropolitan WUI contexts.

2. METHODOLOGY AND FRAMEWORK DESCRIPTION

2.1 Overall workflow

The proposed framework is presented in Figure 1. First, wildfire hazard is defined at the landscape scale by selecting representative scenarios on how fire may propagate from the surrounding terrain toward the WUI community. Guided by relevant WUI wildfire impact situations that represent the types of emergency conditions responders may face, and grounded in the local fire regime (fire history, fire weather, fuels, and topography), these scenarios provide the basis for estimating fire behaviour metrics and preferential spread pathways under severe but plausible conditions. Fire design scenarios can consider ignition points located close to the WUI (i.e., rapid onset fires) or fires that develop over large forested areas before impacting a community.

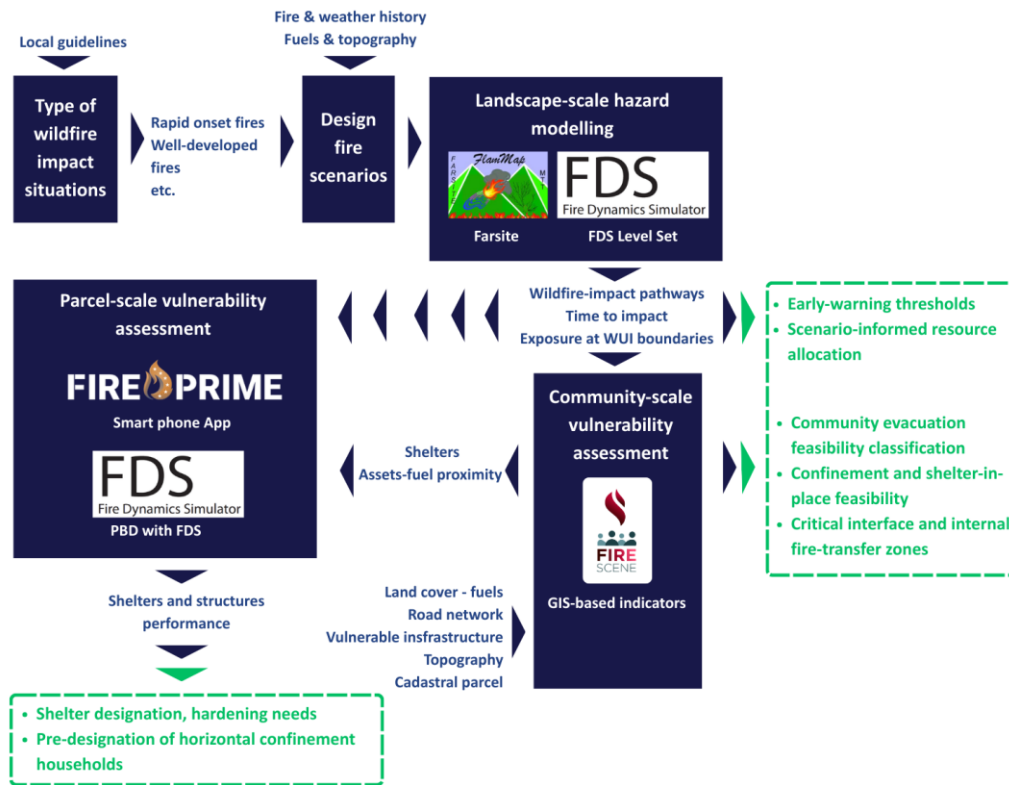


Figure 1: Workflow of the proposed framework. Blue boxes indicate the tasks and methods used to perform them, together with their corresponding inputs and outputs. Green boxes highlight outcomes that are directly relevant for operational pre-incident planning.

The defined design fire scenarios are then simulated. The modelling approach is adapted to the type of fire scenario considered, distinguishing between rapid onset fires and well-developed fires. In the latter case, FARSITE [11] is used to simulate fire spread at landscape scale and to derive time-dependent exposure conditions at the WUI boundary. For rapid onset fires, FDS Level Set [12] is applied to analyse fire behaviour closer the community, allowing a more detailed representation of wind–terrain interactions and fire propagation where local effects become critical.

Simulation results are then used to evaluate community capacity and constraints in terms of evacuation and confinement feasibility, and to define realistic exposure inputs for the building-scale vulnerability analysis of structures located along the WUI perimeter in direct contact with

the wildland. Community response capacity is assessed at two complementary levels: first, by considering wildfire exposure at the outer community boundary derived from the simulations; and second, by evaluating internal vulnerability indicators that characterise its potential fire behaviour within the settlement, its size and morphology, the vegetation–asset interaction, the presence of critical infrastructure and vulnerable occupants, and the egress and emergency vehicle accessibility within the WUI community [13].

At the building scale, the framework incorporates two different methodologies: a performance-based design (PBD) analysis [14], applied to buildings that could potentially function as temporary shelters which is informed by the landscape-level simulation results to account for wildfire exposure; and a quantitative risk assessment method [15], applied on a house-by-house basis, particularly for dwellings located along the community perimeter and directly exposed to the approaching wildfire front.

The results of these analyses are ultimately integrated into decision-support processes for emergency pre-planning, assisting authorities in resource allocation for anticipatory and suppression actions, and in preparing evacuation and confinement strategies at both community and sub-community (e.g., horizontal confinement) levels.

The following sub-sections describe each step of the framework in detail, providing the methodological explanation and the justification for the choices made at each stage of the analysis.

2.2 Wildfire hazard and scenario definition

As described above, this first step involves selecting representative design fire scenarios—based on relevant wildfire impact situations and the local fire regime—to simulate how wildfire may reach a WUI community and quantify the exposure needed for subsequent community and building vulnerability assessments.

Wildfire impact situations

In WUI environments, distinguishing between different wildfire impact situations is essential for defining representative design fire scenarios and anticipating the operational challenges that responders may face. These situations describe how a fire originates, develops, and reaches the community, and are therefore framed from an operational perspective. Recent Spanish guidance for WUI emergency planning explicitly proposes a typology of wildfire impact situations based on their dynamics and implications for response [16]. This classification, which is consistent with international WUI planning literature [e.g. 17, 18], is adopted here to define the design fire scenarios used in this study.

According to the Spanish WUI guideline [16], a first and particularly critical scenario corresponds to *rapid onset fires*, in which ignition, fire growth, and impact on the WUI occur within a very short time frame. These events are typically characterised by very fast rates of spread, often driven by wind and slope, leaving emergency services with minimal time to organise a response. In such cases, evacuation is frequently not feasible and the existence of

pre-established action plans, including potential confinement areas, becomes essential. These fires are especially dangerous when ignitions occur at the bottom of slopes or narrow valleys, where topographic acceleration can lead to short but extremely rapid uphill runs. A second scenario described in [16] involves a *well-developed fire front* impacting the WUI perimeter, where a consolidated wildfire advances toward a populated area. Response times are generally longer, allowing emergency services to anticipate the impact and prepare the interface zone. Under these conditions, evacuation is often the preferred strategy, as removing the civilian population reduces the complexity of the emergency. This situation may represent a worst-case scenario when associated with high-intensity or plume-dominated fire behaviour. A third scenario identified in [16] corresponds to a *fire originating within the WUI settlement* itself, immediately threatening people and assets. In this case, fire may spread internally through the urbanised area and potentially propagate towards adjacent wildland fuels. The evolution of the event depends strongly on the WUI typology, the continuity of combustible elements between properties, the presence of ornamental and structural fuels, the implemented preventive measures, and the effectiveness of the initial response.

Local fire regime and fire behaviour patterns

Design fire scenarios should be defined as representative, high-impact combinations of ignition location, fuel conditions, topography, and fire weather that are plausible for the study area and informative for emergency planning [19–21]. Rather than relying on a single arbitrary “worst case,” the literature recommends grounding these scenarios in the local fire regime and historical records, which guide the selection of ignition locations, weather inputs, and fuel-moisture conditions that correspond to severe but credible fire behaviour during the active burning period. This typically involves percentile-based weather characterisation together with fuel moisture assumptions consistent with summer fire-spread conditions.

A key component of this process is the identification of likely ignition patterns. This is commonly achieved by analysing the spatial distribution of historical fire origins in relation to topography and slope aspect, as these factors strongly influence both where ignitions occur and how fires subsequently propagate across the landscape [e.g. 20, 22]. Such analyses help identify recurrent corridors toward WUI communities and therefore guide the placement of representative ignition points for scenario simulations. Fuel moisture conditions are generally incorporated using two different approaches. One consists of dynamically estimating moisture from weather observations or fire danger indices for the specific dates being modelled, aiming to reproduce the actual fuel state during those events [e.g., 23]. The other assigns fixed fuel-moisture sets representing different severity levels (e.g., “severe” and “very severe” summer conditions), a practice frequently adopted in planning-oriented fire spread modelling where consistency with fire weather is prioritised over day-specific accuracy [e.g., 24, 25].

In many regions, detailed post-fire analyses have also led to the identification of recurrent fire spread patterns associated with characteristic combinations of topography and fire weather. In Catalonia, for example, ten typical fire spread patterns have been described (e.g., topographic standard, coastal topographic, wind-driven, wind-driven with relief, plume-dominated) [26]. These classifications, together with the specific features of the study area (terrain, prevailing fire weather regimes, and fuel continuity), provide an additional framework for defining design fire

scenarios. In this context, regional initiatives such as PREVINCAT [27] provide repositories of documented fire events and predefined scenario descriptions that can be used to inform scenario selection in a structured and context-specific manner.

Overall, in this work, the definition of design fire scenarios is framed as a general procedure intended to represent the main wildfire impact situations that can affect WUI communities while remaining compatible with operational planning needs. In our approach we select rapid-onset fires, characterised by short time-to-impact at the settlement, and well-developed fire fronts advancing from the surrounding landscape. Fires originating within the community are not considered, as in compact metropolitan WUI settings their development is typically limited compared with externally approaching wildfires. For rapid-onset situations, we propose defining scenarios by: (i) identifying potential ignition locations within a short buffer around the settlement (in the order of hundreds of metres) that combine terrain and fuel configurations favourable to rapid fire arrival, such as canyon bottoms or toe-of-slope areas aligned with dominant wind directions; (ii) selecting weather inputs from historical observations by identifying prevailing wind regimes and choosing severe but representative hours, whose meteorological variables are used directly in the simulations; and (iii) assigning fixed fuel-moisture sets consistent with the severity of the selected weather conditions. For well-developed fire fronts, scenarios are defined following two complementary approaches. First, significant historical wildfire events are reproduced to capture documented fire-spread dynamics under known conditions. Second, additional scenarios are constructed using a rationale similar to that applied for rapid-onset fires, but considering ignition points located at greater distances within the surrounding forested areas and aligned with the prevailing wind direction toward the community. In this case, weather inputs are again selected from historical records for the relevant wind regimes, but corresponding to very severe meteorological conditions and associated fuel-moisture content sets.

Globally, the aim of this procedure is to generate a limited yet representative set of design fire scenarios that are both physically plausible and operationally meaningful, providing a structured basis for subsequent wildfire spread simulations and vulnerability analyses in WUI contexts.

2.3 Wildfire hazard simulation

Operational wildfire simulators such as FARSITE are widely used in planning contexts to translate predefined scenario inputs into spatial fire-behaviour indicators, including rate of spread, fireline intensity, flame length, and dominant spread pathways [11]. These outputs can be directly interpreted as exposure patterns for communities and assets and, importantly, expressed in terms of time-dependent fire arrival and intensity at the WUI boundary, variables of direct relevance for emergency planning and vulnerability assessment.

In parallel, recent research has increasingly adopted ensemble or probabilistic simulation approaches—such as burn probability, conditional flame length, or likelihood-weighted intensity metrics—to characterise the range of possible wildfire outcomes across landscapes (e.g., [28]). While these approaches are valuable for strategic risk analysis and long-term prioritisation, they

are less suited to the detailed exploration of a limited number of high-impact scenarios required for pre-incident operational planning.

A further limitation is that, despite advances in wildfire modelling, no currently available operational fire spread model is capable of explicitly resolving the complex and detailed configuration of WUI environments, where vegetation, buildings, and small-scale terrain features interact. Research efforts are progressively addressing this gap by enabling finer-scale representation of fire–structure interactions [29], but these approaches remain computationally demanding and not yet operationally applicable at landscape scale.

In this context, the proposed methodology adopts a dual modelling approach tailored to different wildfire impact situations. FARSITE is used to simulate design fire scenarios involving well-developed fire fronts, which typically evolve over longer time scales, originating at larger distances. This allows an efficient representation of landscape-scale fire spread. In contrast, FDS Level Set is used to simulate rapid-onset fire scenarios in which ignition occurs close to the settlement and fire impacts develop over short time scales. This modelling approach allows fire propagation to be analysed at finer spatial and temporal resolution, explicitly capturing the influence of local wind, terrain, and proximity to buildings. Such detail is particularly important near WUI communities, where small-scale features can strongly affect fire behaviour and exposure. The combined use of FARSITE and FDS Level Set is therefore driven by operational relevance and computational efficiency, ensuring that higher-resolution simulations are applied where they provide the greatest added value for assessing exposure and vulnerability at the WUI.

2.4 Exposure and vulnerability assessment at community scale

At the community scale, the risk of a WUI settlement being severely affected by wildfire depends on several interacting factors. These include the potential for fire to propagate through the settlement—largely influenced by the WUI typology (e.g., intermix, interface) and by the fire intensity, which is itself conditioned by terrain and fuels. In addition, socio-demographic characteristics, road access, and the quality of the internal road network play a key role in how the community responds to a fire emergency, determining whether confinement or evacuation strategies can be effectively implemented.

Community-scale vulnerability assessment frameworks in the literature typically analyse how spatial configuration, built characteristics, accessibility, vegetation proximity, and social factors influence settlement susceptibility to wildfire, without explicitly modelling fire spread within the community. These approaches combine such variables into composite indices representing inherent vulnerability under assumed exposure conditions ([30, 31]). In this context, Vacca et al. [2] proposed a Structural Vulnerability Index tailored to WUI settlements, integrating indicators related to exposure, internal propagation potential, and emergency response capacity.

Building on this work, the approach adopted here translates these indicators into an assessment of how challenging or feasible it is to implement evacuation or shelter-in-place strategies for emergency planning. The methodology, developed within the FIRESCENE project [13], evaluates WUI community capacity for both evacuation and confinement using a set of

GIS-based, automated indicators describing external and internal settlement characteristics. External exposure indicators are derived from landscape-scale fire simulations, while internal indicators characterise potential fire behaviour within the settlement, its size, vegetation–asset interaction, the presence of vulnerable infrastructure, and accessibility for evacuation and emergency vehicle access. Potential fire behaviour is represented through two indicators—fire transfer capacity and potential fire intensity. Settlement size and asset–fuel interaction reflect overall internal exposure conditions, whereas accessibility is evaluated through road quality and the number of independent access points. Most indicators inform the feasibility of confinement strategies, while settlement size, vulnerable infrastructure, and accessibility are particularly relevant for evacuation planning (Table 1).

Table 1: Indicators included in the exposure and vulnerability assessment at community scale

Indicator	Categories	Confinement challenges	Evacuation Challenges
Fire transfer capacity	Intermix, interface, isolated	Included	
Fire intensity	Low / Medium / High	Included	
WUI Size	Big / Small	Included	Included
Assets-fuel proximity	Low /High	Included	
Presence of Vulnerable infrastructures	Low /High	Included	Included
Road quality	Poor / Adequate		Included
Number of accesses	Low / High		Included

2.5 Building-scale vulnerability

Parcel-scale vulnerability analysis examines how fire can reach a building through the fuels present in its immediate surroundings—whether wildland fuels, ornamental vegetation, or man-made elements—and how the building itself responds to fire exposure. This involves assessing both the pathways by which flames and heat can impinge on the structure and the susceptibility of the building envelope and systems to sustain that impact. A range of methodologies addressing this problem can be found in the literature.

Several studies have proposed indicator-based frameworks to assess building vulnerability in WUI contexts by combining structural characteristics, defensible space, and surrounding fuel conditions into composite scores. Early approaches, such as the WUI Building Risk Index [32], relied on expert-driven weighting, while more recent works increasingly draw on post-fire damage observations to identify and weight the most relevant predictors of impact [33,34].

Other authors adopt multi-criteria or fuzzy-logic formulations to represent vulnerability as a gradual condition rather than fixed classes, incorporating both building features and fuel proximity [35, 36]. Alongside these indicator-based approaches, more detailed methodologies grounded in performance-based design (PBD) have emerged, where building vulnerability is assessed through physics-based analysis of fire exposure. These approaches rely on Computational Fluid Dynamics (CFD) simulations to quantify heat transfer, flame attachment, and ignition potential at façades, openings, and other vulnerable elements (e.g. [14]).

The framework proposed here combines both perspectives. A simplified risk assessment is first applied to buildings located along the community perimeter, where the highest wildfire impact is expected. This is performed using an operational version of the method developed in [36] within the FIREPRIME project [15], implemented through a smartphone application to facilitate field assessment. Subsequently, a more detailed PBD analysis is conducted for selected buildings that may serve as potential community shelters, allowing a thorough evaluation of their capacity to withstand wildfire exposure.

2.6 Integration and decision-support outputs

Overall, the proposed framework is based on the integration of hazard, exposure, and vulnerability results across scales into a coherent set of decision-support outputs tailored to pre-incident planning. Landscape-scale fire simulations provide time-dependent estimates of fire arrival, intensity, and approach pathways at the WUI boundary for a specific set of design fire scenarios that reflect local fire history and fire weather conditions in a systematic manner. These outputs are combined with community-scale vulnerability indicators to characterise not only whether a settlement is exposed, but also how difficult it may be to manage that exposure in operational terms. In parallel, building-scale analyses refine this picture by identifying structures that are particularly vulnerable to fire impact, as well as those that may offer adequate performance to support shelter-in-place strategies under specific scenarios. The integrated outputs are translated into planning-relevant information that can be directly used by fire services and civil protection authorities. These include the identification of scenarios and neighbourhoods with limited evacuation feasibility, areas where horizontal confinement may be preferable, priority zones for fuel treatment or access improvement, and buildings suitable for use as temporary shelters under defined fire scenarios. By explicitly linking expected fire behaviour to community response capacity and building performance, the framework supports scenario-based pre-planning, resource allocation, and the definition of response strategies before an emergency occurs. In this way, the methodology shifts the use of modelling tools from post-event analysis or generic risk screening toward anticipatory, operationally grounded decision-making in metropolitan WUI environments.

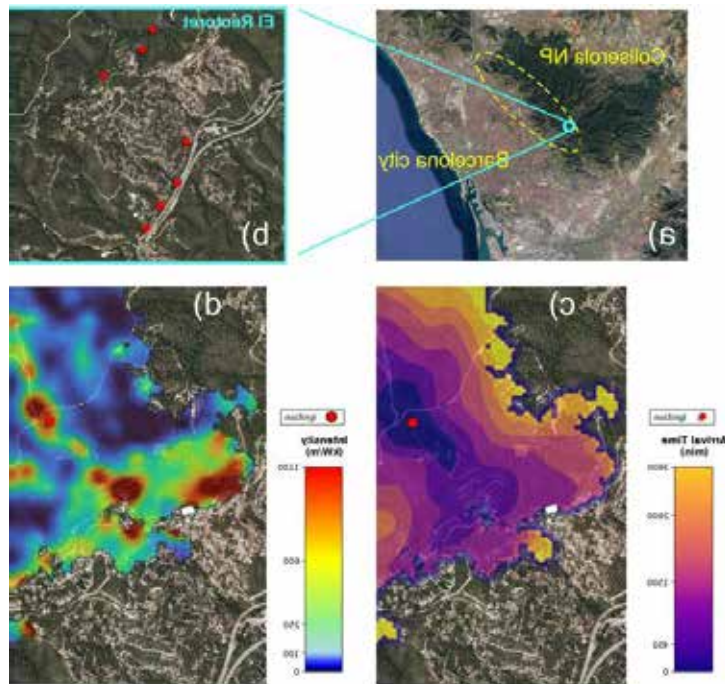
3. CASE STUDY: BARCELONA WUI COMMUNITIES – CAN RECTORET

3.1 Description of the study area

Barcelona, like many Mediterranean metropolitan areas, has progressively expanded toward surrounding forested landscapes, leading to the development of residential areas within the

WUI. Much of this expansion has occurred along the perimeter of Collserola Natural Park, where several neighbourhoods were built without specific consideration of wildfire risk or WUI fire management principles. As a result, these areas combine high wildfire exposure with complex topography, strong vegetation–asset interaction, and constrained access for emergency response. Moreover, the WUI of Barcelona is densely inhabited, hosts diverse sociodemographic profiles, and is intensively used for recreational activities, increasing both exposure and operational complexity during wildfire emergencies.

From an operational perspective, wildfire emergency planning and response within the WUI areas of Barcelona municipality fall under the responsibility of Bombers de Barcelona, in coordination with regional fire and civil protection agencies. Within the municipal boundary, ten WUI neighbourhoods are directly exposed to wildfire risk from the natural park. This relatively limited number of communities offers a valuable opportunity to develop detailed, community-specific wildfire risk assessments and to integrate them into finescale preincident planning practices.



In the following subsection, the framework is applied to one of these ten neighbourhoods, El Rectorat (Figure 2), which is characterised by detached housing, steep terrain, narrow access roads, and a high degree of vegetation continuity within and around the settlement. The neighbourhood is exposed to potentially high-impact wildfire scenarios under the predominant synoptic weather conditions that have historically led to severe WUI fire events in the Barcelona metropolitan area. El Rectorat also contains a civic centre designated as a potential community shelter, located along the northern boundary of the settlement.

3.2 Workflow application – preliminary results

Several scenarios were defined to analyse wildfire hazard in El Rectorat. Rapid-onset fire scenarios were constructed by selecting 7 ignition points within a 500 m buffer around the settlement (see Figure 2), prioritising terrain–fuel configurations that favour short time-to-impact, such as canyon bottoms and toe-of-slope locations aligned with dominant wind directions. Ignition locations were identified based on topography, fuel continuity, drainage structure, and proximity to access routes. Weather scenarios were derived from historical observations at the Fabra Observatory located within the natural park. Hourly records from 2000–2025 were filtered to warm months (May–October) daytime hours (11:00–19:00), and a wind-rose analysis identified two dominant wind-direction families (SW and NE). Within each family, representative historical hours near the P90 wind-speed percentiles were selected to define severe but physically consistent design weather conditions.

For well-developed fire fronts, three scenarios were defined following the criteria described above. The first scenario involves a large, long-running wildfire developing under north-easterly winds, with an ignition point located approximately 1 km from the boundary of El Rectorat. The second scenario represents a large, long-running wildfire developing under south-westerly wind conditions, with an ignition point located in Molins de Rei, approximately 5 km from El Rectorat. Both scenarios were simulated under very severe weather conditions (P95 level) with corresponding fuel-moisture contents, representing potentially high-impact fire fronts approaching the community from the surrounding forested landscape. The third scenario reproduces the historical conditions of the Sant Cugat del Vallès wildfire of 11 August 1994, which occurred under severe summer weather and spread rapidly through forested slopes driven by north-westerly winds. The fire burned approximately 150 ha of vegetation, caused damage to several dwellings and infrastructure, and led to the evacuation of dozens of residents.

Figure 2 presents the results of the first scenario defined as a well-developed fire front driven by north-easterly winds. The simulation shows that, in the absence of suppression activities, the wildfire reaches the north-eastern boundary of El Rectorat approximately 15 hours after ignition, first impacting the outer row of houses. The fire then requires around 25 hours to reach the designated community shelter. These timelines are operationally relevant, as they indicate that this scenario allows sufficient time for planned evacuation and coordinated response, rather than requiring immediate confinement measures. In addition, the simulation estimates that the community shelter would be exposed to a fireline intensity of approximately 1000 kW/m, information that directly informs the subsequent building-scale vulnerability analysis and supports decisions regarding shelter suitability, hardening measures, and protection priorities under this fire scenario.

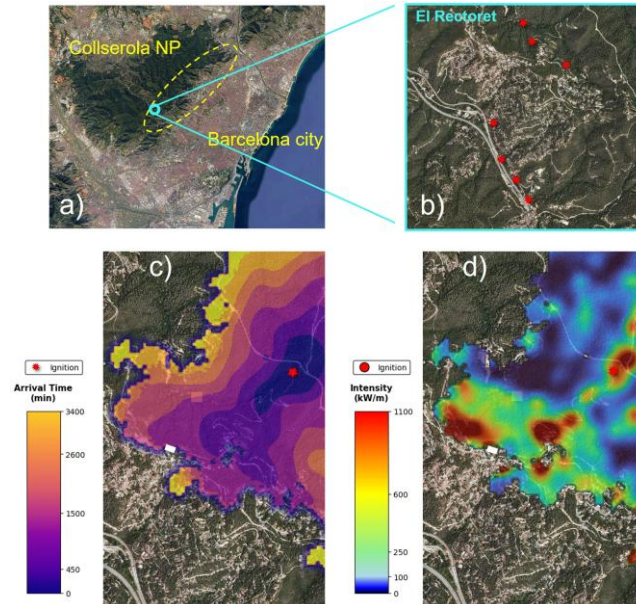


Figure 2: a) Location of the case study, with yellow dashed area indicating the WUI of the municipality of Barcelona; b) El Rectoret neighbourhood, where red stars indicate the ignition points of the rapid-onset design fire scenarios; c) fire arrival time map and d) fireline intensity map for the first well-developed design fire scenario (north-easterly wind-driven), with the ignition point indicated by a red star and the community shelter highlighted by a white rectangle.

Regarding the community-scale exposure and vulnerability assessment, the indicators calculated following the FIRE-SCENE methodology [13] characterise El Rectoret as a WUI intermix settlement. This configuration favours fire propagation within the community, with potentially high fire intensity driven by the combination of dense pine forest fuels and complex topography, including steep slopes and canyon features. The settlement is also relatively large in the context of Catalan WUI communities, with a high degree of vegetation–asset proximity and the presence of vulnerable infrastructures, all of which make confinement strategies particularly challenging. In terms of evacuation, the internal road network presents notable constraints, as streets are narrow and winding, limiting manoeuvrability for emergency vehicles. However, the relatively high number of access points connecting the neighbourhood to the surrounding road network improves overall egress capacity, making evacuation a plausible option when sufficient lead time is available.

At the building scale, a set of structures was selected for detailed vulnerability analysis based on the results of the landscape-scale hazard assessment. These included, among others, the first row of houses along the NE boundary of El Rectoret, as well as the building identified as a potential community shelter, both directly exposed to the approaching north-eastern design fire fronts. Figure 3 shows the community shelter together with the results of the quantitative fire risk assessment obtained using the FIREPRIME App [15], which operationalises the risk

assessment algorithm proposed in [36], as well as selected outputs from the PBD analysis used to evaluate its potential vulnerability under the considered fire scenarios. According to the results, the shelter presents a high risk of fire spread to the building, driven by the presence of natural and non-natural combustible elements in close proximity to the façades, as well as structural vulnerabilities associated with unprotected glazing systems.

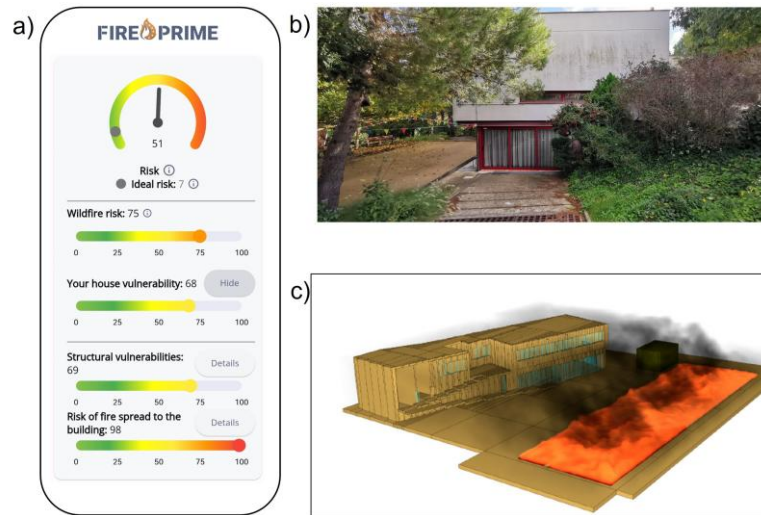


Figure 3: Vulnerability analysis of the community shelter: (a) screenshot of the main results screen of the FIREPRIME App showing the calculated risk level (51); (b) photograph of the community shelter (NW façade); (c) FDS-Smoke view of the NE façade of the shelter impacted by a design wildfire scenario.

The preliminary results provide insights that are directly relevant for emergency planning. They indicate the need to harden the community shelter structure—particularly by protecting glazing systems on the NE façade—expand and prioritise fuel treatments, especially along the north-eastern boundary where the shelter is located, and plan for evacuation or horizontal confinement of the first rows of houses exposed to potential fire fronts approaching from the north-east. In addition, the results highlight critical access and exposure conditions that can inform pre-positioning of firefighting resources and early-warning actions. Ongoing analyses will further extend these findings by providing guidance on response strategies for south-westerly fire scenarios, including longer lead times, evacuation phasing, and protection of critical access routes.

4. CONCLUSIONS

This paper presented an integrated multi-scale framework for WUI wildfire risk assessment that links landscape-scale fire hazard, community-scale vulnerability, and building-scale exposure within a coherent, scenario-based methodology. By connecting wildfire simulations with spatial vulnerability indicators and targeted building analyses, the framework addresses the

fragmentation that often limits the operational usefulness of existing approaches. The main methodological contribution lies in the structured integration of modelling tools across scales, aligning model complexity with operational relevance. The application to a metropolitan WUI community demonstrates how the framework can generate outputs that are both scientifically robust and directly applicable to pre-incident planning. In practice, these outputs can be incorporated into existing planning instruments, including evacuation and confinement protocols and municipal emergency plans. Scenario-specific timelines of fire arrival support the definition of decision triggers, while community vulnerability classifications and building-level assessments inform prioritisation, shelter designation, and resource deployment. Although demonstrated for a case study in Barcelona, the framework is transferable to other Mediterranean WUI cities facing similar wildfire challenges.

5. ACKNOWLEDGMENTS

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Session 1

Sesión 1

Sessão 1

INFLUENCE OF PARTICLE SIZE AND SAMPLE SIZE IN THE THERMAL SUSCEPTIBILITY OF SOLID BIOMASS



Blanca Castells Somoza*

E.T.S. Ingenieros de Minas
y Energía & Laboratorio
Oficial J.M. Madariaga
(LOM)- TECMINERGY,
Universidad Politécnica de
Madrid, Spain



Bjarne C. Hagen

Western Norway University
of Applied Sciences,
Haugesund, Norway



Nieves Fernandez-Anez*

Western Norway University
of Applied Sciences,
Haugesund, Norway

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1. INTRODUCTION

Solid biomass materials are widely used in energy production, industrial processes, and storage applications, which makes their fire and thermal hazard characterization a critical aspect of fire safety engineering. One of the key parameters influencing the ignition and self-heating behaviour of biomass is its thermal susceptibility, which is strongly affected by the physical characteristics of the material [1, 2]. Among these characteristics, particle size and sample size play a fundamental role in heat transfer, oxygen diffusion, and reaction kinetics, directly impacting the likelihood of thermal runaway and spontaneous ignition [3, 4, 5].

Thermal susceptibility can be determined using thermogravimetric analysers (TGA), measuring the loss of weight that a sample loses when heated at a controlled heating rate. This technique has gained popularity, being used to characterise solid materials as well. However, the use of this technique has not been standardized for achieving the same goals, making it challenging to compare results from different sources.

Nevertheless, TGA presents several limitations that cannot be overcome, mainly related to the size of the samples that can be tested, normally of the order of μL (size) [6]. The use of these limited size questions the representativity of the tests, not ensuring homogeneity, and not allowing for testing of particle sizes different than dust ones. However, new developments in the machinery

* Corresponding author: nieves.fernandez@hvl.no

have allowed the introduction of larger sample holders that allow the test of larger fractions of samples and different particle sizes.

Previous studies have demonstrated that variations in particle size can significantly alter the thermal response of biomass, as smaller particles typically exhibit higher surface-area-to-volume ratios, leading to enhanced oxidation rates and heat generation. Similarly, sample size influences internal heat accumulation and dissipation, which are critical factors in self-heating phenomena. However, despite their recognized importance, the combined and systematic influence of particle size and sample size on the thermal susceptibility of solid biomass remains insufficiently understood, particularly under controlled experimental conditions relevant to fire safety assessments.

To characterize biomass, their kinetic reactions can be studied, and the kinetic parameters of thermal decomposition, oxidation, and pyrolysis processes are defined. To obtain meaningful kinetic parameters for biomass samples it is essential to test multiple heating rates, small sample mass in a controlled atmosphere [7]. These TGA-derived kinetic parameters are used for self-heating and spontaneous ignition modelling, thermal susceptibility assessment, numerical simulations of smouldering and ignition, and comparison of biomass with different particle sizes or treatments [8 - 11].

From the thermogravimetric analysis is possible to define kinetic parameters such as the activation energy (E_a), which provides insightful information to understand the thermal reactivity and the decomposition mechanisms that take place when performing sample's combustion and pyrolysis. Because of that, in the last decades several authors have focused on defining the kinetic parameters of different biomass samples, specially using model-free methods such as Friedman, Kissinger-Akahira-Sunose (KAS) and Flynn-Wall-Ozawa (FWO) [12]. Indeed, activation energy for wood pyrolysis and combustion has been largely determined, reporting values in a wide range: between 65 and 190 kJ/mol when using KAS and FWO models [13, 14, 15, 16], and slightly lower values when applying Friedman method [17, 18]. Although it is known that the size and geometry of the crucible impact the test results [19, 20], biomass kinetic studies typically use only one crucible size which is often not reported, and linear heating rates are applied (usually 5, 10, 15 and 20 K/min). Therefore, although it is known that sample mass, and crucible size and geometry might impact the reaction results [21, 22], there is a lack of studies that focus on determining these differences or addressing this issue.

In this context, the present study aims to experimentally investigate the influence of particle size and sample size on the thermal susceptibility of solid biomass. By conducting controlled laboratory experiments and analysing temperature evolution and self-heating behaviour, this work seeks to clarify how these parameters affect thermal stability and ignition propensity. The results contribute to a better understanding of biomass fire hazards and provide valuable insights for risk assessment, safe storage design, and the development of preventive measures in fire safety engineering applications.

2. MATERIALS AND METHODS

2.1 Materials

Wood pellets have been tested to analyse the influence of particle size and crucible size in their thermal susceptibility. These wood pellets are commercially available from SolørBioenergi, with specifications of an energy content of 17.28 MJ/kg, moisture content of 7-9 % and ash content of 0.5%.

The pellets were tested in three particle sizes, one of less than 1 mm, one of more than 1 mm and pellets as available. For the first two particle sizes, the pellets were milled and sieved with a 1 mm mesh sieve, and the fractions were separated as bigger than and smaller than and tested. The pellets have a medium length of 6 mm and a medium width of 3 mm.

Table 1. List of tests developed

Particle size	Heating rate	Crucible size
Less than 1 mm	5 K/min	85 µL
		3.4 mL
		5 mL
	13 K/min	85 µL
		3.4 mL
		5 mL
	20K/min	85 µL
		3.4 mL
		5 mL
More than 1 mm	5 K/min	85 µL
		3.4 mL
		5 mL
	13 K/min	85 µL
		3.4 mL
		5 mL
	20K/min	85 µL
		3.4 mL
		5 mL
Pellets	5 K/min	85 µL
		3.4 mL
	13 K/min	85 µL
		3.4 mL
		5 mL
	20K/min	85 µL
		3.4 mL
		5 mL

2.2 Methods

2.2.1. TGA

Thermogravimetric tests have been carried out in a NETZSCH STA F3 with three crucible sizes: 85 μL , 3.4 mL and 5 mL, all of them made of silica, and three heating rates: 5 K/min, 13 K/min and 20 K/min. To analyse the influence of particle sizes, three particle sizes have been tested: dust of less than 1 mm (fine fraction), dust of more than 1 mm (coarse fraction), and pellets (in the case of the two bigger crucibles, expect for 5 K/min and 5 mL crucible which could not be performed due to practical issues).

The TG tests have been carried out under an atmospheric environment, using synthetic air with a flow of 50 mL/min into the equipment, as well as a protective flow of 20 mL/min of Nitrogen into the balance. The initial temperature for all the tests is 30 °C and the final one is 800 °C. The sample introduced in the crucibles is mass-constant, being 40 mg for the first, 1300 mg for the second and 2000 mg for the third, approximately.

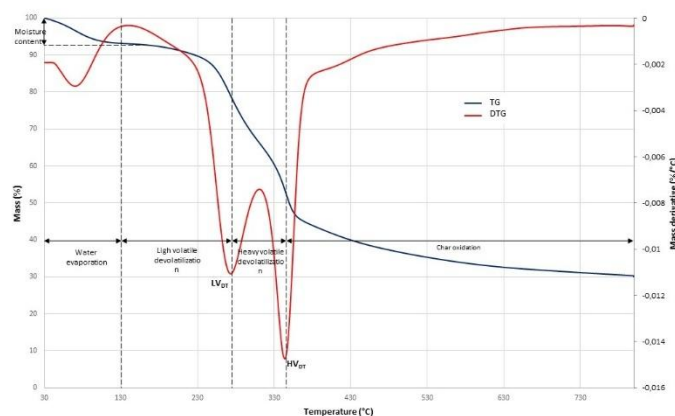


Figure 1. Typical TG and DTG curves obtained from biomass.

Thermal susceptibility of solid materials has been widely determined by the study of thermogravimetric (TG) curves. TG measures the weight of a sample when heated following an established heating rate and flowing a process gas. Typical results from TG (Figure 1) include both the TG curve showing the mass change related to time, and the first derivative of that curve (dTG). Studying these two graphs, the main parameters that are determined are the reaction onset temperature or induction temperature (IT) from the TG curve and the temperature of devolatilization of light volatiles (MLT_LV) and of heavy volatiles (MLT_HV) from the dTG curve. The IT represents the temperature at which the sample starts rapidly losing weight, meaning that the material starts to disintegrate. The MLT represents the point of maximum weight loss, being the MLT_LV related to the decomposition of light volatiles (such as hemicellulose, when considering lignocellulosic biomass samples), and the MLR_HV to the decomposition of heavier

volatiles (such as cellulose and part of lignin, when considering lignocellulosic biomass samples). Finally, the remaining mass is determined showing the final residue after the process.

2.2.2. Reaction kinetics

Kinetic analysis has been performed using three different methods: Friedman, Kissinger-Akahira-Sunose (KAS) and Flynn-Wall-Ozawa (FWO) [23, 24, 25]. All three methods are isoconversional methods (also called model-free methods), defining the kinetic parameters without assuming reaction mechanisms. Friedman is a differential method while KAS and FWO are integral methods.

For the Friedman method, $\ln(d\alpha/dt)$ vs. $1/T$ is plotted for each heating rate, leading to a straight line, in which the activation energy is proportional to the slope of this line. The equation that represents Friedman method is shown in equation (1). Similar procedure is applied when using KAS and FWO methods, however the plots have to be $\ln(\beta/T^2)$ vs. $1/T$, and $\ln(\beta)$ vs. $1/T$, respectively. The equation for KAS model is shown in equation (2) and for FWO in equation (3) in Table 2.

Table 2. Equations for Friedman, KAS, and FWO models

$\ln\left(\beta \cdot \frac{d\alpha}{dT}\right) = \ln(A \cdot f(\alpha)) - \frac{E_a}{R \cdot T}$	(1)
$\ln\beta = \ln\left(\frac{A \cdot E_a}{R \cdot g(\alpha)}\right) - \frac{E_a}{R \cdot T}$	(2)
$\ln\beta = \ln\left(\frac{A \cdot E_a}{R \cdot g(\alpha)}\right) - 5.331 - 1.052 \cdot \frac{E_a}{R \cdot T}$	(3)

Where β represents the heating rate, α the conversion degree, A the pre-exponential factor, E_a the activation energy, R the universal gas constant, T the temperature and $g(\alpha)$ the integral form of the reaction model.

3. THERMOGRAVIMETRIC ANALYSES

The results obtained when measuring mass loss under different heating rates are plotted in Figure 2 for the 85 μ L crucible, Figure 3 for the 3.4 mL crucible and Figure 4 for the 5 mL crucible.

Results obtained for the smallest crucible (85 μ L) (Figure 2) show high similarities between the two studied particle sizes, while variations can be observed between the tested heating rates.

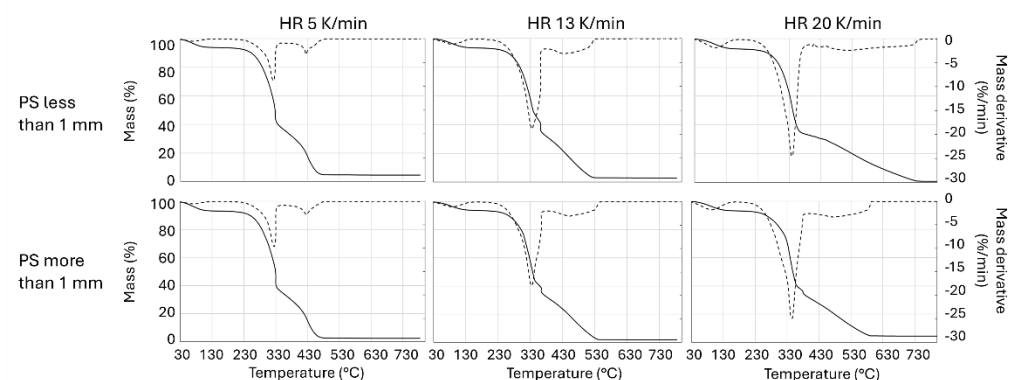


Figure 2. Thermogravimetric and first derivative curves tested with an 85 μL crucible, for three heating rates (5 K/min, 13 K/min and 20 K/min from left to right), and two particle sizes (less than 1 mm and more than 1 mm from top to bottom).

When the sample size is larger, approximately 1300 mg introduced in a 3.4 mL silica crucible, the first observed difference is the absence of the second peak in the dTG curves, even for the smallest heating rates. The increase of the mass loss peak with increasing heating rate is also observed in this case, where a significant difference is observed. This difference is observed as a function of heating rates, while it is not significant when increasing particle sizes.

The first peaks obtained in the dTG curves become considerably larger when the heating rates are increased. While this peak increases, the second one decreases, almost disappearing for the 20 K/min cases. This variation is translated to the TG curve in a more continuous loss of weight during the test, mainly from approximately 300 °C to 500 °C, where the slopes of the TG curves are steeper in the case of lower heating rates. The disappearance of the second peak, representing the high volatiles emission, is characteristic and shows that when increasing the heating rates there is an acceleration of the processes and they overlap, not being possible to differentiate between processes and when they occur. Indeed, a thermal lag is produced as the sample cannot reach furnace temperature due to the rapid heating, and therefore, the curve is slightly shifted to the right [26].

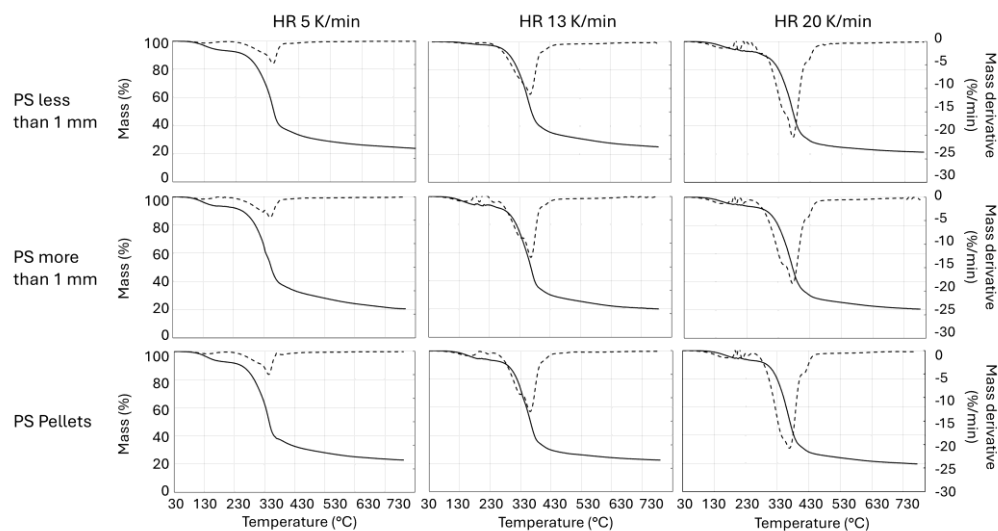


Figure 3. Thermogravimetric and first derivative curves tested with a 3.4 mL crucible, for three heating rates (5 K/min, 13 K/min and 20 K/min from left to right), and three particle sizes (less than 1 mm, more than 1 mm and pellets from top to bottom).

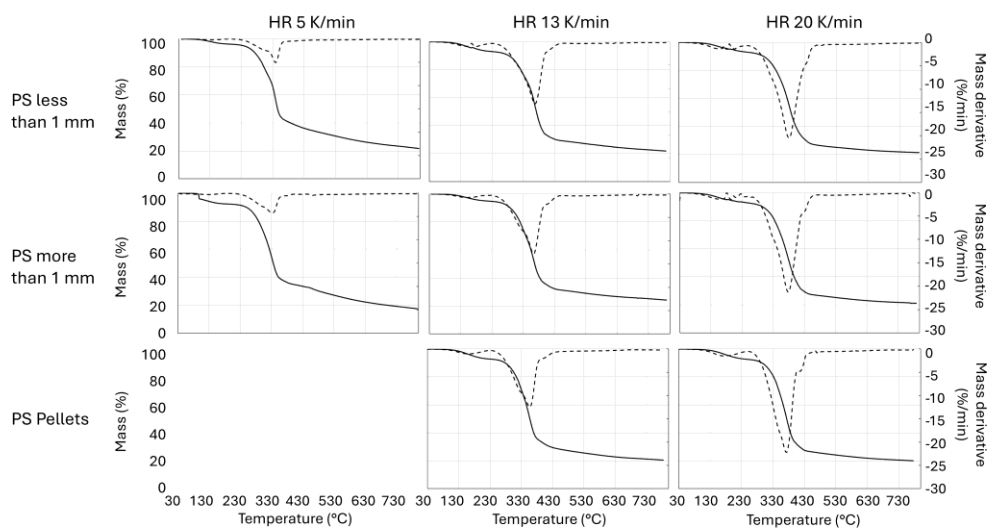


Figure 4. Thermogravimetric and first derivative curves tested with a 5 mL crucible for three heating rates (5 K/min, 13 K/min and 20 K/min from left to right), and three particle sizes (less than 1 mm, more than 1 mm and pellets from top to bottom).

The results obtained for the 5 mL crucible are very similar to the ones for 3.4 mL, not observing two peaks for any of the heating rates, and with similar obtained values.

When comparing the numerical results derived from the TG and dTG curves significant differences can be found. In particular, three obtained parameters are considered, which are the residual mass (Figure 5), the induction temperature and the maximum loss weight temperature (Figure 6).

Firstly, a clear difference in the residual mass is observed between the μL and the mL sizes, being less than 5% for the smallest crucible, but around 20% in the case of the bigger ones. When increasing crucible size, the amount of sample and its thickness increases, leading to limitations in mass and heat transfer. Oxygen cannot homogeneously access the inner part of the sample when using mL crucibles, therefore, part of the carbonaceous material does not completely oxidize, resulting in a greater amount of unburnt carbonaceous material.

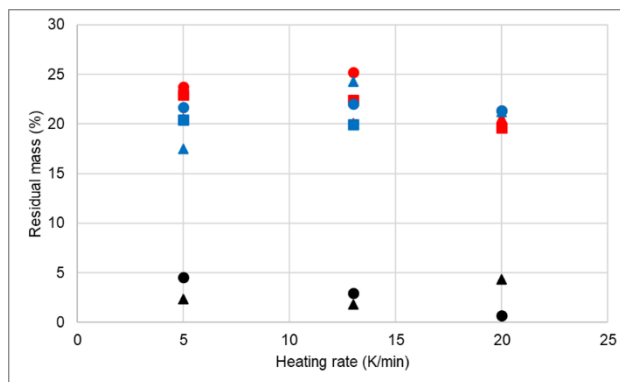


Figure 5. Residual mass after tests for the three tested heating rates, 5 K/min, 13 K/min and 20 K/min. Dots represent particle size of less than 1 mm, triangles particle size of more than 1 mm and squares pellets. Black-colored marks represent 84 μL crucible, red-colored marks represent 3.4 mL crucible and blue-colored represent 5 mL.

IT does not show any specific trend. Again, the thermal lag can be seen when addressing IT, as the curve shifts to the right when increasing the heating rate. Besides, it seems that greater crucible sizes also increase the IT values, therefore, the combustion effectively begins at higher temperatures when the greater volumes are used. This is consistent with greater resistance to heat and mass transfer mechanisms in greater volumes, and the presence of thermal gradients, in which the inner particles of the sample do not reach the same temperature as the surface particles.

In the case of the position of the first peak of the dTG curve, there are two clear tendencies that can be observed in Figure 6. First, there is an increase in the values obtained depending on the heating rate of the test. Second, there is a clear difference in the results obtained depending on the crucible size studied, with lower values for the smallest crucible, and larger values for the

crucibles that involve samples of the size of milliliters. However, there is no significant difference observed between the two biggest crucible sizes, 3.4 and 5 mL.

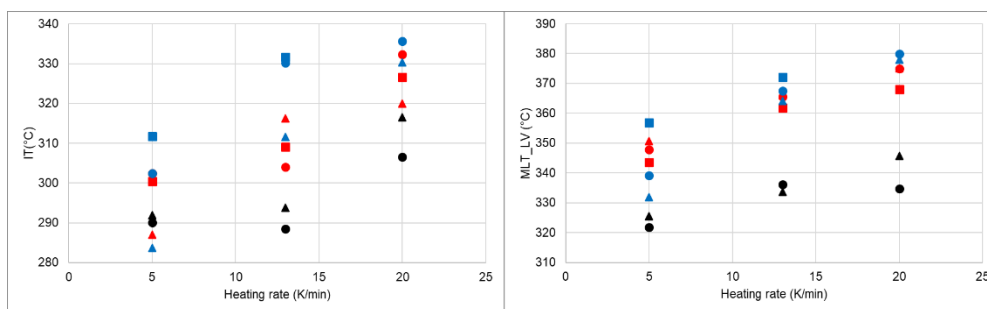


Figure 6. Induction temperature (left) and maximum mass loss temperature for low volatiles (right) for the three tested heating rates, 5 K/min, 13 K/min and 20 K/min. Dots represent particle size of less than 1 mm, triangles particle size of more than 1 mm and squares pellets. Black-colored marks represent 84 μ L crucible, red-colored marks represent 3.4 mL crucible and blue-colored represent 5 mL.

Nevertheless, the results between IT and MLT are coherent and show similarities, as both parameters describe the delay in the acceleration of combustion is due to kinetic and transfer effects, rather than intrinsic changes in the chemistry of the material.

4. KINETIC ANALYSES

From the TGA data it is possible to apply the different kinetic models to obtain activation energy. The pellets cannot be tested when using 0.85 mL crucible size, as the sample do not fit inside, therefore E_a is not defined (ND) for these conditions. On the other hand, in this study TGA using pellets and 5 mL crucible was not performed, therefore, no activation energy is reported. Further studies should consider performing the test using this crucible size, as usually literature focuses on small crucible size. The obtained results when applying each method can be seen in Table 3.

Table 3. Activation energy values obtained from analysing TG and dTG results.

	Fine			Coarse			Pellets		
	Friedman	KAS	FWO	Friedman	KAS	FWO	Friedman	KAS	FWO
0.85	170.87	189.89	190.25	168.01	177.49	178.36	NA	NA	NA
3.4	182.49	144.18	146.75	221.74	168.82	170.21	193.5	137.9	140.43
5	112.28	79.97	85.76	121.18	97.10	102.14	NA	NA	NA

Regarding crucible sizes, a tendency shows that greater volume produces a reduction in the energy activation value, which suggests that other effects besides kinetic reactions, take place and reduce E_a . Hu et al., [27] studied the diffusion influence in TGA kinetics, finding out that when external crucible diffusion is not considered, the energy activation significantly changes. This fact can explain the tendency found in the results reported in this study as the gas inside TGA furnace

has to reach not only sample surface but also the spaces between particles, therefore, greater crucible size might produce a stagnant gas zone which increases resistance to diffusion of the gas towards the sample and reducing activation energy.

On the other hand, there are also differences when addressing the particle size, as coarse sample led to greater E_a values than the fine fraction, which was already pointed out by Zhai et al. [28]. Indeed, it is well known that the particle size of the sample produces variations in the TGA curves [29]. The fact that E_a increases with the particle size can be explained due to thermal gradients and heat transfer limitations [30, 31]. When particle size is increased, so is thermal gradient that produces lower temperature inside the particles which might indicate that for the same conversion degree, higher temperatures are required to produce the decomposition of the sample [32].

However, for the 3.4 mL, the sample in the form of pellets was also tested, and this tendency is no longer found, as the E_a decreases if compared to the coarse results. In order to properly address this issue, pellets should be tested in the 5 mL crucible, but it is feasible that when using the pellets the gas does not reach the inner particles of the sample, leading again to resistance to diffusion effect, which produces the decrease in the E_a values.

The kinetic method also produces differences in the activation energy, especially when comparing integral methods (Friedman) and differential methods (KAS and FWO). KAS and FWO generally provide more consistent results with each other, while differential methods can be more sensitive to local variations in conversion rate, producing higher E_a values in certain conversion degrees [33, 34]. This can be seen indeed in the reported results, as Friedman E_a values are slightly greater than KAS and FWO values for almost every sample.

From the results obtained the TGA conditions significantly vary the results. It has been previously pointed out that the heating rate influences the results, as higher heating rates might lead into a thermal lag [35] that significantly modifies the obtained results due to the limited heat transfer. However, most of the studies in which kinetics are determined use greater heating rates, and so, to properly compare the test results with previously published literature, usually heating rates between 5 and 20 K/min are used, even if it is known the influence of the heating rate on the TGA curve characteristics [36].

5. CONCLUSION

The results clearly show that sample size, defined by crucible volume, governs the thermal response of biomass in TGA, while particle size has a negligible effect under the conditions studied. Microlitre-scale samples exhibit similar TG and dTG behaviour regardless of particle size, with heating rate being the primary parameter influencing mass loss. In contrast, millilitre-scale samples display overlapping reaction stages and the disappearance of distinct dTG peaks, indicating strong heat and mass transfer limitations. Comparable results for the 3.4 mL and 5 mL crucibles demonstrate that beyond a critical sample size, further increases in volume do not significantly alter the measured thermal behaviour.

Millilitre-scale samples also produce substantially higher residual mass ($\approx 20\%$) than microlitre-scale samples ($< 5\%$), confirming incomplete oxidation due to restricted oxygen diffusion and

internal thermal gradients. Induction temperature and maximum mass loss temperature increase with both heating rate and crucible size, reflecting thermal lag effects rather than changes in intrinsic reactivity. These findings demonstrate that TGA-derived thermal and kinetic parameters are strongly biased by sample size and crucible geometry, underscoring the need for careful experimental design and explicit reporting when using TGA for biomass thermal susceptibility and fire hazard assessments.

It was shown that activation energy obtained from TGA data is not an intrinsic parameter of the samples, but it heavily depends on the test conditions. Kinetic methods, crucible and particle size, influence E_a values due to heat transfer and gas diffusion processes. A decrease in E_a is observed when increasing crucible volume and an increase in E_a was found when increasing particle size, associated with intraparticle thermal gradients. These results highlight the need to properly define and report test conditions in TGA kinetic studies and deeply understand how these conditions can influence the results.

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CARACTERIZACIÓN DEL TAMAÑO DE PARTÍCULA DE MATERIALES PULVERULENTOS COMBUSTIBLES: UN NUEVO ENFOQUE

Sergio Ruiz
Investigador FPI
UR - Logroño
España

Alejandro Varela
Investigador FPI
UR - Logroño
España

Rubén Lostado
Catedrático
UR - Logroño
España

Julia Arbizu
Profesora CDr
UR - Logroño
España

M. Martínez-Calvo
Profesora TU
UR - Logroño
España

Alberto Tascón*
Profesor TU
UR - Logroño
España

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1. INTRODUCCIÓN

La caracterización física de materiales pulverulentos, específicamente su distribución de tamaño y la forma de las partículas, constituye un parámetro crítico para predecir su comportamiento, siendo especialmente relevante en términos de reactividad e inflamabilidad. Es bien conocido que el tamaño de partícula influye en la sensibilidad a la ignición y en la severidad de explosión de estos materiales (1, 2). En general, las fracciones más finas favorecen la ignición y aumentan la severidad de explosión, debido a su mayor relación área/volumen, lo que intensifica los procesos de pirólisis y facilita el acceso del oxígeno a las partículas sólidas.

Desde el punto de vista morfológico, las partículas de polvo de biomasa son generalmente alargadas y suelen presentar formas aciculares o forma de gancho (3). Esto las aleja de la idealidad esférica asumida tradicionalmente en materiales como el carbón o los polvos metálicos (2, 4). La omisión de la morfología dificulta una comprensión completa del comportamiento de estos materiales (5). Las partículas pulverulentas de biomasa, al ser de tipo fibroso, presentan una superficie de contacto con el oxígeno mayor que la de una esfera de volumen equivalente, pudiendo alterarse significativamente la cinética de combustión. Por ello, la caracterización no debe restringirse únicamente al tamaño de partícula, sino que debería incorporar descriptores morfológicos adicionales.

En este contexto, el tamizado mecánico y la difracción láser, que son las técnicas predominantes para la determinación del tamaño de partícula de muestras pulverulentas, no resultan adecuadas

* Autor correspondiente — SASF group, University of La Rioja, C/ Madre de Dios 53, 26006 Logroño (Spain).

Telef.: +34 941 299733, E-mail: alberto.tascon@unirioja.es

y pueden introducir errores cuando se aplican. Sin embargo, este efecto no suele ser tenido en cuenta a la hora de interpretar los resultados y sus implicaciones en seguridad industrial. En el caso del tamizado mecánico, las partículas se clasifican principalmente según su anchura (la segunda dimensión menor) y no por su longitud máxima ni por el diámetro equivalente a una esfera, permitiendo el efecto de que partículas con una longitud muy superior a la apertura del tamiz pueden atravesarlo al orientarse vertical o diagonalmente (6). Por otro lado, la difracción láser determina la distribución granulométrica a partir del patrón de dispersión de la luz generado al atravesar un haz láser una nube de partículas. Esta técnica presenta el mismo sesgo de esfericidad equivalente, dado que los algoritmos asumen que las partículas son esferas perfectas. Estudios comparativos entre distintas técnicas granulométricas han puesto de manifiesto que la difracción láser tiende a subestimar la fracción de partículas de mayor tamaño y no representa adecuadamente las irregularidades superficiales ni la fibrosidad características de las partículas pulverulentas de madera (7).

Castells *et al.* (8) resaltaron las importantes incertidumbres asociadas a los materiales biomásicos y a la determinación de sus propiedades fisicoquímicas y de inflamabilidad, destacando especialmente la falta de consenso en la definición y caracterización del tamaño y la forma de partícula.

Ante estas limitaciones, el análisis de imagen digital se presenta como una posible alternativa a los métodos tradicionales de determinación del tamaño de partícula. Los enfoques basados en visión por computadora permiten medir las dimensiones reales de un gran número de partículas individuales mediante la determinación de diversos parámetros geométricos y el empleo de algoritmos (6).

En este trabajo se ha aplicado el tratamiento digital de imágenes para determinar el tamaño y morfología de las partículas correspondientes a 5 muestras de pélets de pino obtenidas mediante molienda y tamizado. A partir de la información obtenida tras analizar ≥ 1.000 partículas por muestra, se calcularon parámetros estadísticos representativos, que fueron comparados con los parámetros de inflamabilidad y explosividad determinados conforme a ensayos normalizados.

2. MATERIALES Y MÉTODOS

2.1. Preparación de las muestras

Como material de estudio se emplearon pélets de pino (*Pinus sylvestris*) de categoría A1, con un diámetro de 6 mm y longitudes comprendidas entre 3,15 y 40 mm, fabricados por Coterram (León, España). El material fue sometido a un proceso de molienda mediante un molino eléctrico de martillos GME-1100C de la marca Garhe (Amorebieta, España) equipado con un tamiz interno de apertura 2 mm.

Posteriormente, el polvo resultante se clasificó mediante tamizado mecánico empleando una tamizadora Controls D 403 (Milán, Italia), empleando tamices de acero inoxidable según norma ISO 3310 (9) con aperturas de malla de 400 μm , 250 μm y 80 μm . La Tabla 1 muestra las cinco fracciones granulométricas (F1-F5) seleccionadas para el análisis.

Tabla 1: Clasificación de las fracciones de polvo de biomasa de pino

Fracción	Rango de tamaño (apertura de malla)
F1	< 400 μm
F2	400-250 μm
F3	<250 μm
F4	250-80 μm
F5	< 80 μm

2.2. Digitalización de las imágenes

Para la captura de imágenes se utilizó un microscopio trinocular Motic BA-310-LED equipado con una cámara digital Moticam 1080 (Xiamen, China). El sistema se calibró mediante un portaobjetos de calibración del propio fabricante, integrando la escala mediante el software Motic Images Plus 3.0 para asegurar la trazabilidad de las mediciones en cada objetivo.

Las muestras de polvo de biomasa se dispersaron de forma uniforme sobre portaobjetos de vidrio (ver Figura 1). Se emplearon cantidades mínimas de polvo, distribuidas manualmente, para garantizar una monocapa de partículas y minimizar errores por aglomeración o solapamiento. Por cada una de las 5 fracciones se analizaron 6 portaobjetos y en cada uno de ellos se capturaron aproximadamente 20 campos de visión aleatorios, utilizando objetivos con aumentos $\times 4$ y $\times 10$, en función del tamaño de polvo de la fracción, asegurando la representatividad de la muestra original. Las imágenes se almacenaron en formato TIFF sin compresión.

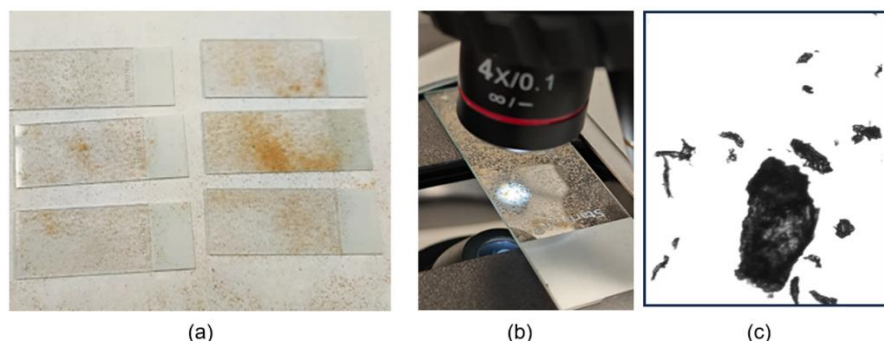


Figura 1: Metodología de digitalizado de imágenes: (a) Dispersión del polvo sobre portaobjetos, (b) Visualización en microscopio y (c) Ejemplo de imagen obtenida a partir del digitalizado

2.3. Tratamiento y análisis de imágenes

Las imágenes extraídas de las fracciones granulométricas de polvo de pino fueron procesadas mediante el software ImageJ (10) siguiendo estos pasos: primero se realizó una calibración en función del objetivo usado en el microscopio y se convirtieron a escala de grises de 8 bits; a continuación, se segmentaron diferenciando las partículas del fondo mediante intensidad de grises y se convirtieron a imágenes binarias; por último, se extrajeron valores de distintos

parámetros de interés (área, perímetro, diámetro máximo y mínimo de Feret, circularidad, relación de aspecto y diámetro equivalente).

Para describir la forma de las partículas se siguió el método propuesto por Gil *et al.* (11), que propuso un sistema de clasificación heurística basado en dos descriptores adimensionales: la relación de aspecto (*aspect ratio* o AR) y la solidez (S):

- Relación de aspecto: define la elongación de la partícula mediante el cociente entre sus diámetros de Feret ($AR = \text{Longitud} / \text{Anchura}$).
- Solidez: mide la rugosidad o irregularidad del contorno, calculada como la relación entre el área de la partícula (A_p) y el área de su envolvente convexa (A_c)

Utilizando estos descriptores, las partículas se categorizaron en: círculos o cuadrados (si $AR < 1,15$), rectángulos (si $1,15 \leq AR < 3,3$ y $S \geq 0,7$), rectángulos fibrosos (si $AR \geq 3,3$ y $S \geq 0,7$), ganchos (si $1,15 \leq AR < 3,3$ y $S < 0,7$) y ganchos fibrosos (si $AR \geq 3,3$ y $S < 0,7$).

2.4. Relación con los parámetros de inflamabilidad y explosividad

Los datos geométricos y morfológicos de las partículas de cada muestra, que fueron obtenidos mediante el tratamiento de imágenes con el software ImageJ, se utilizaron posteriormente para obtener correlaciones estadísticas con parámetros de inflamabilidad y explosividad mediante el software de código abierto Weka 3.8.6 (12).

Específicamente, esta herramienta se empleó para desarrollar modelos de clasificación normalizados mediante regresión lineal Ridge. Se seleccionó la regresión Ridge frente a una regresión lineal ordinaria debido a su capacidad para manejar la multicolinealidad. Dado que varios parámetros morfológicos suelen estar altamente correlacionados entre sí (como el área y la relación de aspecto con los diámetros de Feret), la penalización estadística que introduce el método Ridge evita el sobreajuste (*overfitting*) y estabiliza los coeficientes, permitiendo identificar de forma fiable el peso relativo de cada variable morfológica (13).

El modelo se configuró para determinar el peso relativo de cada variable morfológica sobre los parámetros experimentales de inflamabilidad y explosividad. Los datos de salida utilizados para el entrenamiento del modelo se muestran en la Tabla 2; parte de estos datos ya fueron presentados previamente (14).

Tabla 2: Datos de inflamabilidad y explosividad para las fracciones de polvo estudiadas

Fracción (μm)	TMin ($^{\circ}\text{C}$)	EMI (mJ)	LIE (g/m^3)	P _{max} (bar)	K _{st} (bar·m/s)
<400	400	660	125	10.0	98
400-250	440	200	60	7.7	95
<250	380	23	30	7.9	131
250-80	550	>1000	>1000	5.8	74
<80	440	>1000	250	7.6	88

Los parámetros mostrados en la Tabla 2 fueron determinados experimentalmente en laboratorio siguiendo procedimientos normalizados: TMI_n es la temperatura mínima de ignición de una nube de polvo, determinada en el horno Godbert-Greenwald (15); EMI es la energía mínima de ignición calculada a partir de ensayos en el aparato MIKE 3 (15); LIE es el límite inferior de explosividad o concentración mínima explosiva (16), P_{max} es la presión máxima de explosión (17) y K_{St} es el índice de explosividad del polvo (18), todos ellos determinados mediante ensayos en la esfera de 20 litros. Más información sobre estos ensayos puede encontrarse en (19).

3. RESULTADOS

3.1. Características de las partículas

El análisis digital de imágenes permitió determinar distintos parámetros para caracterizar el tamaño y forma de las partículas de polvo de cada muestra. De cada parámetro lo que realmente se obtuvo fue una distribución de valores, a partir de la cual se pueden obtener valores estadísticos habituales, como los percentiles d_{10} , d_{50} y d_{90} , la amplitud (*span*), la media, la mediana, etc. (15).

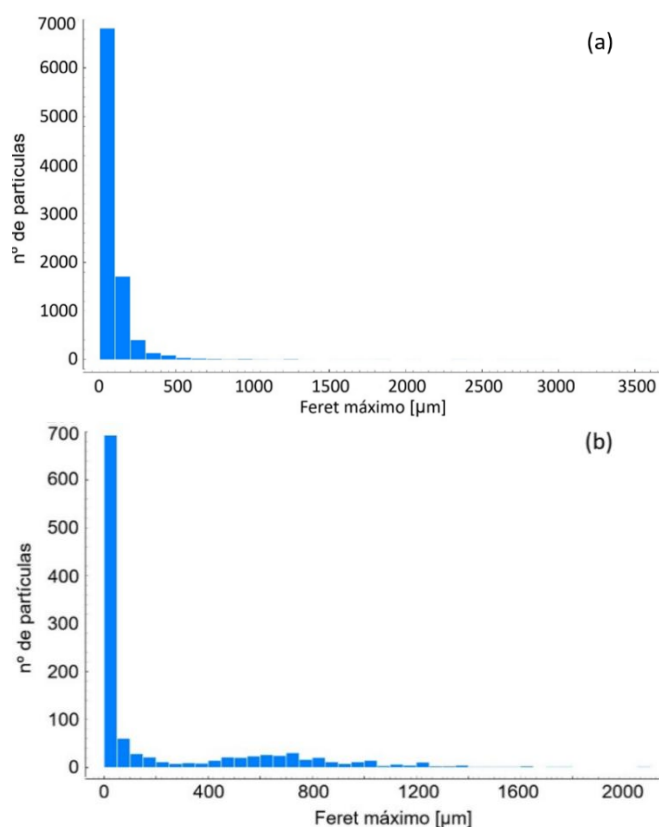


Figura 2: Distribución del diámetro de Feret máximo: (a) F1, < 400 μm y (b) F2, 400-250 μm.

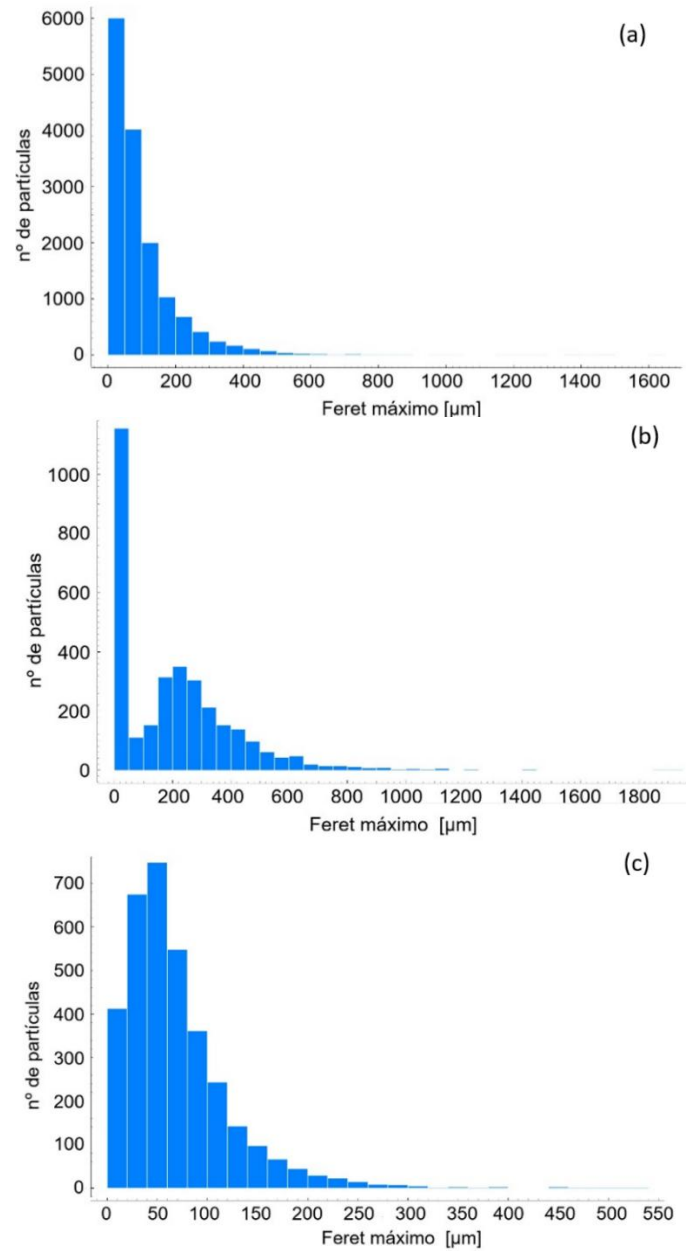


Figura 3: Curvas de distribución de los diámetros de Feret máximos para las fracciones: (a) F3, < 250 μm, (b) F4, 250-80 μm y (c) F5, < 80 μm.

A modo de ejemplo, las Figuras 2 y 3 muestran las curvas de distribución del diámetro de Feret máximo, que sirve para caracterizar la longitud de las partículas. Es importante resaltar que estas distribuciones indican el número de partículas para cada tamaño del parámetro considerado, en

este caso el diámetro de Feret máximo; distribuciones ponderadas por masa o por volumen son lo habitual cuando se usa difracción láser o tamizado (20) y se presentarán en futuros trabajos.

El análisis de estas distribuciones revela que, en todas las fracciones estudiadas (incluidas aquellas acotadas entre dos tamices consecutivos: fracciones F2 y F4), existía una elevada heterogeneidad granulométrica con una presencia significativa de partículas fuera del tamaño de los tamices utilizados. Todas las fracciones estaban formadas por partículas con longitudes muy superiores a la apertura del tamiz, partículas dentro del intervalo de los tamices utilizados y una población muy relevante de partículas finas.

La presencia de estas partículas finas en todas las fracciones (incluyendo las fracciones F2 y F4) puede atribuirse a fenómenos de cohesión entre partículas y de obturación de los tamices (3), y pone de manifiesto la incapacidad del tamizado mecánico para generar fracciones verdaderamente homogéneas de material, al menos cuando se trabaja con partículas fibrosas. Es importante resaltar que, al tratarse de distribuciones que reflejan el número de partículas, el gran número de partículas de pequeño tamaño distorsiona los resultados de las métricas habitualmente utilizadas para reportar la granulometría; sin embargo, estas partículas pequeñas, en la mayoría de fracciones, supondrán una fracción muy pequeña del volumen total de la muestra (21).

Tabla 3: Porcentaje de número de partículas para cada clase morfológica

Fracción	Circular/Cuadrada	Rectangular	Rectangular fibrosa	Gancho	Gancho fibroso
<400	4%	69%	12%	8%	6%
400-250	9%	75%	9%	3%	4%
<250	5%	75%	9%	8%	4%
250-80	6%	64%	10%	11%	9%
<80	4%	73%	11%	8%	4%

Todas las fracciones presentaron valores de circularidad (mediana) inferiores a la unidad, junto con relaciones de aspecto elevadas, confirmando el carácter alargado e irregular de las partículas. La Tabla 3 muestra el porcentaje de cada clase de partículas según la clasificación morfológica explicada anteriormente. Las formas compactas (círculo/cuadrado) representan una parte minoritaria de las muestras, mientras que predominan las partículas alargadas (rectangular y rectangular fibrosa). Por su parte, la presencia de partículas clasificadas como gancho y gancho fibroso pone de manifiesto la generación de fragmentos con contornos complejos y concavidades, incluso en las fracciones de muestra más finas.

Cabe señalar que la presencia de partículas aglomeradas y su tratamiento puede introducir incertidumbres en el análisis mediante imágenes de microscopía. En el presente estudio, la influencia de la aglomeración entre partículas se mitigó mediante un procedimiento de tratamiento de imagen basado en segmentación manual. Las imágenes fueron revisadas individualmente para identificar los agregados, que fueron separados en sus distintas partículas

individuales antes de la extracción de los parámetros geométricos, evitando así la interpretación de conjuntos de partículas como entidades de mayor tamaño.

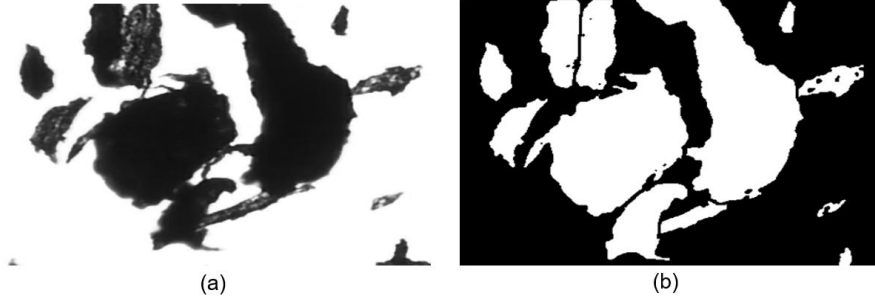


Figura 4: Segmentación de partículas aglomeradas: (a) imagen original, (b) imagen binarizada y segmentada

3.2. Correlación con la inflamabilidad y explosividad

Se generaron modelos de regresión lineal tomando como variable dependiente cada uno de los parámetros de inflamabilidad y explosividad, seleccionando los parámetros morfológicos más relevantes. Todos los modelos presentaron coeficientes de correlación superiores a 0,95, con valores de error absoluto relativo y raíz del error cuadrático medio (RAE y RRSE por sus siglas en inglés) en el rango de 10-30 %, lo que indica un buen ajuste y capacidad explicativa.

A modo de ejemplo, el modelo obtenido para TMI_n fue el siguiente:

$$TMI_n = 0,1631 \cdot C_{d90} + 0,6615 \cdot F_{max, d90} + 0,5893 \cdot S_{d50} - 0,4133 \quad (1)$$

donde C_{d90} es el percentil d_{90} de la circularidad, que se define como $(4\pi \cdot \text{área} / \text{perímetro}^2)$, $F_{max, d90}$ es el percentil d_{90} del diámetro máximo de Feret, que es la mayor distancia entre dos puntos cualesquiera situados en el perímetro de la partícula, y S_{d50} es la mediana de la solidez, que ya fue definida en el apartado 2.3.

Los parámetros morfológicos más influyentes identificados para cada una de las salidas de los modelos fueron éstos:

- TMI_n : La temperatura mínima de ignición en nube está gobernada principalmente por el tamaño de las partículas más grandes siendo los parámetros más influyentes el diámetro de Feret máximo d_{90} (relación directa) y la solidez d_{50} (relación directa). Este resultado indica que el proceso de ignición está gobernado por la inercia térmica, representada por el tamaño longitudinal de las partículas, y el grado de compactación del perímetro, ya que las partículas más largas y compactas requerirán temperaturas más elevadas para inflamarse.
- EMI : La energía mínima de ignición está dominada por parámetros geométricos de la fracción más fina, siendo los parámetros más influyentes el diámetro de Feret mínimo d_{10} y el perímetro d_{10} (ambos con relación inversa). Es decir, la ignición se ve favorecida por

partículas que, siendo finas, presentan una elevada irregularidad superficial (mayor perímetro de contacto con la energía de ignición).

- LIE: La concentración mínima explosiva mostró una mayor dependencia con el d_{90} del área de las partículas (relación directa) y con el diámetro de Feret máximo d_{90} (relación inversa). Estos resultados sugieren que partículas de mayor tamaño (área) requieren mayores concentraciones, mientras que partículas más alargadas favorecen la sostenibilidad de la combustión y disminuyen el LIE.
- P_{max} : La presión máxima de explosión mostró una dependencia principal con la forma de las partículas, siendo los parámetros más influyentes la relación de aspecto d_{10} (relación directa) y la solidez d_{90} (relación inversa), evidenciando que partículas más alargadas e irregulares generan explosiones más severas.
- K_{St} : El índice de explosividad del polvo mostró una mayor relación con los factores de circularidad d_{90} (relación inversa) y Feret máximo d_{10} (relación directa). Esto indica que las partículas más alargadas o fibrosas favorecen una mayor severidad de explosión.

En conjunto, los resultados mostraron que el comportamiento de inflamabilidad y explosividad del polvo de pélets de pino está dominado por la morfología de las partículas, con los diámetros de Feret y la solidez como los parámetros más influyentes.

Es evidente que el método aquí presentado necesita todavía ser depurado y hay que resolver ciertas incógnitas en los parámetros obtenidos, así como ampliarlo a más muestras de otros materiales. Sin embargo, los resultados presentados en este estudio son prometedores y pueden abrir un nuevo camino para una caracterización más exacta y completa de las muestras de polvo combustible.

4. CONCLUSIONES

En este trabajo se ha llevado a cabo una caracterización exhaustiva del tamaño y morfología de cinco muestras de partículas de polvo de pélets de pino. El análisis de las imágenes digitales obtenidas mediante microscopio óptico permitió identificar distribuciones de tamaño muy heterogéneas y marcadamente asimétricas, con elevados valores de amplitud de las curvas de distribución. Desde el punto de vista morfológico, todas las fracciones estudiadas estuvieron dominadas por las partículas alargadas, siendo minoritaria la presencia de formas compactas circulares o cuadradas.

La aplicación de modelos de regresión lineal permitió identificar los parámetros morfológicos más influyentes en los fenómenos de inflamabilidad y explosividad. Los resultados parecen sugerir que la sensibilidad a la ignición está gobernada por una competencia de tamaños, en la que la inercia térmica de la fracción gruesa y la reactividad superficial de la fracción fina desempeñan papeles complementarios, mientras que la severidad de la explosión depende de forma crítica de la longitud de las partículas fibrosas y de sus irregularidades superficiales. Por todo ello, puede considerarse que utilizar un único parámetro (habitualmente el diámetro d_{50}) para expresar el tamaño de una muestra es una simplificación excesiva que puede dar lugar a errores.

En conjunto, la metodología empleada en este trabajo ha demostrado su capacidad para caracterizar el polvo de biomasa, integrando tamaño, morfología y comportamiento frente a la ignición y explosión.

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**OPERATIONAL WILDFIRE ENSEMBLES FOR ELECTRIC GRID ASSETS:
MAPPING BURN PROBABILITY AND EXPOSURE**



Juan Luis Gómez*
Associate
Researcher,
Comillas (ICAI)-IIT
ITEFI-CSIC,
Spain



Alexis Cantizano†
Professor
Comillas (ICAI)- IIT
Spain



Pablo Ayala‡
Professor
Comillas (ICAI)- IIT
Spain

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1. ABSTRACT

Wildfires are increasingly affecting electric power systems through two coupled pathways: ignitions initiated by grid assets (e.g., faults, conductor–vegetation contact, arcing) and damage or operational disruption when fires reach overhead transmission corridors, substations, and supporting structures. Utilities, therefore, need quantitative, spatially explicit methods that turn fire-behavior uncertainty into actionable indicators at the asset level.

This conference paper presents an operational workflow for building wildfire ensembles and deriving burn probability and time-to-impact metrics for power transmission infrastructure. The workflow builds on open-data landscape preparation, combining public forest maps and inventories with LiDAR-derived canopy structure to generate high-resolution fuels and canopy

* Juan Luis Gómez — Institute for Research in Technology, ICAI, Comillas Pontifical University, C/ Alberto Aguilera 25, 28015, Madrid (Spain).
Telef.: +34 5422800; Instituto de Tecnologías Físicas y de la Información “Leonardo Torres Quevedo”. C/ Serrano, 144, 28006, Madrid (Spain).

Telef: +34 915618806, E-mail: juanluis.gomez@csic.es

† Alexis Cantizano — Institute for Research in Technology, ICAI, Comillas Pontifical University, C/ Alberto Aguilera 25, 28015, Madrid (Spain).
Telef.: +34 5422800, E-mail: alexis.cantizano@iit.comillas.edu

‡ Pablo Ayala — Institute for Research in Technology, ICAI, Comillas Pontifical University, C/ Alberto Aguilera 25, 28015, Madrid (Spain).
Telef.: +34 5422800, E-mail: pablo.ayala@iit.comillas.edu

layers. Fire spread is simulated using FlamMap together with a calibrated Cellular Automata (CA) model. Ensemble modelling propagates uncertainty in ignition location, wind regimes, and fuel moisture, so outputs can be expressed as probability and arrival-time ranges rather than single deterministic estimates. The outputs are post-processed into gridded burn-probability and fire-arrival-time maps, and then aggregated within corridor buffers to produce segment-level exposure indices for planning and operations. In this contribution, we focus on the methodology and its data requirements; a full case-study validation and quantitative performance assessment are the subject of ongoing work.

1. INTRODUCTION

Large and extreme wildfires are becoming more common in many regions. Climate change leads to extended drought and high temperature periods, reducing the moisture content of dead and live fuels, in turn increasing the chance of dangerous wind-driven fires that burn large areas of land [1]. Land-use change can also increase exposure in areas with a previously benign fire prevalence. The expansion of human populations increases wildfire risk and threatens Wildland Urban Interface (WUI) communities and Industrial Interface (WII) areas, which may include critical infrastructures such as transportation, chemical plants, water supply, and gas and power systems [2]. The relationship between wildfires and power systems is inherently bidirectional. On one hand, wildfires can disrupt or damage power transmission infrastructure, including lines, towers, substations, and generation facilities, leading to outages and wider societal impacts. On the other hand, power-system failures can also act as ignition sources or contribute to fire escalation under hot, dry, and windy conditions. In practice, this means the grid is both vulnerable to wildfire as an infrastructure system and, under certain circumstances, part of the wildfire ignition chain [3–6]. European assessments also stress that wildfires can trigger Natech events. These include technological accidents and cascading failures across critical infrastructure. They call for coordinated prevention and preparedness wherever hazardous or critical assets are exposed [7,8].

Wildfires can affect power transmission infrastructure through several mechanisms (Table 1). Some act at long range. Smoke, hot gases, and ash can reduce air insulation strength and increase the likelihood of flashovers and trips [9,10]. Operators may also need to de-rate lines or temporarily shut them down, and outages can propagate through interconnections [11]. Other mechanisms act close to the fire. Flames and convective heating can damage poles and tower components, degrade polymer insulators, and ignite auxiliary equipment [3]. Radiant heat can anneal aluminum conductors, increase sag, and reduce mechanical strength [12]. This can result in clearance violations and increase fault risk.

On the ignition side, several frameworks estimate the probability that overhead faults ignite nearby fuels. These results can guide investments such as selective upgrades, undergrounding, and operational shutoff policies [5,6,13]. On the impact side, risk-rating approaches combine wildfire spread outputs with grid and asset data to prioritize mitigation at the corridor or component level. Resilience-focused reviews also summarize practical options, especially vegetation management and asset hardening, for utility planning [14].

Table 1. Main wildfire-to-transmission impact mechanisms and typical vulnerabilities [1,9,10,15].

Mechanism	Indicative spatial range¹	Examples / Failure modes
Flame contact & convective heating	0–10 m	Wood poles charring or collapsing; polymer insulator degradation; ignition of auxiliary equipment
Radiant heat	10–100 m	Conductor annealing and strength loss; increased sag; tower hardware overheating
Smoke, hot gases, ash deposition	100 m – several km	Reduced air insulation strength; line-to-ground flashover; post-fire contamination and delayed trips
Embers / spotting	Hundreds of meters to >1 km	Secondary ignitions inside corridors; fire spread into access roads and substations; increased suppression difficulty

¹ These ranges are indicative and should not be interpreted as universal thresholds, since actual impact distances depend on fire intensity, flame geometry, wind, topographic screening, and asset configuration.

Recent literature documents impactful cases in both directions. On 24 July 2021, severe wildfire conditions in southern France contributed to a one-hour separation of the Iberian Peninsula from the Continental Europe synchronous area. The event involved the loss of key 400 kV circuits and cascading trips. It highlighted the need for early environmental risk identification and clear communication protocols [16]. In March 2023, a brush fire in Argentina damaged high-voltage transmission lines near the Atucha area, causing a major outage that disrupted service for nearly 20 million users [17]. In July 2023, wildfire conditions in Québec caused the loss of three transmission lines, leaving hundreds of thousands of customers without power [18]. Several major wildfires in the United States have been directly linked to electrical power infrastructure failures. In California, the 2018 Camp Fire, the deadliest and most destructive wildfire in the state's history, was ignited by a malfunctioning transmission line during strong wind conditions [19]. More recently, it was concluded that the 2023 Maui Fire originated from fallen and subsequently re-energized power lines that ignited dry vegetation near Lahainaluna Road. The resulting conflagration killed more than 100 people and destroyed much of the historic town of Lahaina [20]. Disruptions of this type can also propagate into other critical services and industrial processes.

Decision-support tools should answer two practical questions: where fires are likely to burn and how fast they can reach critical corridors. They also need to summarize uncertainty in a way operators can use [5]. Current risk methods are moving beyond static hazard maps. They increasingly combine time-updated fire forecasts (ensembles and data assimilation), physics-based models of asset fragility and tripping, and network-level resilience metrics for prioritization.

A key challenge is uncertainty. Fire spread depends on fuels, canopy structure, topography, weather, and suppression actions. Operational wildfire ensemble modelling is a practical way to manage this uncertainty. It converts many plausible fire evolutions into burn-probability and time-

to-impact products at the spatial scale of grid decisions. In our recent work, burn probability and fire arrival time were used as interpretable observables for uncertainty-aware decision support [21–23]. This paper has two main objectives: to describe an implementable, open-data workflow to generate burn-probability and time-to-impact layers for transmission corridors, and to define corridor-buffer exposure metrics that translate gridded hazard into segment-level indicators. The emphasis is on reproducible data integration and on risk translation to assets, rather than on presenting a full validation campaign.

2. METHODS

This study translates wildfire spread simulations into actionable indicators for power transmission corridors, while explicitly accounting for uncertainty. The workflow consists of:

- Building high-resolution landscape and fuels cartography.
- Running wildfire simulations under representative meteorological scenarios.
- Defining an ensemble design to sample uncertainty.
- Summarizing hazard outputs.
- Intersecting these fields with transmission corridor geometries to compute exposure.

2.1 Input datasets and preprocessing

Gridded (raster format) landscape inputs are required by operational fire simulators (the so-called LCP layers): topography, surface fuel models, canopy structure, and time-dependent weather/fuel-moisture fields. Following open-data procedures for simulation-driven risk assessment, this can be done by integrating airborne LiDAR, national forest maps, and inventories [21,23]:

- Digital Terrain Model (DTM): elevation, slope, and aspect rasters, forming the main geometric constraints for spread.
- Surface fuels: land-cover/forest-map tiles and LiDAR information from the National Aerial Orthophotography Plan (PNOA) are used to model the distribution of the standard fuel models in the domain.
- Canopy structure: the Spanish National Forestry Inventory (IFN) plot attributes (species, height, DBH) are linked to LiDAR metrics to estimate canopy height (H), canopy base height (CBH), and canopy bulk density (CBD). Regression residuals provide uncertainty bands that are sampled to create perturbed canopy layers for ensemble runs.
- Wind fields: station or forecast winds are downscaled to gridded wind speed/direction with a fast solver (e.g., WindNinja) to capture terrain effects.
- Fuel moisture: dead-fuel moisture is modelled [24] from a rolling meteorological time series (temperature, relative humidity), combined with topography and canopy shading.
- Infrastructure geospatial data: transmission line polylines (spans), tower locations, and substations. When available, corridor LiDAR supports estimates of conductor/vegetation clearance for fragility analyses.

In this work, all these layers are projected to a common coordinate reference system and resampled to a single grid resolution (typically 20–30 m for planning). In the case study used here as methodological support [21], the wildfire-model inputs were harmonized on a common 25 × 25 m raster grid over an 8 × 8 km domain. Topography (DTM, slope, and aspect) was derived at 25

m; Spanish Forest Map [25] at scale 1:50000 (MFE50) polygons were intersected with the same 25 m raster to assign surface fuel models; Fourth National Forest Inventory (IFN4) plots [26] were used as point observations to train regressions that were then extrapolated to the 25 m grid; and LiDAR point clouds from the Spanish Orthophoto Program (PNOA) [27] were processed to derive canopy metrics consistent with that final simulation support. Although some LiDAR preprocessing may use finer intermediate supports, the operational fire-model layers were assembled on the common 25 m grid.

2.2 Wildfire spread modelling: FlamMap and Cellular Automata

We use two modelling approaches. First, FlamMap (Rothermel) estimates the rate of spread, flame length, and fire-line intensity under steady weather. Second, a Cellular Automata (CA) simulator produces time-resolved perimeters. The CA is an in-house model developed by the authors [21]. It operates on a regular square lattice with a Moore neighborhood and propagates fire through precomputed travel times between neighboring cells derived from FlamMap spread rates under an elliptical fire-growth assumption. The model was evaluated against the 2012 Cocentaina wildfire in the province of Alicante, southeast Spain, using the observed burned perimeter, documented fire evolution, local meteorological observations, and suppression information from post-fire reports. In that study, the CA was validated by comparing its behavior with MTT-based static simulations and then tested under dynamic wind and moisture updates. Figure 1 summarizes the workflow.

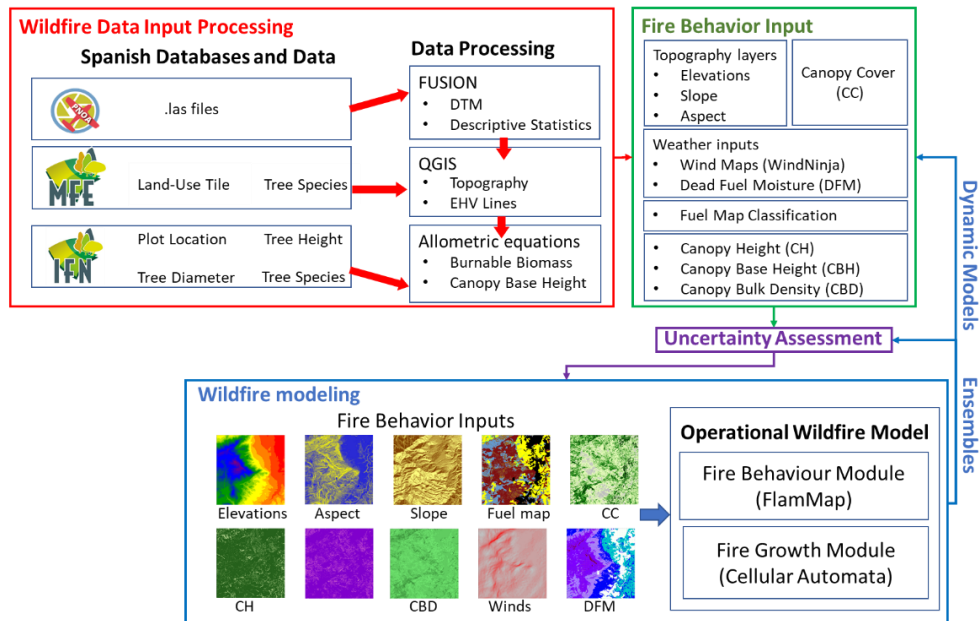


Figure 1: End-to-end workflow for corridor-based wildfire risk assessment of transmission lines, from input data preparation (terrain, fuels, and canopy layers) to ensemble fire-spread simulation [21].

2.3 Ensemble design and uncertainty propagation

Ensemble members are designed to represent plausible combinations of the key drivers governing wildfire spread and response. Ignitions may be sampled on a regular grid to support hazard mapping, or placed strategically near transmission corridors to evaluate the potential for grid-caused ignitions. In planning applications, wind regimes are derived from historical observations (e.g., government weather agencies such as AEMET in Spain) or climatic reanalysis (e.g., ECMWF ERA5). In operational settings, the ensemble can be conditioned on weather-forecast members. Within each simulation, winds may be downscaled to terrain-resolved grids, and dead-fuel moisture can be updated from temperature and relative humidity, while accounting for canopy and topographic modifiers. Fuels and canopy attributes are treated as uncertain inputs sampled from model residuals. Uncertainty propagation is treated here as a structured ensemble design rather than as a formal Latin Hypercube scheme. Canopy inputs are perturbed around regression medians using confidence bands (e.g., $\pm 2\sigma$) derived from LiDAR–IFN models, and these perturbed layers are then combined with alternative ignition and meteorological settings.

Suppression can also be incorporated by varying response time, resource availability, and the probability of successful containment.

Thus, each ensemble member corresponds to one specific realization of these factors. The ensemble size is selected so that burn-probability estimates stabilize at the decision scale (segment or corridor) [22]. Each run yields a burned/unburned footprint and a fire-arrival-time surface at the grid-cell level. To translate these gridded outputs into asset-relevant indicators, we subdivide each transmission line into analysis segments and construct corridor buffers around each segment. A near-field buffer (e.g., 0–20 m) captures direct thermal exposure and within-right-of-way ember effects, while a far-field buffer (e.g., 150–1,000 m) captures broader exposure relevant for EHV corridors, including smoke-related susceptibility. For each segment, we compute exposure indices as the mean burn probability within each buffer. Figure 2 presents the EHV transmission network, power plants, and substations considered in this study.

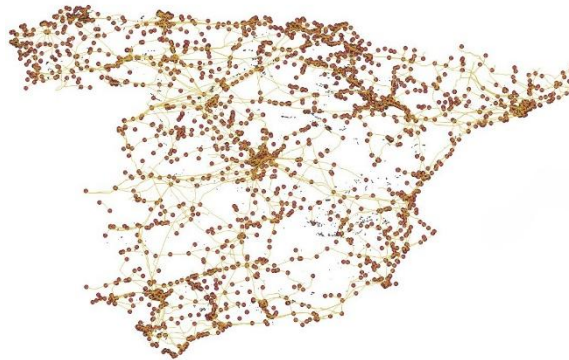


Figure 2: Map of Spain showing extra-high-voltage (EHV) transmission lines, power plants, and major substations.

2.4 Operationalization: planning and near-real-time modes

The workflow supports two complementary uses. In planning mode, long-term climatology and representative historical extremes are used to identify persistently high-exposure corridors and to inform structural measures such as vegetation management prioritization, selective hardening, or undergrounding. In near-real-time mode, the same workflow is updated with forecast weather and fuel-moisture conditions to support short-term operational decisions, including crew pre-positioning, targeted patrols, and, where permitted, preventive de-energization. Because the simulation core is computationally efficient, these updates can be produced routinely once the data pipeline is automated [22].

3. PREVIOUS RESULTS AND TRANSFERABLE INSIGHTS

Our recent work shows how open geospatial data can be used to produce uncertainty-aware wildfire products directly usable for infrastructure screening [21]. The landscape was built from raster layers that can be derived at scale: topography, fuel-model mapping, canopy structure, and time-varying wind/moisture forcing. Canopy uncertainty was made explicit by linking National Forest Inventory plot attributes to LiDAR metrics and then sampling perturbed canopy layers around the regression medians using confidence intervals (e.g., $\pm 2\sigma$). This allows uncertainty in canopy height/base height/bulk density to be propagated into the fire spread model through an ensemble, producing fire-risk cartographic products that describe not only likely burned areas but also where results are more sensitive to input uncertainty. The same study also highlighted that dynamic wind and dead-fuel moisture inputs are critical; static forcing can lead to unreliable predictions when conditions evolve during the event.

A second transferable idea comes from our Wildland–Industrial Interface (WII) analyses [23]: the exposure of an asset is not a single distance threshold but a buffer design choice that should reflect the impact pathway being studied. In that work, industrial sites were surrounded by one or more buffer zones spanning near-field to far-field ranges, and exposure was computed by intersecting those buffers with wildfire-hazard layers (and fuel/vegetation conditions) to identify which facilities fall inside hazardous surroundings. Buffer sizes can be selected to reflect local mechanisms (e.g., direct flame/heat versus ember-driven spot exposure), and they can be treated as a sensitivity parameter when translating gridded hazard into asset-level risk indicators. This “buffered intersection” logic transfers directly to transmission corridors.

Figure 3 shows the line-buffer analysis for the same Cocentaina study area. The simulations were conducted over the same 8×8 km domain, represented on a 25 m grid and parameterized with topography, fuel models, and canopy layers derived from public forest and LiDAR datasets. To provide a consistent comparison, the transmission-line buffers were analysed under the same meteorological setting, using a northwesterly wind of 15 km/h and dead-fuel moisture estimated from the preceding month of meteorological observations. The CA uses the fire behavior module in FlamMap to estimate the fire spread rates, under static conditions for a 5 h period. The resulting fire-arrival-time surface was then intersected with alternative corridor buffers of 50, 100, and 150 m. The results show how exposure increases as buffer width expands: the 50 m buffer captures the earliest direct encroachment into the immediate line surroundings, whereas the 100 m and 150 m buffers include a progressively larger share of the advancing fire front and therefore represent broader zones of potential thermal, smoke, and ember-related influence. This provides

a simple and transparent way to translate wildfire spread simulations into corridor-level indicators for power transmission infrastructure.

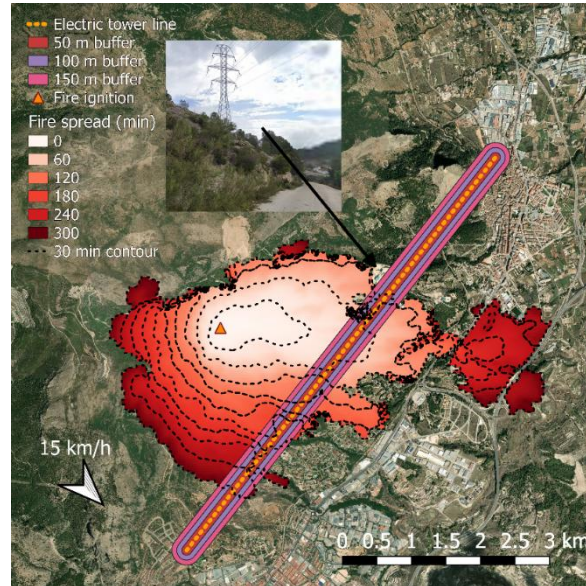


Figure 3: Wildfire exposure of a transmission line in the Cocentaina study area, represented through 50, 100, and 150 m corridor buffers.

4. CONCLUSIONS

This paper presents a practical workflow to assess wildfire exposure in power transmission infrastructure. The proposed approach combines wildfire simulation, open geospatial data, and corridor-based spatial analysis to support both long-term planning and short-term operational decision-making. Its main contribution is to translate fire-spread modelling into infrastructure-oriented indicators that can help identify vulnerable corridors and support mitigation prioritization.

Next steps include applying the workflow to a fully specified regional transmission corridor, calibrating and validating fragility functions for smoke-induced trips and thermal damage, and evaluating mitigation portfolios that combine suppression planning, vegetation treatments, and operational policies under climate-informed scenarios.

5. ACKNOWLEDGMENTS

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EFFECTO DE LA COMPACTACIÓN EN LA TEMPERATURA DE IGNICIÓN DE CAPAS DE POLVO DE BIOMASA LIGNOCELULÓSICA



Alejandro Varela
Investigador FPI
UR - Logroño
España



F. Javier García
Catedrático
UNIZAR - Huesca
España



Alberto Tascón*
Profesor TU
UR - Logroño
España

Palabras clave: Acumulaciones de polvo; Incendio; Pélets de pino; Serrín de chopo; Polvo combustible.

* Autor correspondiente — SASF group, University of La Rioja, C/ Madre de Dios 53, 26006 Logroño (Spain).
Telef.: +34 941 299733, E-mail: alberto.tascon@unirioja.es

1. INTRODUCCIÓN

En el marco de las políticas de descarbonización de la Unión Europea, se estableció el compromiso de que, para el año 2030, al menos el 42,5% del consumo final bruto de energía procediera de fuentes renovables (1). Esta meta responde a la necesidad de mitigar el cambio climático a través de una reducción drástica de las emisiones de CO₂. Consecuentemente, el uso de la biomasa como fuente de energía ha cobrado un protagonismo creciente en las últimas décadas (2).

Durante el transporte y manejo de grandes cantidades de biomasa se liberan partículas de polvo, cuya presencia se asocia a la ocurrencia de incendios y explosiones en industrias (3). El polvo se acumula formando capas y depósitos que pueden sufrir procesos de ignición si están en contacto con una superficie caliente. Entre los diversos factores que influyen en la ignición, la compactación es de los menos estudiados y, además, los resultados disponibles parecen mostrar algunas tendencias contradictorias (4, 5).

La Temperatura Mínima de Ignición en Capa (MIT_L) es la menor temperatura de una superficie caliente, expresada en múltiplos de 10 °C, que produce la ignición de una capa de polvo de 5 mm de espesor depositada sobre esa superficie en un tiempo determinado. Se obtiene mediante ensayo en equipo de placa caliente según la norma internacional UNE-EN ISO/IEC 80079-20-2 (6). La norma española UNE 22330 (7), enfocada en carbones, también considera el ensayo de capas de polvo.

Por otro lado, la norma UNE-EN 60079-14 (8) regula el diseño de las instalaciones eléctricas en atmósferas explosivas para evitar que éstas actúen como fuente de ignición. Cuando se prevé la acumulación de capas polvo de hasta 5 mm, la norma establece que la temperatura superficial máxima admisible de los equipos ($T_{m\acute{a}x}$) debe ser al menos 75 K inferior a la MIT_L. Cuando exista la posibilidad de capas mayores a 5 mm, dicha norma indica que se debe reducir más la temperatura $T_{m\acute{a}x}$ y proporciona para ello un gráfico orientativo. Sin embargo, algunos trabajos recientes han resaltado que la temperatura de ignición de capas también depende de la compactación de la capa y del tamaño de partícula, existiendo además incertidumbres adicionales sobre las interrelaciones entre estas tres variables (5, 9).

El objetivo de este estudio fue analizar el efecto del tamaño de partícula, el espesor de la capa de polvo y la compactación en la temperatura mínima de ignición, además de comparar entre sí dos materiales que plantean peligros de incendio y explosión en muchas instalaciones industriales.

2. MATERIALES Y MÉTODOS

En este estudio se han empleado dos tipos diferentes de biomasa lignocelulósica. En primer lugar, se utilizaron pélets comerciales con certificación de calidad A1 (10) fabricados a partir de madera descortezada de pino silvestre (*Pinus sylvestris*) procedente de masas forestales y plantaciones. Estos pélets fueron suministrados por la empresa Coterram Generación (León, España) y se molieron posteriormente para generar muestras de polvo. En segundo lugar, se

seleccionó un residuo de chopo (*Populus* sp.) generado en la planta de procesamiento de madera y fabricación de tableros de la empresa Garnica (La Rioja, España); este material se recibió en forma de serrín, sin aditivos, manteniendo las condiciones originales de su recogida en la industria. La apariencia visual de estos materiales se muestra en la Figura 1.



Figura 1: Pélets de pino (izquierda) y serrín de chopo (derecha)

De cada material se estudiaron dos muestras con distinta granulometría, obtenidas mediante tamizado. Las dos muestras de pélets de pino consistieron en partículas de tamaño inferior a 2000 μm y partículas de tamaño inferior a 250 μm . En el caso del serrín de chopo, la muestra gruesa consistió en el material tal y como se recibió de la industria (tamaño inferior a 5000 μm), mientras que la muestra fina fueron partículas de tamaño inferior a 400 μm .

Para los ensayos de ignición se empleó un equipo de placa caliente (ver Figura 2) construido según la norma UNE-EN ISO/IEC 80079-20-2 (6). Se emplearon tres anillos metálicos diferentes para formar capas de espesor 5, 10 y 20 mm, respectivamente. Durante los ensayos se midió la temperatura de la muestra mediante un termopar tipo K colocado dentro de la capa a una distancia de 2-3 mm respecto a la superficie caliente (modelo empleado: 406-482 TC-Direct, Uxbridge, UK).

El valor de MIT_L se determinó de forma iterativa empleando capas de polvo nuevas en cada ensayo. El procedimiento comenzaba mediante la selección de una temperatura de consigna en la placa. A continuación, se rellenaba el anillo metálico con la muestra hasta formar una capa de polvo homogénea y sin compactar. Cada ensayo se daba por concluido tras confirmar si la muestra había alcanzado o no la ignición. De acuerdo con la norma UNE-EN ISO/IEC 80079-20-2 (6), hay ignición si se cumple una de las siguientes tres condiciones: presencia de llama o de brasas, si la temperatura de la muestra alcanza 450 $^{\circ}\text{C}$ o si la temperatura de la muestra supera en 250 K la temperatura de la placa. Además, la curva temperatura-tiempo registrada durante el ensayo fue estudiada para verificar si la capa había sufrido sólo un proceso de autocalentamiento o si realmente se había producido un salto brusco debido a la ignición.

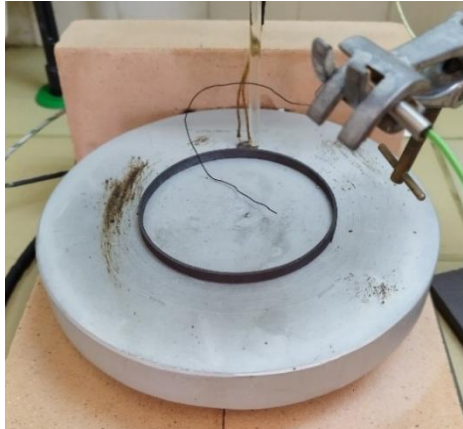


Figura 2: Equipo de placa caliente

Posteriormente, el ensayo se repetía a una temperatura 10 K inferior cuando se había producido ignición, o a una temperatura 10 K superior en el caso de que no hubiera habido ignición. Finalmente, el valor de MIT_L se estableció como la temperatura más baja a la que se observó ignición, tras confirmar la ausencia de la misma en dos ensayos a una temperatura 10 K inferior.

Además, los ensayos también se llevaron a cabo aplicando una compactación previa a la capa de polvo mediante un peso de 1,4 kg (178 kg/m^2 o $1,75 \text{ kPa}$). Pasados 5 segundos, el peso se retiraba y se volvía a enrasar el anillo con material nuevo sin compactar para asegurar que el espesor de la capa era constante. El resto del ensayo se realizó de la misma manera que para las muestras no compactadas. Para conocer el efecto de la compactación, se determinó en cada ensayo –tanto en los ensayos con compactación como en los ensayos sin compactación– la densidad aparente de la capa de material. Para ello, se calculó el volumen definido por cada anillo y se determinó el peso del material utilizado en cada ensayo para formar la capa (descontando el material descartado que se caía fuera del anillo durante el proceso de enrase).

3. RESULTADOS Y DISCUSIÓN

Todas las muestras alcanzaron ignición dentro del rango de temperaturas ensayado, lo que confirma su clasificación como materiales combustibles bajo las condiciones experimentales. Los resultados para muestras sin compactar se muestran en la Tabla 1. Se observa que los valores de MIT_L de las muestras de pélet de pino son más altos que los del serrín de chopo, es decir, éste último material tendría mayor facilidad de ignición ante superficies calientes. Los tiempos de ignición, considerados como el momento del ensayo en el que primero se cumple cualquiera de los criterios de ignición, también se muestran en la Tabla 1. Las muestras sin tiempo de ignición se corresponden con aquellas donde sólo se cumplió el criterio de la presencia de brasas, y éstas fueron detectadas al manipular la muestra una vez terminado el ensayo.

Los datos presentados en la Tabla 1 indican que no hay diferencias entre las fracciones granulométricas de ambos materiales. La única excepción fue el polvo de pélet con espesor de 5 mm, en el que se registró un descenso de 10 K al emplear la fracción fina. Santamaría-Herrera *et al.* (11) estudiaron capas de 5 mm de polvo de roble y de pino procedente de aserraderos y fábricas y ensayaron muestras originales y fracciones finas, obteniendo resultados similares: el valor de MIT_L de las muestras gruesas sin tamizar coincidía con el de las fracciones más finas.

Tabla 1: MIT_L y tiempo de ignición (t) para capas sin compactar

Muestra	Capa 5 mm		Capa 10 mm		Capa 20 mm	
	MIT _L (°C)	t (min)	MIT _L (°C)	t (min)	MIT _L (°C)	t (min)
<i>Pélet de pino</i>						
< 2000 µm	330	20	300	-	280	-
< 250 µm	320	10	300	20	280	55
<i>Serrín de chopo</i>						
< 5000 µm	310	6	290	17	270	30
< 400 µm	310	10	290	12	270	35

Puede observarse de la Tabla 1 que el aumento en el espesor de la capa de polvo produjo una disminución del valor de MIT_L y un aumento en el tiempo necesario para la ignición; esta tendencia se cumplió para las dos fracciones granulométricas y para los dos materiales. Es decir, los resultados muestran una dependencia clara respecto al espesor de la capa, de manera acorde a la teoría de ignición de Frank-Kamenetskii (4). Para una misma fracción, los valores de MIT_L para las capas de 10 mm fueron 20 K menores que los de las capas de 5 mm (30 K menos en el caso de la fracción gruesa de pélets de pino). Asimismo, al pasar de un espesor de 10 mm a 20 mm los valores descendieron otros 20 K para las cuatro muestras ensayadas. Estas reducciones son mucho menores que las que sugiere la norma UNE-EN 60079-14 (8), conclusión a la que también llegaron Fernandez-Anez *et al.* (12) para diversas mezclas de polvo de lodos de depuradora, pélets de madera torrefactados y carbón. Por su parte, Val-Aguasca *et al.* (9) ensayaron distintas fracciones de residuo de polvo de trigo acumulado en cosechadoras y obtuvieron descensos entre 20 y 40 K en MIT_L, dependiendo de la muestra, al aumentar el espesor de 5 a 10 mm y de 10 a 15 mm.

La Figura 3 ilustra la evolución de la temperatura de la capa durante un ensayo sin ignición y durante un ensayo con ignición. En el primer caso, la curva creció hasta una temperatura máxima ligeramente menor que la temperatura de consigna y luego descendió suavemente. En el segundo caso, la curva mostró un incremento mayor, superándose claramente la temperatura de consigna del ensayo con varios picos y un descenso final. Comparando ambas curvas puede observarse la transición que se produce en el material al aumentar 10 K la temperatura del ensayo, que se corresponde con el fenómeno de la ignición.

Los resultados de los ensayos desarrollados con compactación de la capa se muestran en la Tabla 2. Puede deducirse que la compactación de la capa redujo el valor de MIT_L en 10 K

respecto a la capa sin compactar, en todas las muestras excepto en la fracción gruesa de pélet de pino (para los tres espesores estudiados) y en la fracción gruesa de serrín de chopo (únicamente para el espesor de 5 mm). Fernández-Añez y García-Torrent (5) estudiaron el efecto de la compactación colocando un peso de 2,2 kg sobre una capa de 50 mm de polvo de biomasa durante 30 segundos y observaron que, dependiendo de la muestra, el valor de MIT_L podía aumentar 10 K, bajar 10 K o mantenerse constante; en el caso concreto de polvo de pélets de madera, obtuvieron también una reducción de 10 K.

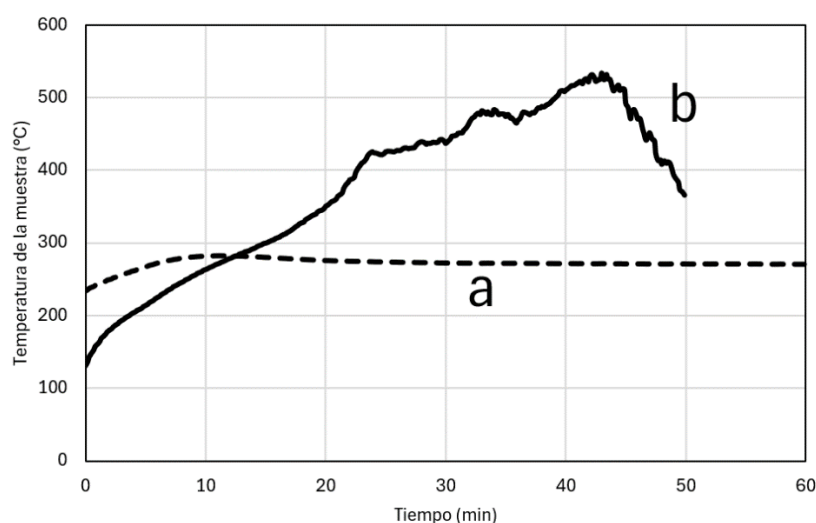


Figura 3: Evolución de la temperatura para la muestra $< 250 \mu\text{m}$ de pélet de pino durante el ensayo a 290°C (curva a) y durante el ensayo a 300°C (curva b)

La Tabla 3 muestra los valores medios de densidad aparente que se calcularon para los ensayos realizados. La compactación produjo un aumento de la densidad que varió entre el 12% y el 35%, dependiendo del tipo de muestra. Los datos indican que la compactación aumentó más la densidad en las muestras de chopo que en las muestras de pélet de pino; y que, para ambos materiales, la densidad creció más para las muestras finas que para las muestras gruesas. Estos cambios en la densidad aparente de las capas explican, al menos en parte, las variaciones en MIT_L debidas a la compactación: la temperatura de ignición disminuyó principalmente en las muestras finas y, si se comparan materiales, disminuyó en un mayor número de casos para el serrín de chopo que para el polvo de pélet de pino.

El efecto de la granulometría de las muestras es evidente al analizar los resultados de las capas compactadas; la fracción fina de pélet de pino fue más sensible a la ignición para todos los espesores, así como también la fracción fina de chopo para la capa de 5 mm. Al aumentar el espesor de la capa de 5 a 10 mm, el valor de MIT_L de las muestras finas bajó 20 K mientras que el de las muestras gruesas disminuyó 30 K. Por otro lado, los valores de todas las muestras descendieron 20 K al aumentar el espesor de 10 a 20 mm, tal y como ocurrió en las capas sin compactar. El tiempo de ignición también mostró una tendencia similar a los valores obtenidos para las capas sin compactar.

Tabla 2: MIT_L y tiempo de ignición (t) para capas compactadas

Muestra	Capa 5 mm		Capa 10 mm		Capa 20 mm	
	MIT _L (°C)	t (min)	MIT _L (°C)	t (min)	MIT _L (°C)	t (min)
<i>Pélet de pino</i>						
< 2000 µm	330	-	300	47	280	-
< 250 µm	310	20	290	25	270	65
<i>Serrín de chopo</i>						
< 5000 µm	310	5	280	14	260	41
< 400 µm	300	4	280	13	260	38

Tabla 3: Densidad aparente media de las capas ensayadas sin compactar (ρ_1), de las capas compactadas (ρ_2) e incremento en la densidad debido a la compactación ($\Delta\rho$).

Muestra	ρ_1 (kg/m ³)	ρ_2 (kg/m ³)	$\Delta\rho$ (%)
<i>Pélet de pino</i>			
< 2000 µm	432	485	+12,3%
< 250 µm	265	320	+20,8%
<i>Serrín de chopo</i>			
< 5000 µm	147	191	+29,9%
< 400 µm	133	179	+34,6%

4. CONCLUSIONES

En este estudio se ha determinado la temperatura mínima de ignición de capas de polvo ante una superficie caliente para dos biomásas diferentes y dos fracciones granulométricas de cada una de ellas, para tres espesores de capa y comparando también el efecto de la compactación de la capa.

La compactación facilitó la ignición reduciendo 10 K la temperatura mínima de ignición, aunque en algunos ensayos no se detectó ninguna variación. El aumento en el espesor de la capa siempre redujo la temperatura crítica. Sin embargo, la granulometría sólo mostró efectos en unos pocos ensayos. Por otro lado, se observaron diferencias notables en el comportamiento de los dos materiales estudiados.

5. AGRADECIMIENTOS

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Session 2

Sesión 2

Sessão 2

WOOD JOINTS IN SINGLE SHEAR UNDER FIRE, COMPARISON BETWEEN PROTECTED AND UNPROTECTED



João Aguiar
MSc
DEM, ISEP, IPP –
Porto, Portugal



Elza M.M. Fonseca*
Professor
DEM, ISEP, IPP –
Porto, Portugal

Keywords: Wood joint; fire; char layer; temperature.

1. ABSTRACT

Unlike previous numerical studies on dowelled timber or steel-to-timber connections under fire, which mainly focused on double-shear wood-steel-wood configurations or on thermal response only, this work investigates single-shear glulam-to-steel dowel joints and explicitly models both char-layer evolution and load-bearing degradation, with and without passive protection. The proposed design equations extend the Eurocode 5 approach by incorporating geometric parameters and the effect of gypsum-board protection into the fire-resistance design of single-shear joints.

More specifically, this study examines the behaviour of single-shear wood joints with steel dowels exposed to standard fire, combining the analytical Eurocode 5 formulation with calibrated finite element numerical models.

The numerical methodology was previously validated against published experimental data. A coupled thermomechanical model was then developed to evaluate the temperature evolution, char-layer formation, and load-bearing capacity of single-shear timber joints under fire, accounting for temperature-dependent thermal and mechanical properties of the materials.

* Autor correspondente — LAETA, Departamento de Engenharia Mecânica, Instituto Superior de Engenharia do Porto, Instituto Politécnico do Porto. Rua Dr. Bernardino de Almeida, nº 431, 4200-072 Porto. PORTUGAL. e-mail: elz@isep.ipp.pt

While Eurocode 5 provides conservative estimates for joint capacity at room temperature, its fire-design provisions do not explicitly consider the influence of joint geometry or passive protection on structural performance.

Based on the numerical results, two practical design equations are proposed, enabling the calculation of the residual load-bearing capacity of a single-shear joint as a function of fire exposure time.

2. INTRODUCTION

Previous research on connections in fire has mainly investigated double-shear steel-to-timber or wood-steel-wood joints, often focusing on thermal fields, charring rates, or the influence of density and protection materials, and less on the complete thermo-mechanical response of single-shear joints [1]. Experimental and numerical works have demonstrated the importance of dowel diameter, plate configuration, wood density and gypsum-board protection, but design methods remain largely based on simplified Eurocode 5 rules that do not explicitly account for these parameters in fire [2].

The type of wood to be used in this work is designated as Glulam, which, according to the definition of the EN 1194:1999 standard [3], is a structural component constituted by joining layers of wood, parallel to the grain. It is one of the most widely used products in wooden structures, offering enormous geometric flexibility [4]. It is a technologically advanced product, composed of different species of wood, with high resistance and stability. In addition to the advantages presented above, it is easily integrated with other insulation materials [5]. The different resistance classes are defined according to the EN 1194:1999 standard [3].

This work uses the mechanical and thermal properties of the materials that make up the joints under study, wood, steel and plasterboard. To develop heat transfer models and evaluate the fire resistance of the joints, knowledge of the properties at high temperatures is necessary. Some of these properties are described in Eurocode 3 (Part 1-1) [6] and (Part 1-2) [7] for steel, and in Eurocode 5 (Part 1-2) [8] for wood. The properties of plasterboards will be obtained through literature [5], [9], [10].

Fire protection measures, both passive and active, are employed in buildings and other engineering structures to keep component temperatures below critical levels and to limit the spread of flames [11]. Active protection systems offer an immediate response to extinguish fires, while passive systems contain fire and slow its progression. Building designs should include both types of protection, as they work together to safeguard lives and protect the structure as a whole [12], [13]. Prioritising effective fire safety is essential in any construction project, and these systems must be installed by certified professionals. The various systems require regular maintenance to remain effective; an inadequately maintained fire safety system is as ineffective as having no protection at all [13].

To ensure the fire resistance of a structure, the materials used must be analysed according to the criteria of load capacity, integrity, and thermal insulation, as per ISO 834 [14]. Depending on their

function, structural elements are defined, which support external loads and must maintain this support in the event of a fire; and the compartment elements, which maintain the separation between adjacent areas in the event of a fire. It is worth noting that an element can fulfil one or both functions simultaneously, as per ISO 834 [14]. Standard fire resistance is determined by applying the boundary conditions specified by the standard fire curve over a period [14], [15].

For the development of this work, a validation of the adopted numerical methodology was carried out previously, based on the analysis of wood joints subjected to fire, according to an experimental study by another author. So, in this work, using the calibrated numerical model, only the results of the dimensioning of a single-shear joint, the fire-resistance effect in the protected or non-protected joint, are presented. In the thermal analysis, the evolution of the nodal temperature, the temperature field inside the joint, and the charring rate of the wooden elements are obtained. In the thermomechanical analysis, the resistant load of the joints and their evolution throughout fire exposure are evaluated, comparing the results obtained between joints with and without passive protection.

As a conclusion, the present study contributes by (i) developing a validated finite-element thermo-mechanical model for single-shear glulam joints with steel dowels under standard fire, (ii) quantifying the influence of joint geometry and passive protection on temperature field, char-layer development and load-bearing capacity, and (iii) proposing two simple design equations for the fire-resistant load capacity of protected and unprotected single-shear joints, thereby extending the Eurocode based design framework for this connection type.

The contribution is related to the study about single shear glulam dowel joints, where different ones about double shear dowelled joints, often in tension, are found in the literature. Also, a fully coupled thermo-mechanical finite element model is proposed, in comparison to other uncoupled models related to only thermal or mechanical solutions.

3. MATERIALS AND METHODOLOGY

Thermal properties of wood and steel were considered according to Eurocode 5, part 1-2 [8] and according to Eurocode 3, part 1-2 [7], respectively. The density of steel is considered a temperature-independent parameter, and the value adopted is 7850 kg/m^3 , according to Eurocode 3, part 1-1 [6]. The steel emissivity is equal to 0.7 [7], and for wood was taken equal to 0.8 [8]. The mechanical properties of steel were S275 [6], and for wood, GL32H was chosen as glulam wood [16]. Regarding the choice of insulation material, and for the developed models, it was decided to use the properties of type X plasterboard, used as passive protection against the action of fire [9], [10]. The emissivity of gypsum was taken equal to 0.8 [8].

ANSYS® was used as the finite element method for transient thermal and non-linear material analysis and to verify the thermomechanical behaviour due to coupling solution problems. The numerical calculation was performed for a 3D solid wood joint in single shear and subjected to fire exposure. An incremental tensile load was imposed to determine the maximum load capacity resistance in the wood joint.

For thermal analysis, all components (wood members and dowels) are assumed to be in perfect contact; in mechanical analysis, contact elements are also considered.

In the numerical analysis, the boundary conditions used are related to convection and radiation due to the exposed fire in front of the external surface of the connection. The initial temperature in the numerical model was considered equal to 20 °C. The emissivity of the environment will be taken as a constant value and equal to 1, Eurocode 1, part 1-2 [15]. The external surface of the connection is exposed to the standard fire curve ISO 834 [12] for 3600 seconds. The convection coefficient is equal to 25 W/m²K, according to Eurocode 1, part 1-2, [15].

For thermomechanical analysis, an incremental tensile load was imposed on the free end and a fixed end on the opposite side. The temperature previously obtained in the thermal analysis was added for a corresponding time of exposure to fire.

About the geometry for the studied wood joint represented in Figure 1, Eurocode 5 part 1-1 [17] provides simplified equations for calculating the load-carrying capacity of a single-shear plane in connection. To the design of wood joints, the aim is to determine the main dimensions (width, height and thickness of the wood elements, minimum spacing and edge/end distances between the dowels and the wood element). The number of dowels is an important parameter in the connection design, with the arrangement by lines and columns.

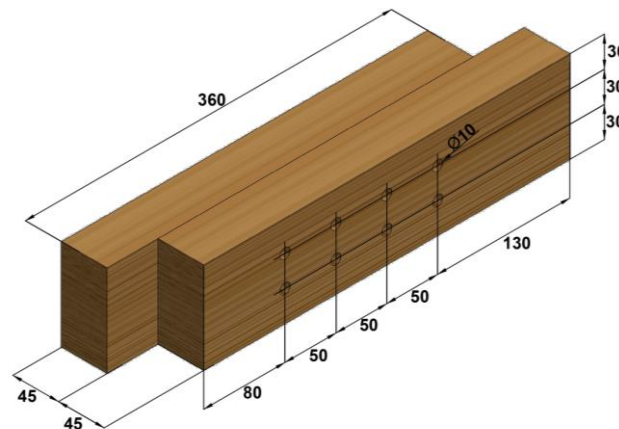


Figure 1 – The wood joint dimensions

Figure 2 shows the finite element meshes of the joints studied without and with protection. The dimension of the edge of each finite element is 6 mm, depending on the minimum size allowed in the model with the plasterboard.

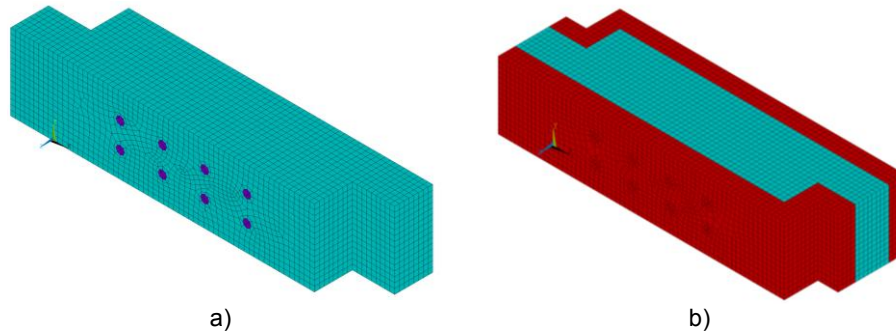


Figure 2 – The mesh wood joint: a) without protection, b) with protection

The mesh used in the thermal study is identical to that used in thermomechanical analysis, where it is necessary to use elements with the same nodes. The protected joint is analysed with 23 mm of type X plasterboard throughout the entire area that is considered affected by the action of fire.

4. RESULTS AND DISCUSSION

Based on numerical results, Figures 3 and 4 show the temperature gradient for 3600 s of exposure to fire, in the unprotected and protected joints, respectively.

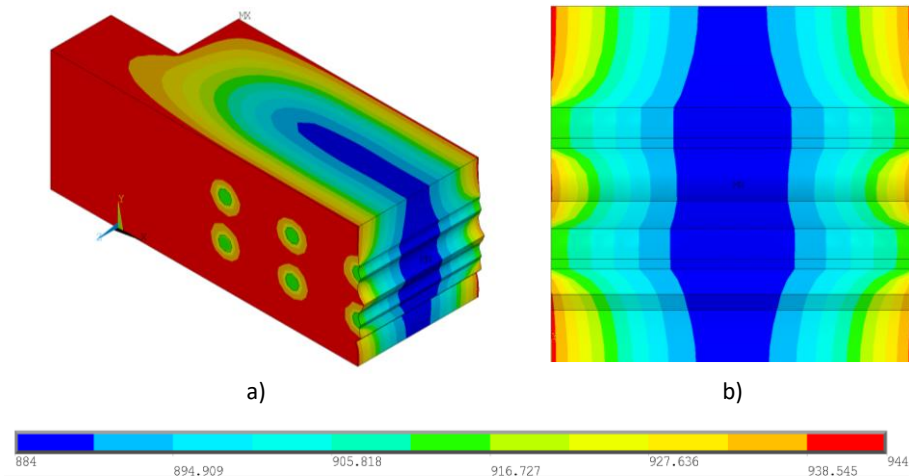


Figure 3 – Wood joint without protection, time of fire exposure of 3600 s: a) part of an isometric view and b) inside of the joint. Temperature in °C

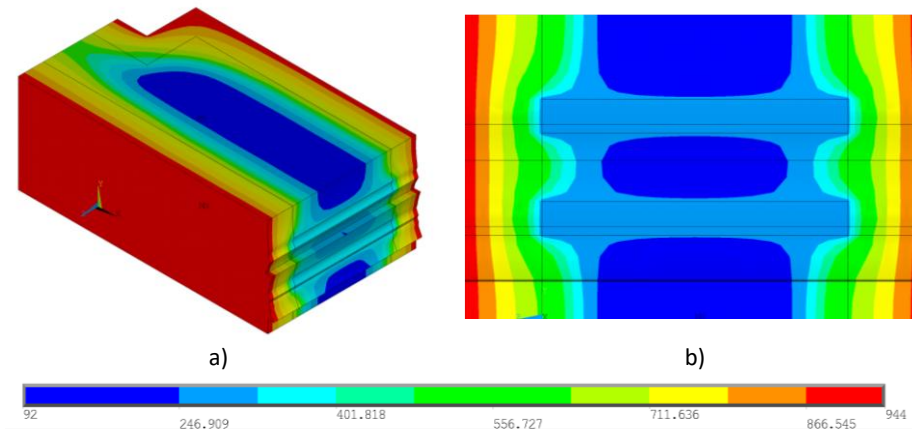


Figure 4 – Wood joint with protection, time of fire exposure of 3600 s: a) part of an isometric view and b) inside of the joint. Temperature in °C

Considerable differences are observed between the temperature gradients inside the two joints.

For 3600 s of exposure to fire, the minimum temperature in the unprotected joint is 884°C, which indicates total char of the wood and complete loss of its mechanical strength. In the protected joint, the minimum temperature recorded is 92°C, notably lower.

The maximum temperature recorded for both models is almost identical, approximately 944°C. The temperature on the surface exposed to the fire depends mainly on the temperature curve considered, ISO 834 [14], and on the instant considered; this is not the case for materials with high thermal conductivity, such as steel, which quickly transfer heat throughout the element.

The loss of load-bearing joint capacity is directly associated with the char layer progression, which leads to a reduction in the resistant cross-section.

To demonstrate the evolution of the resistant cross-section over time of exposure to fire, Figure 5 shows in a) and b) the non-char wood of the numerical models, excluding the finite elements whose temperature exceeds 300°C. The numerical results of the joint without protection are observed for 1200 s, and of the protected joint for 3000 s, to demonstrate the remaining wood joint.

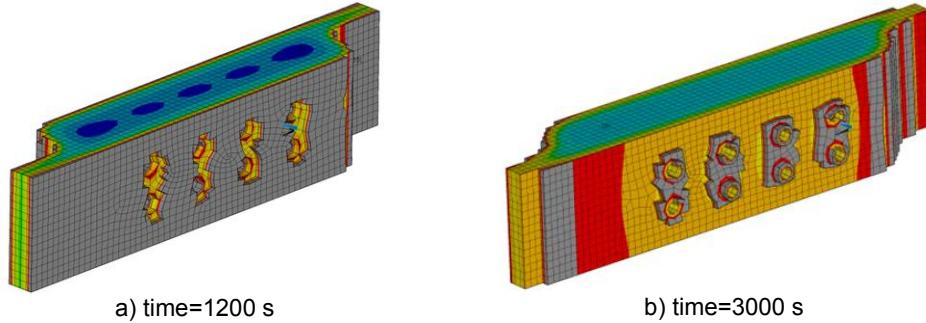


Figure 5: Char layer of wood joint a) without protection, b) with protection

As shown, the unprotected joint undergoes a faster reduction in thickness, particularly in the fastener region. At 1200 s, the joint region is considerably compromised. In the protected joint, the insulating effect of the plasterboard slows down degradation, and it is possible to observe, even at 3000 s, the presence of preserved material around the dowels, despite the more advanced char effect in the peripheral areas of the joint.

In the thermomechanical analysis, the resistance joint capacity is evaluated for different fire exposure times to quantify the decrease in mechanical resistance over time and analyse the effectiveness of the plasterboard protection.

Figure 6 presents the results obtained, with second-degree polynomial trend curves, according to two different design equations to be used for protected or non-protected wood joints in the resistant load calculation.

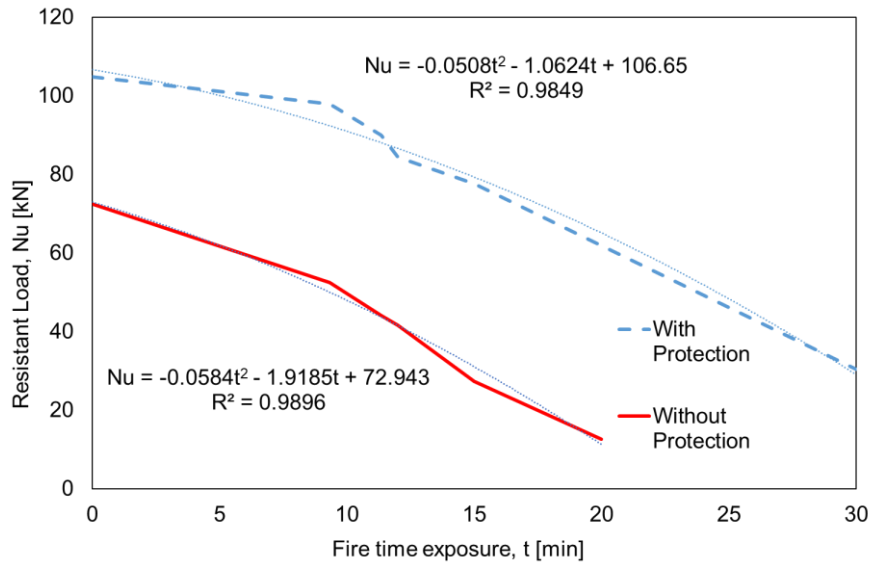


Figure 6: Design equations for wood joints

The coefficients of both polynomials come from a validated 3D thermomechanical finite element model, previously checked against experimental results on similar connections, which ensures that the equations represent a degradation trend. Also, the separate polynomials for protected and unprotected configurations quantify the beneficial effect of passive protection on the residual load-bearing capacity along the fire duration.

The respective equations are provided in the graph, allowing the prediction of the resistant load as a function of the time of fire exposure, useful for wood joints design in single shear for construction, with the configuration under study. Other studies need to be increased, to guarantee a large application in design with other typical connections, which can help the load calculation easily.

These design equations extend the Eurocode 5 framework to the fire domain by directly relating the resistance of single-shear glulam–steel dowel joints to the duration of fire exposure, with and without gypsum-board protection.

5. CONCLUSION

The comparison between the models quantifies the effect of passive protection over time. The protected joint exhibits a more gradual degradation, maintaining its structural load-bearing capacity for a substantially longer period. This behaviour underscores the importance of passive protection and the need for design methodologies better tailored to the material properties and to the variability of timber joint configurations.

Based on the results obtained, two easy-to-use design equations are proposed, allowing the calculation of the resistant load in wooden joints, with or without protection, in single shear as a function of the exposure to fire.

These user-friendly equations are intended for preliminary design and quick checks, allowing practitioners to estimate the resistance of single-shear joints at a specified fire exposure time without performing detailed numerical simulations.

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ANÁLISE NUMÉRICA DO COMPORTAMENTO TERMOMECÂNICO DE VIGAS DE AÇO FORMADO A FRIO COM ABERTURAS NA ALMA



Ana Antônia*
Mestranda
UFMG – BH
Brasil



João Paulo C. Rodrigues
Professor
UC - Coimbra
Portugal, UFMG –
BH, Brasil



Francisco C. R.
Professor
UFMG – BH
Brasil

Palavras-chave: Análise numérica; Elementos finitos; Aço formado a frio; Incêndio; Aberturas na alma; Comportamento termomecânico.

1. INTRODUÇÃO

O uso de perfis de aço formados a frio (PFF) no Brasil tem se expandido nas últimas décadas [1], especialmente em sistemas construtivos industrializados como o *Light Steel Framing* (LSF). Esses sistemas se destacam pela leveza estrutural, racionalização de materiais e rapidez de execução, fatores que têm impulsionado sua adoção em diferentes tipologias de edificações [2]. No contexto estrutural, vigas formadas a frio são frequentemente utilizadas como elementos de piso e cobertura [2], sendo comum a presença de aberturas em suas almas para a passagem de instalações elétricas e hidrossanitárias.

Embora o aço seja um material incombustível, suas propriedades mecânicas sofrem significativa degradação quando submetidas a temperaturas elevadas, resultando na redução da resistência e da rigidez dos elementos estruturais [3]. No caso de perfis formados a frio, caracterizados por chapas de pequena espessura e elevada esbeltez, esses efeitos podem ser ainda mais pronunciados [2,3]. A presença de aberturas na alma introduz descontinuidades geométricas que alteram o fluxo de tensões e reduzem a área resistente da seção, podendo desencadear mecanismos de falha locais, como o mecanismo de Vierendeel [4]. Apesar de sua relevância

* Autora correspondente – Departamento de Engenharia de Estruturas, Escola de Engenharia, Universidade Federal de Minas Gerais (UFMG).

Telef.: +55 31 971742408, E-mail: limaanaantonia@ufmg.br

prática, o dimensionamento de perfis formados a frio com aberturas ainda não é tratado explicitamente pelas principais normas brasileiras, como a ABNT NBR 14762:2010 [5] para temperatura ambiente e a ABNT NBR 14323:2013 [6] para situação de incêndio.

No âmbito internacional, o estudo do comportamento de vigas com aberturas na alma em temperatura ambiente possui uma trajetória consolidada, com contribuições clássicas de Redwood [7] e desenvolvimentos mais recentes de Schafer, que propôs metodologias para prever a resistência de perfis perfurados por meio do Método da Resistência Direta [8]. Entretanto, em situação de incêndio, a literatura é significativamente mais limitada e concentrada principalmente em perfis laminados. Estudos envolvendo vigas celulares e casteladas, como os de Kada et al. [9] e Bailey e Mesquita et al. [10,11], têm contribuído para o entendimento do comportamento de vigas com aberturas em altas temperaturas. Mais recentemente, Sam et al. [12] investigaram experimental e numericamente o comportamento pós-incêndio de vigas formadas a frio com aberturas. Ainda assim, são raros os trabalhos que avaliam o comportamento durante a exposição ao fogo de perfis de chapa fina utilizados em sistemas *Light Steel Framing*, considerando a diversidade de geometrias de perfis, espessuras e configurações de aberturas empregadas na prática.

Diante desse contexto, o presente trabalho investiga, por meio de simulações numéricas em elementos finitos realizadas no software Abaqus, o comportamento termomecânico de vigas de aço formadas a frio com e sem aberturas na alma, submetidas à curva de incêndio padrão ISO 834 [13]. A pesquisa busca avaliar a influência do tipo de perfil, da espessura da chapa, do nível de carregamento e da configuração das aberturas na temperatura crítica e nos modos de falha das vigas, contribuindo para o avanço do conhecimento sobre o desempenho de sistemas em *Light Steel Framing* em situação de incêndio.

2. MODELAGEM NUMÉRICA

As faixas paramétricas adotadas neste estudo foram definidas com base em perfis comerciais normalizados pela ABNT NBR 15253:2014 [14] e em condições típicas de projeto estrutural, de modo a representar configurações realistas e tecnicamente relevantes (Tabela 1). Foram selecionadas as espessuras de 0,8 mm e 1,25 mm, pertencentes à série normalizada (0,8; 0,95; 1,25 mm). A escolha desses dois valores permitiu contemplar perfis mais esbeltos e mais robustos, ao mesmo tempo em que se limitou o número total de simulações numéricas, garantindo a viabilidade computacional do estudo. As alturas de alma de 140 mm e 200 mm foram escolhidas a partir da série comercial (90, 140 e 200 mm). Os perfis com altura de 90 mm não foram considerados, uma vez que a introdução de aberturas na alma nesses elementos é estruturalmente menos relevante para a passagem de instalações prediais, além de apresentar menor interesse do ponto de vista da resposta resistente.

A variação do número de aberturas foi investigada, uma vez que, em aplicações reais, é comum a presença de múltiplas aberturas ao longo do vão, e não apenas um único furo isolado. Dessa forma, buscou-se avaliar possíveis efeitos de interação entre aberturas adjacentes sobre a redistribuição de tensões e sobre os mecanismos de instabilidade. Foram analisadas configurações com até três aberturas, considerando a necessidade de um espaçamento mínimo de aproximadamente 600 mm entre os centros dos furos, bem como a não coincidência das

aberturas com a região de aplicação da carga concentrada. Estabeleceu-se uma distância de 800 mm entre os eixos das aberturas, garantindo que o carregamento não incidisse diretamente sobre esses vãos.

Tabela 1: Parâmetros considerados no estudo paramétrico

Parâmetro	Valores Adotados
Altura da alma (h)	140 mm / 200 mm
Espessura (t)	0,8 mm / 1,25 mm
Formato da abertura	Oblongo (38x115 mm) / Circular (Ø42 mm)
Número de aberturas (N)	1, 2 e 3 ou sem aberturas
Nível de carregamento	30% / 50% / 70% da resistência em temperatura ambiente
Perfil	C, I e R

Também foram consideradas diferentes geometrias de aberturas (Figura 1), com o objetivo de analisar a influência do formato na concentração de tensões locais e no comportamento termomecânico global das vigas. A ABNT NBR 15253:2014 [14] recomenda uma abertura oblonga com dimensões de 38 mm de altura por 115 mm de comprimento. Essa geometria apresenta dimensões semelhantes às investigadas experimentalmente por Moen e Schafer [15], que observaram que tal configuração não exerce influência significativa sobre a capacidade resistente de barras comprimidas em temperatura ambiente. Adicionalmente, foi adotada uma abertura circular com razão entre a altura do furo e a altura da alma tal que não se esperasse impacto significativo na resistência global, de forma análoga ao caso oblongo. Assim, foi escolhida a razão de 0,30, de acordo com investigações de Yao [16], resultando em um diâmetro de 42 mm para a viga com altura de alma de 140 mm, correspondente à menor altura analisada neste estudo.

No que se refere ao nível de carregamento, a norma brasileira ABNT NBR 14323:2013 [6] e o Eurocode EN 1993-1-2 [3] estabelecem que, em situação de incêndio, a solicitação de projeto deve ser considerada como:

$$S_{Sd} = 0.7S_{Rd} \quad (1)$$

em que S_{Sd} representa a solicitação de projeto e S_{Rd} a resistência do elemento estrutural em temperatura ambiente. Com base nesse critério normativo e em estudos prévios sobre estruturas de aço em situação de incêndio, foram adotados níveis de carregamento correspondentes a 30%, 50% e 70% da carga resistente à temperatura ambiente, uma vez que o nível de solicitação é reconhecido como um dos parâmetros mais influentes na resistência ao fogo de elementos estruturais metálicos.

As propriedades do material (aço ZAR 280, $f_y = 280$ MPa) foram definidas segundo um modelo constitutivo elastoplástico com degradação térmica conforme prescrito pela EN 1993-1-2 [3]. A relação tensão–deformação real foi empregada a fim de incorporar os efeitos de encruamento e da redução de área, conforme recomendado na documentação do software Abaqus. As condições de contorno representaram apoios articulados fixo e móvel, com restrições laterais destinadas a impedir deslocamentos horizontais. A aplicação da carga concentrada foi realizada

por meio de superfícies analíticas rígidas, utilizando-se *tie constraints* para evitar instabilidades numéricas associadas a problemas de contato. Imperfeições geométricas iniciais foram introduzidas a partir dos modos de flambagem obtidos em análise de bifurcação linear, com amplitudes correspondentes a $L/1000$ para imperfeições locais e $L/500$ para imperfeições globais, conforme recomenda a ABNT NBR 8800:2024 [17]. A Figura 1 apresenta o esquema da viga adotada no modelo numérico.

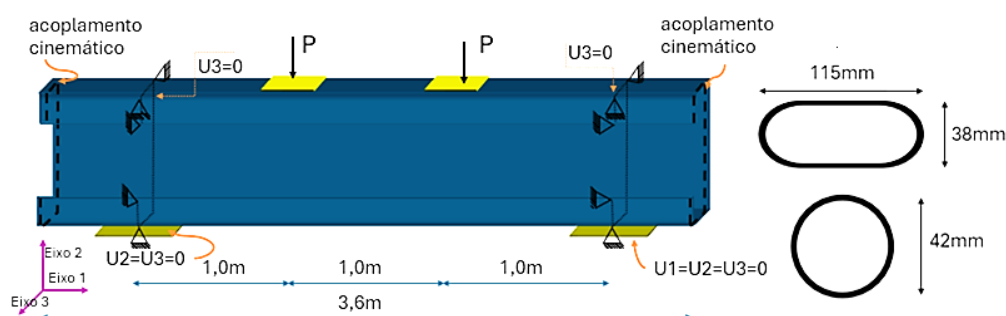


Figura 1: Reprodução esquemática da viga e aberturas estudadas

No que se refere às análises térmicas, foi adotada a curva de incêndio padrão ISO 834, com coeficiente de convecção igual a $20 \text{ W/(m}^2\cdot\text{K)}$ e emissividade superficial de 0,7. Devido à indisponibilidade de elementos termomecânicos acoplados com ordem de interpolação adequada no Abaqus Standard, optou-se por uma estratégia desacoplada. Inicialmente, realizou-se uma análise transiente de transferência de calor; em seguida, os campos de temperatura obtidos foram importados como *Predefined Field* na análise mecânica. A discretização da malha empregou elementos prismáticos triangulares (*wedge*) de segunda ordem nas regiões próximas às aberturas, evitando-se o uso de elementos piramidais devido a dificuldades de convergência observadas em malhas mais refinadas. O método de Riks foi adotado para a análise estrutural, possibilitando a captura do comportamento pós-crítico e melhorando a convergência numérica em cenários caracterizados por forte não linearidade geométrica e efeitos de instabilidade.

Modelos do ensaio numérico seguirão a nomenclatura: C-AOB008-30PP-N3. Decupando: C (perfil), A (grupo A: altura de 140/142mm; grupo B: demais), OB (tipo de abertura: alongada; podendo ser CI ou circular), 008 (espessura: 0,8 mm; ou 1,25 mm), 30PP (% da carga aplicada) e N3 (número de aberturas).

3. VALIDAÇÃO DO MODELO

A validação do modelo numérico foi realizada com base nos dados experimentais de Laím [18], que investigou vigas de aço formado a frio sob incêndio. O processo de calibração foi conduzido em duas etapas: temperatura ambiente e temperatura elevada.

Inicialmente, para a calibração em temperatura ambiente, foi realizado um estudo de convergência de malha com três níveis de refinamento (#20, #15 e #10) para os perfis C, I e R.

Os resultados, apresentados na Figura 2, mostram a estabilização da carga de pico com o aumento do refinamento da malha. Para o perfil C, as cargas de pico obtidas foram de aproximadamente 10,34 kN (malha #20), 10,32 kN (malha #15) e 10,29 kN (malha #10), com uma diferença inferior a 0,3% entre as malhas #15 e #10, justificando a escolha da malha #10. Para o perfil I, as cargas de pico foram de aproximadamente 43,69 kN (malha #20), 44,19 kN (malha #15) e 47,05 kN (malha #10), sendo esta última cerca de 6,5% superior à malha #15. Para o perfil R, as cargas de pico atingiram aproximadamente 51,7 kN (malha #20), 50,86 kN (malha #15) e 51,72 kN (malha #10), com uma diferença de aproximadamente 1% entre as malhas #15 e #10, confirmando a convergência dos resultados. No entanto, o custo computacional é muito alto para malhas densas.

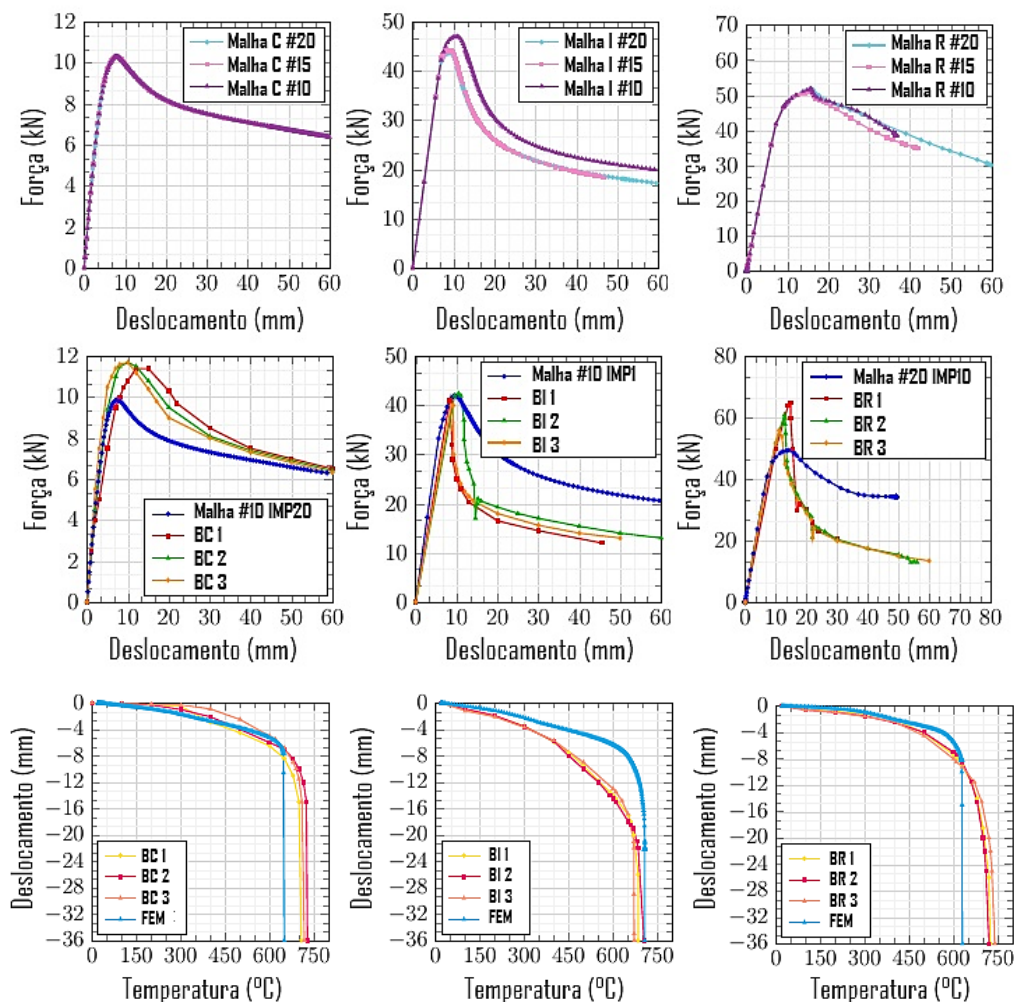


Figura 2: Convergência de malha e comparação com resultados experimentais em temperatura ambiente e elevada

Com as malhas #10 (para os perfis C e I) e #20 (para o perfil R) selecionadas, os resultados numéricos em temperatura ambiente, conforme ilustrado na Figura 2, mostraram boa aderência aos ensaios, com curvas força-deslocamento capturando adequadamente a rigidez inicial, a carga máxima e o amolecimento pós-pico. Para o perfil C, a carga máxima numérica (9,9 kN) situou-se dentro da faixa experimental (10,5–11,7 kN). Para o perfil I, o pico numérico ($\approx 42,0$ kN, considerando a introdução de imperfeições geométricas) coincidiu com os valores experimentais (40–43 kN). O perfil R apresentou maior discrepância (subestimação de $\approx 30\%$ em relação aos 55–65 kN experimentais), atribuída à sensibilidade do modelo e às simplificações nas condições de contorno e no modelo constitutivo, embora o comportamento pós-crítico tenha sido adequadamente capturado.

Por fim, a análise térmica desacoplada, cujos resultados também são apresentados na Figura 2, demonstrou capacidade satisfatória em reproduzir a evolução da temperatura ao longo do tempo, com diferenças médias inferiores a 5% em relação às medições experimentais. A estratégia de importação do campo térmico como condição pré-definida mostrou-se eficaz para incorporar efeitos térmicos em elementos estruturais sem graus de liberdade térmicos, validando a abordagem desacoplada para problemas termomecânicos quase-estáticos.

4. ANÁLISE PARAMÉTRICA E DISCUSSÕES

A evolução dos deslocamentos verticais e laterais durante o aquecimento permitiu identificar três fases distintas do comportamento termomecânico: (1) fase de expansão térmica dominante, até aproximadamente 300°C, com deslocamentos reduzidos; (2) fase de degradação progressiva da rigidez, entre 300°C e 550°C, caracterizada pelo aumento gradual das deformações devido à perda de rigidez do aço; e (3) fase de crescimento acelerado dos deslocamentos e colapso, a partir de 550°C, quando a estrutura atinge sua temperatura crítica (Θ_{cr}). Além disso, a Tabela 2 apresenta os resultados obtidos na análise paramétrica.

Os mecanismos de falha foram identificados a partir de critérios geométricos extraídos dos deslocamentos nodais e da análise da distribuição do campo de tensões. A flambagem lateral com torção (FLT) foi o modo de instabilidade predominante nos perfis C e I, caracterizada por deslocamentos laterais simétricos ao longo do vão. A flambagem local da alma foi observada principalmente nos perfis C, sendo associada a variações abruptas na derivada do deslocamento lateral ao longo da altura da seção, indicando instabilidade localizada do painel de alma. A distorção da seção transversal foi quantificada pela razão entre os deslocamentos lateral e vertical (u_1/u_2), a qual apresentou incremento súbito próximo ao colapso, especialmente nos perfis R, evidenciando a perda de rigidez e de forma da seção. Nos perfis com aberturas, observou-se o início do mecanismo de Vierendeel, identificado pela concentração de tensões ao redor das perfurações, ainda que de baixa magnitude. De forma geral, a presença de aberturas não alterou qualitativamente os modos globais de falha, porém intensificou os deslocamentos laterais e introduziu concentrações de tensão localizadas. O perfil R apresentou colapso dominado pela plastificação concentrada na região central, conforme indicado pelos campos de deformação plástica equivalente (PEEQ), em vez de um mecanismo de instabilidade global.

Para aplicações em que a temperatura ambiente é a condição crítica de dimensionamento, o aumento da espessura da chapa se configura como uma estratégia direta para ganho de capaci-

dade resistente. A adoção de perfis com espessura de 1,25 mm, em substituição a perfis de 0,8 mm, proporciona um acréscimo médio de 40% na carga crítica de flambagem (P_{cr}), representando uma alternativa eficiente para situações que demandam maior capacidade estrutural. Quando a geometria do perfil puder ser ajustada sem restrições arquitetônicas significativas, a escolha por perfis com maior altura de alma mostra-se vantajosa. Os perfis da série B (altura da alma = 200 mm) apresentaram resistência aproximadamente 30% superior aos da série A (140 mm), em decorrência do aumento da rigidez geométrica da seção transversal.

Tabela 2: Tempos, temperaturas críticas médias e cargas aplicadas

Amostra	Carga (N)	Temperatura (°C)	Tempo (min)	Razão de Carga
C-A008-PP30	193,10	699,57	13min 8s	30%
C-A008-PP50	321,83	606,29	7min 39s	50%
C-A008-PP70	450,56	482,29	4min 9s	70%
C-A125-PP30	334,17	725,43	16min 37s	30%
C-A125-PP50	556,95	635,14	9min 45s	50%
C-A125-PP70	779,73	517,29	6min 8s	70%
C-B008-PP30	244,04	722,29	15min 13s	30%
C-B008-PP50	406,74	639,57	9min 4s	50%
C-B008-PP70	569,43	559,14	5min 57s	70%
C-B125-PP30	462,15	694,71	13min 28s	30%
C-B125-PP50	770,25	602,29	8min 21s	50%
C-B125-PP70	1078,34	484,00	5min 10s	70%
I-A008-PP30	770,28	689,57	12min 21s	30%
I-A008-PP50	1283,81	600,14	7min 33s	50%
I-A008-PP70	1797,33	474,71	4min 19s	70%
I-A125-PP30	1267,66	697,86	13min 58s	30%
I-A125-PP50	2112,76	609,57	9min 2s	50%
I-A125-PP70	2957,86	504,00	5min 53s	70%
I-B008-PP30	1010,96	703,71	13min 26s	30%
I-B008-PP50	1684,93	619,71	8min 19s	50%
I-B008-PP70	2358,91	505,57	4min 52s	70%
I-B125-PP30	1763,83	712,43	15min 8s	30%
I-B125-PP50	2939,71	621,57	9min 28s	50%
I-B125-PP70	4115,60	510,71	5min 59s	70%
R-A008-PP30	715,22	726,57	18min 40s	30%
R-A008-PP50	1192,03	653,57	12min 46s	50%
R-A008-PP70	1668,84	593,00	9min 59s	70%
R-A125-PP30	1634,08	676,00	16min 29s	30%
R-A125-PP50	2723,47	592,14	12min 7s	50%
R-A125-PP70	3812,86	526,86	9min 46s	70%
R-B008-PP30	991,81	723,14	18min 11s	30%
R-B008-PP50	1653,01	651,00	12min 35s	50%
R-B008-PP70	2314,22	589,43	9min 50s	70%
R-B125-PP30	2193,19	681,71	16min 47s	30%
R-B125-PP50	3655,32	599,86	12min 20s	50%
R-B125-PP70	5117,44	529,43	9min 49s	70%

Quanto à tipologia da seção, a escolha entre perfis C, I e R deve ser orientada pela magnitude das cargas atuantes. Em aplicações que exigem elevada capacidade resistente, os perfis I devem ser preferidos, uma vez que apresentaram valores de P_{cr} aproximadamente 75% superiores aos perfis C. Já os perfis R ainda oferecem ganhos de até 17% em relação a estes últimos, podendo ser uma alternativa interessante quando outros condicionantes de projeto (como conexões ou detalhamento construtivo) forem determinantes.

Em situação de incêndio, os critérios de projeto devem ser substancialmente diferentes, pois os parâmetros geométricos que governam o comportamento em temperatura ambiente perdem relevância. A espessura da chapa, por exemplo, não se configura como parâmetro relevante para melhoria do desempenho em incêndio, uma vez que perfis mais esbeltos (0,8 mm) e mais espessos (1,25 mm) atingiram temperaturas de colapso praticamente equivalentes, com diferença média de apenas 3%, indicando que recursos de projeto devem ser direcionados a outras estratégias de proteção passiva ou ativa, em vez do aumento da espessura. Da mesma forma, a altura da alma também não se mostrou determinante para o comportamento em alta temperatura.

O nível de carregamento em situação de incêndio emerge, de fato, como o fator mais crítico, sendo necessária especial atenção ao dimensionamento de perfis C submetidos a elevadas taxas de ocupação (acima de 50% da carga em temperatura ambiente), pois sua temperatura crítica pode reduzir drasticamente - de 710°C para 510°C quando o carregamento aumenta de 30% para 70% da capacidade em temperatura ambiente, casos em que medidas complementares de proteção contra incêndio se fazem necessárias. Já os perfis I e R demonstraram comportamento térmico mais previsível e estável, sendo opções mais robustas para situações em que não é possível reduzir o nível de carregamento ou onde se deseja maior confiabilidade em cenários de incêndio.

Quanto à presença de aberturas na alma, esta deve ser tratada de forma distinta nos dois cenários de projeto. Em temperatura ambiente, as perfurações reduzem a capacidade resistente (em média 8%), sendo este efeito mais pronunciado em perfis I, de modo que o dimensionamento deve considerar explicitamente a perda de área efetiva, especialmente quando múltiplas aberturas forem previstas. Em situação de incêndio, por outro lado, as perfurações estudadas não comprometem significativamente o desempenho térmico global da estrutura, exceto em perfis C sob elevados níveis de carregamento; para a maioria das aplicações, o projeto pode desconsiderar o efeito das aberturas na temperatura crítica, desde que o nível de carregamento seja moderado (em torno de PP30), sendo necessária atenção adicional e eventual verificação específica apenas para perfis C com aberturas.

A Figura 4 sintetiza os tempos e temperaturas críticas obtidos nas análises termomecânicas para todas as configurações. A Figura 5, por sua vez, detalha a influência de cada parâmetro isoladamente, comparando a temperatura crítica dos perfis com aberturas ($\Theta_{cr,hole}$) em relação aos perfis sem aberturas ($\Theta_{cr,gross}$). Os gráficos estão organizados por: (a) percentual de carga, (b) número de aberturas, (c) tipo de abertura, (d) altura da alma e (e) espessura da chapa.

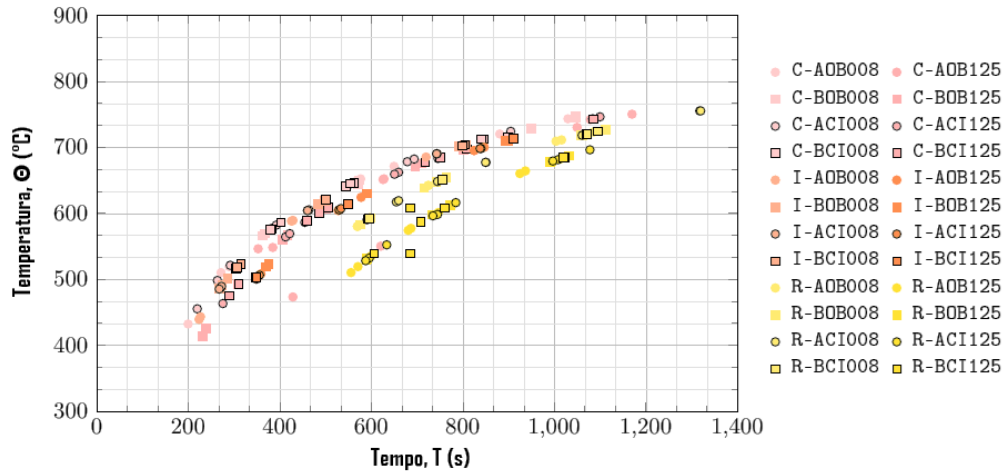


Figura 4: Temperaturas e tempos críticos obtidos por meio da análise FEM

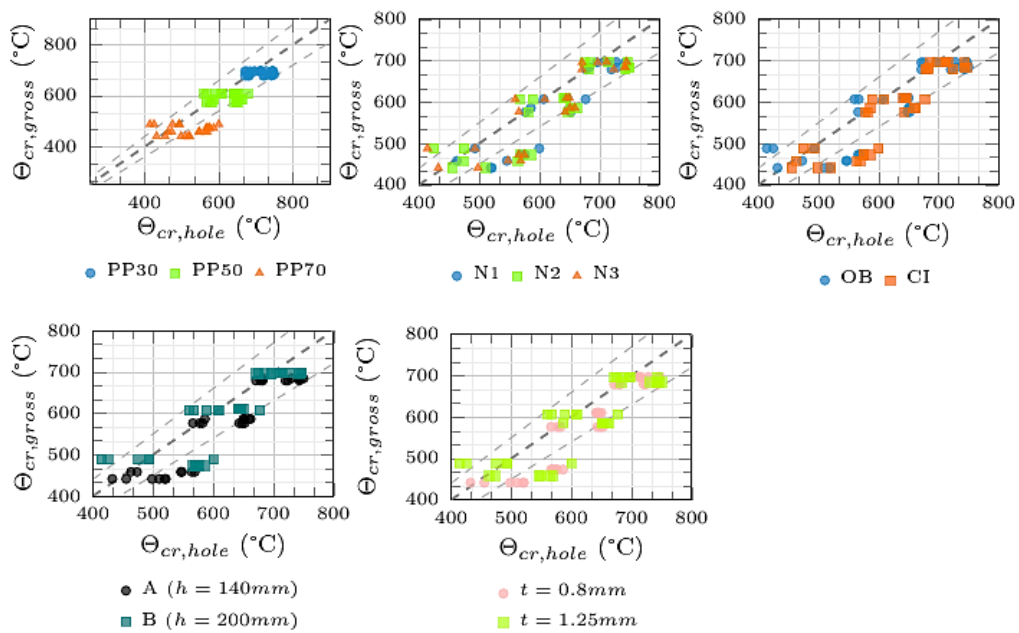


Figura 5: Comparação entre $\Theta_{cr,hole} \times \Theta_{cr,gross}$ obtidos por MEF para diferentes: (a) percentagens de carga, (b) número e (c) tipos de abertura, (d) alturas do perfil, (e) espessuras

Complementarmente, a Figura 6 desagrega os resultados da Figura 5 por tipo de perfil, permitindo uma visualização mais clara do desempenho relativo de cada seção. Observa-se que os perfis C (Figura 6a) concentram a maior dispersão dos dados, enquanto os perfis I (Figura 6b) e, principalmente, os perfis R (Figura 6c) apresentam um comportamento mais consistente, com

a maioria das configurações com aberturas atingindo temperaturas críticas muito próximas às dos perfis sem aberturas, dentro de uma margem $\pm 10\%$ de erro.

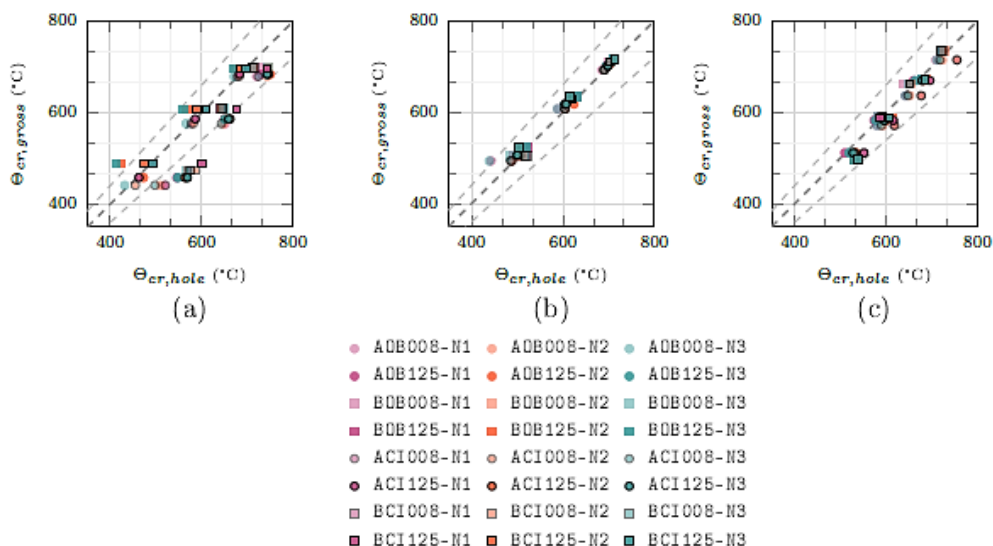


Figura 6: Comparação entre $\theta_{cr,hole} \times \theta_{cr,gross}$ obtidos por MEF para diferentes perfis: (a) C, (b) I e (c) R

Com base nos dados apresentados, nota-se que o tempo de resistência ao fogo dos perfis é drasticamente reduzido sob elevados níveis de carregamento (PP50 e PP70). Conforme detalhado na Tabela 2, os ensaios sob 30% da carga limite (PP30) apresentaram um tempo médio até o colapso de aproximadamente 15min 18s. Essa resistência caiu para cerca de 9min 54s sob 50% da carga (PP50) e para apenas 6,8 minutos sob 70% da carga (PP70). As reduções médias de mais de 35% entre PP30 e PP50, e de aproximadamente 55% entre PP30 e PP70, demonstram de forma inequívoca a sensibilidade da resposta estrutural ao fogo em relação à razão de carga aplicada.

Também, a Tabela 3 apresenta um resumo dos efeitos de cada parâmetro investigado na temperatura crítica, sintetizando as principais implicações práticas para o projeto de vigas em perfil formado a frio com aberturas na alma em situação de incêndio.

5. CONCLUSÕES

Os resultados indicam que a resistência ao fogo de vigas de aço formado a frio é predominantemente governada pelo nível de carregamento, enquanto a influência de parâmetros geométricos, como espessura da chapa e altura da alma, é secundária em situação de incêndio. Assim, o dimensionamento deve priorizar a correta definição da solicitação mecânica em incêndio, uma vez que pequenas variações nesse parâmetro produzem reduções significativas na capacidade resistente. A presença de aberturas na alma, dentro das faixas analisadas, não

alterou de forma significativa a temperatura crítica das vigas, embora tenha provocado concentrações de tensões locais. Para perfis dos tipos I e R, o número e o formato das aberturas podem ser tratados de forma simplificada em análises preliminares. Já para perfis do tipo C sob níveis elevados de carregamento, recomenda-se maior cautela devido à maior sensibilidade a mecanismos de instabilidade.

De modo geral, o comportamento em incêndio é dominado pela degradação térmica do material, superando os efeitos locais das perfurações. Os resultados contribuem para o desenvolvimento de critérios de projeto mais consistentes para vigas de aço formado a frio com aberturas na alma em situação de incêndio.

Tabela 3: Resumo dos parâmetros em temperatura elevada

Parâmetro	Amplitude	Efeito na temperatura crítica	Implicação prática
Proporção de carga	30% a 70% da carga ambiente	Diminuição acentuada ($\Delta \approx -200^{\circ}\text{C}$ de PP30 para PP70)	O nível de carga é determinante para a resistência ao fogo.
Tipo da seção	C, I e R	R tem desempenho pouco superior.	Seções fechadas proporcionam resistência ao fogo adicional.
Espessura	0,8 mm e 1,25 mm	Influência menor ($\Theta_{cr,0.8} / \Theta_{cr,1.25} \approx 1,03$)	A espessura não é um parâmetro significativo
Altura da alma	140 mm e 200 mm	Influência insignificante ($\Theta_{cr,B} / \Theta_{cr,A} \approx 0,99$)	A altura da alma também não impacta na resistência ao fogo.
Abertura	Oblonga e Circular	Influência mínima ($\Theta_{cr,perfurado} / \Theta_{cr,bruto} \approx 0,99$)	As faixas estudadas não impactaram a resistência ao fogo.
Número de aberturas	1 a 3	Baixa influência, com exceção de perfis C sob PP50-PP70.	O número de aberturas pode ser desconsiderado em projetos simplificados para perfis I e R.

6. AGRADECIMENTOS

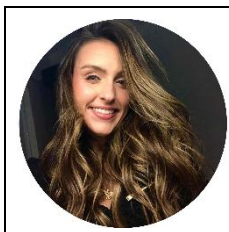
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**CRACK OPENING PATTERN OF FLAT SLABS EXPOSED TO FIRE:
NUMERICAL ANALYSIS ON DISPLACEMENT RATE**



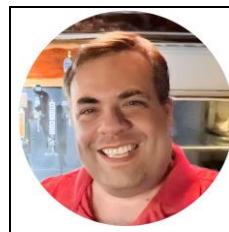
**Andreia Romero
Fanton***

PhD Student
UNICAMP -
Campinas
Brazil



**Luiz Carlos de
Almeida**

Professor
UNICAMP -
Campinas
Brazil



**Leandro Mouta
Trautwein**

Professor
UNICAMP -
Campinas
Brazil

Keywords: fire safety, RC flat slabs, crack opening analysis, punching shear, displacement rate under fire load.

ABSTRACT

Punching shear behavior of reinforced concrete flat slabs under fire is affected by temperature-dependent material degradation, differential thermal expansion, restrained thermal effects, and large-deflection mechanisms. Although punching shear in fire has been widely studied, the influence of loading on crack opening, particularly at elevated temperatures, remains insufficiently understood. Elevated temperatures cause concrete expansion and dehydration, leading to internal cracking and spalling that accelerate heat transfer to reinforcement and intensify cracking. To study load-induced crack opening in fire, nonlinear finite element analyses (NLFEA) were performed using ATENA, calibrated against experimental data. Two unrestrained slab specimens were modeled: one at ambient temperature and one exposed to fire, both 100mm thick with a 0.8% reinforcement ratio. Loading was applied at a constant displacement rate of 2 mm/min before heating and maintained during thermal exposure. Additional analyses varied the applied load and displacement rate to assess crack propagation under fire. Results showed higher temperatures in the numerical model than in experiments, likely due to measurement differences. The study addresses a gap in the literature by clarifying the effect of load and displacement rate on crack opening behavior of flat slabs under fire conditions.

* Autor correspondente — Departamento de Estruturas da Faculdade de Engenharia Civil, Arquitetura e Urbanismo da Universidade Estadual de Campinas. Avenida Albert Einstein, 901 – Cidade Universitária, Campinas – SP – BRASIL. 13083-052. Telef.: +55 14 99636 1994.E-mail: a145318@dac.unicamp.br

1. INTRODUCTION

Punching shear in reinforced concrete slabs exposed to elevated temperatures is influenced by changes in the mechanical properties of steel and concrete under fire, differences in thermal expansion between materials, and structural effects such as in-plane forces caused by restrained thermal expansion, as well as large-deflection load-carrying mechanisms [1]. While considerable research has addressed punching shear behavior in fire conditions, only a limited number of studies have focused on the influence of loading on crack opening in flat slabs, and even fewer under elevated temperature scenarios. Therefore, despite existing knowledge on punching shear under fire, a comprehensive understanding of the crack opening behavior of flat slabs exposed to fire remains lacking.

The thermal expansion and dehydration of concrete induced by elevated temperatures can lead to the formation of internal fissures, in addition to surface spalling. These fissures may act as pathways for direct heat penetration to the reinforcement bars, thereby intensifying thermal stress and promoting the progression of additional cracking. Typically, such cracks extend deeply into the concrete member [2]. The resulting high stress concentrations in the vicinity of these cracks are of critical relevance in structural and material engineering analyses [3].

Two failure mechanisms may occur in reinforced concrete structures: flexural and shear. Flexural failure is ductile and is characterized by the development of visible tensile cracks before collapse. In contrast, shear failure is brittle, occurring with minimal displacement and little warning from crack formation [1]. Punching shear failure arises when a supporting column penetrates the slab, producing a characteristic conical cracking pattern (Figure 1).

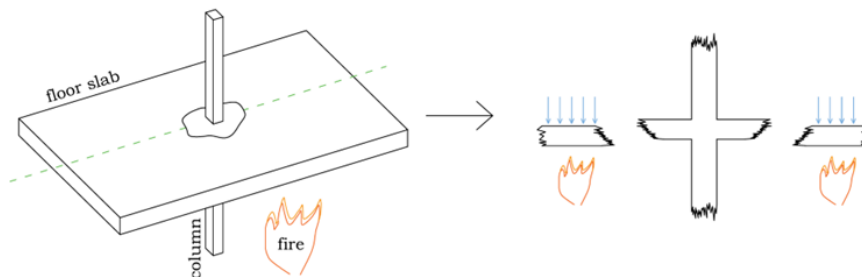


Figure 1: Punching shear (adapted from Smith [1])

Heating causes concrete expansion and dehydration, leading to fissures and spalling that can accelerate reinforcement heating, increase thermal stress, and promote deeper cracking [4]. These cracks create high stress concentrations that are critical in structural analysis. Stress and displacement fields around cracks are commonly analyzed using complex variable methods. Westergaard [5] developed a stress function–based approach to evaluate stresses directly at cracks. As noted by Sadd [6], crack problems involve stress singularities at crack tips and displacement discontinuities, which govern crack initiation and propagation. Fanton et al. [7] investigated the effect of load on crack opening in concrete flat slabs under fire conditions using Nonlinear Finite Element Analysis (NLFEA) with ATENA software [8] and the GiD preprocessor, focusing on applied load and displacement rate.

2. MECHANICAL PROPERTIES OF CONCRETE AT ELEVATED TEMPERATURE

Concrete is a heterogeneous material whose behavior above 60°C is highly complex and commonly represented by temperature-dependent average property curves derived from experiments or numerical studies [9]. In this study, a fracture–plastic concrete model was used, with temperature-dependent properties based on Eurocode 2 (EN 1992-1-2:2023) [10].

Anderberg and Thelandersson [11] proposed a high-temperature constitutive model in which total strain is the sum of thermal, instantaneous stress-related, creep, and transient strains, each derived from specific experimental conditions. A full description of each strain component is given in Fanton [12].

3. NUMERICAL MODELING

To investigate the influence of loading on crack opening behavior in concrete flat slabs under fire conditions, numerical simulations were performed using Nonlinear Finite Element Analysis (NLFEA). The modeling was carried out with the ATENA software [8], with the GiD preprocessor. The study parameters included the applied load and the displacement rate.

The concrete model is based on the fracture-plastic model. For concrete, the temperature-dependent concrete properties [thermal conductivity (k_c - W/m°C), specific heat capacity (ρc), density (ρ), compressive strength (f_c') and thermal expansion strain (ϵ_{th})] are based on Eurocode 2 (EN 1992-1-2:2023) [10]. The modulus of elasticity (E_c), critical compressive displacement (W_d), plastic strain at peak compressive stress (ϵ_{cp}), f_c' and ϵ_{th} coefficients are considered multiplied to the initial value of the parameters at normal temperatures and are shown in Figures 2a, 2b, 2c and 2d.

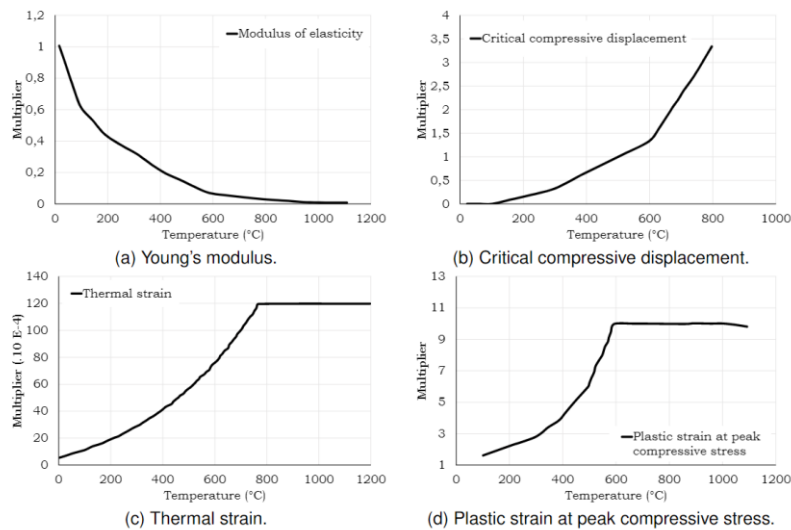


Figure 2. Concrete properties (Adapted from Sadaghian and Farzam [13]).

3.1 Experimental test from literature

The finite element model was calibrated against experimental data reported by Smith [1]. Two slab specimens were considered: AU100-0.8 (tested at ambient temperature, unrestrained, 100mm thickness with a 0.8% reinforcement ratio) and HU100-0.8 (exposed to fire, unrestrained, same dimensions and reinforcement ratio). For the heated specimen, the applied load was adjusted in accordance with BS EN 1992-1-2:2004 [10]. The flat slabs were 1400x1400x100mm 0.8% reinforced, and a central column of 120x120x100mm. No shear reinforcement was used to ensure shear failure. The flat slabs were tested using a 2mm/min displacement rate. The flexural reinforcement consisted of ribbed, cold-worked bars placed at the upper and lower slab faces. A total of 33 $\varnothing 6$ mm longitudinal bars and 33 $\varnothing 6$ mm secondary bars were used, spaced at 42 mm. The concrete cover was 9mm vertically and 7mm at the slab sides. In the compression zone, two bars tied the column stub to the slab preventing reinforcement unzipping during failure. These bars were oriented in the same direction as the flexural reinforcement. Figure 4 shows the reinforcement layout.

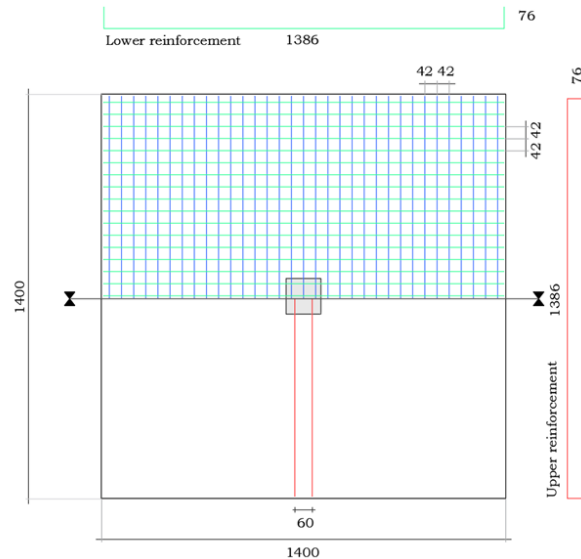


Figure 3. Reinforcement schedule – 100 mm thick slab 0.8% reinforcement ratio (in mm)

3.2 Constitutive models

ATENA [8] models brittle materials such as concrete use a fracture–plastic constitutive model that combines tensile fracture with compressive plasticity. Tensile cracking follows the smeared crack and crack band concepts, with crack propagation governed by nonlinear fracture mechanics and a cohesive crack opening law defined by the Hordijk [14] softening function. Compressive behaviour is described by a hardening/softening plasticity model based on the Menetrey-Willam [15] failure surface, implemented in ATENA through the Fictitious Compression Plane Model. The uniaxial compressive stress–strain law includes a linear post-peak softening branch, with a default post-peak plastic displacement w_d of about 0.5mm for normal concrete. Reinforcement was modelled using the constitutive model material with a

multilinear stress–strain law, where the final strain defines bar failure ($\epsilon = 0.005$, $f_1 = 560$ MPa, $f_2 = 588$ MPa). Steel followed linear elastic behaviour per Hooke's law and plasticity governed by the Von Mises criterion after yielding. A perfect bond between concrete and steel was assumed. The steel plate was modelled as an isotropic elastic material.

3.3 Model calibration at ambient temperature

Calibration aimed to match the experimental load–displacement response and punching shear failure, using the slab centre displacement. A mesh convergence study through the slab thickness (20mm to 5mm) was conducted to improve accuracy. To better represent heating, the mesh was refined toward the heated surface, while a 25mm mesh (56 layers) was used in the slab width and length (Figure 9). This mesh density adequately captures the structural response under fire. Displacement was recorded at the slab centre on the bottom surface using the “monitor for point nearest IP – displacements” condition.

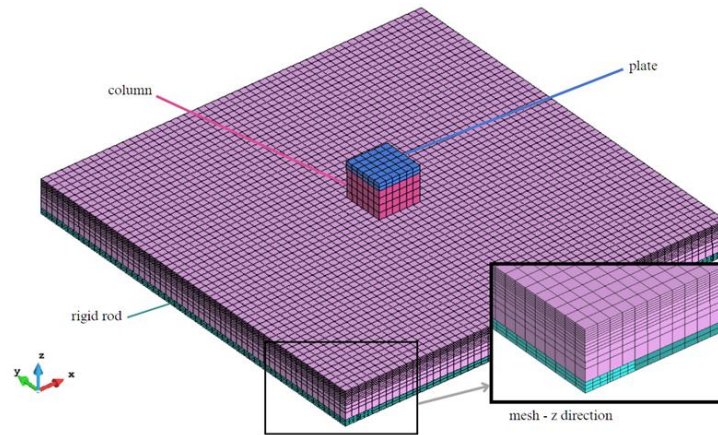


Figure 4. Finite element mesh adopted

As boundary conditions, considering the slab as unrestrained (allowed to expand, and free to rotate), the slab rested on steel rods with spring criteria applied to the middle of bottom surface using the condition “spring for surface”. The vertical stiffnesses adopted for slab AU100-0.8 was $K_v = 100$ MPa. The nonlinear system was solved using the Newton–Raphson method with a line-search algorithm, suitable for thermal loading. Convergence was verified using four criteria: displacement increment, normalized residual force, absolute residual force, and dissipated energy. Tolerances of 0.01 were used for the first three criteria and 0.0001 for dissipated energy. The analysis stopped when errors exceeded the tolerance multiplied by the iteration factors or at the end of the analysis step. The iteration limit was defined as 150. The meshed model consisted of 52107 nodes. The hydraulic loading of 25000kN/m^2 was applied using the condition “displacement for surface”, directly to the 25mm thick steel loading plate, which distributed the load to the $120 \times 120\text{mm}$ column stub surface. It was distributed in 200 load steps.

The concrete properties adopted after calibration are presented on Table 1.

Table 1. Concrete parameters

<i>Parameter</i>	<i>Calibrated value</i>		
elasticity modulus of concrete	E_{cm}	[MPa]	19424.9
Poisson's ratio	ν	-	0.2
direct tensile strength	f_{tm}	[MPa]	1.91
tensile strength	f_{ct}	[MPa]	4.01
cylindrical compressive strength	f_{cm}	[MPa]	-34
concrete fracture energy	G_f	[N/mm]	0.0137
embedded fissure model		-	fixed
size of aggregate		[m]	0.01
shear factor	S_F	-	50
concrete plastic deformation	ϵ_{cp}	-	-0.001750
compressive strength of concrete at the beginning of the nonlinear regime	f'_{c0}	[MPa]	-4.01
post-peak plastic displacement due to compression	w_d	[m]	-0.0005
reduction factor in the compressive strength of concrete	$f_{c,red}$	-	0.8
dimensionless eccentricity parameter	e	-	0.52
shear retention factor	β	-	0
tensile softening curve		-	Hordijk model
compression fracture energy	G_c	[N/mm]	13.7

Figure 5 shows the failure cross-sectional crack patterns of the finite element slab, obtained from ATENA analysis. Clipping plane: (1.4, 0.7, -0.1)x(1.4, 0.7, 0.0)x(0.0, 0.7, -0.1).

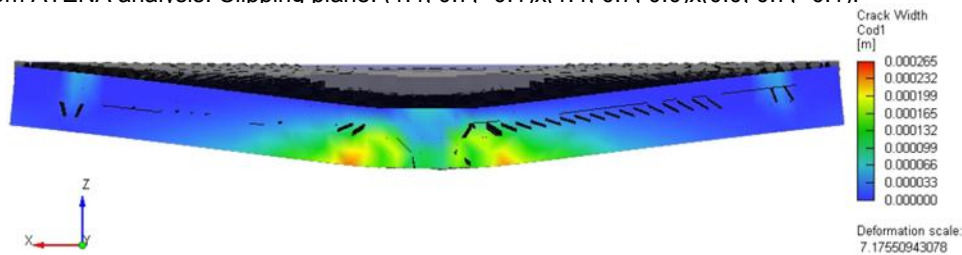


Figure 5. Cross-section of AU-100-0.8-Kv-100 FE slab showing crack pattern.

Figure 6 compares the experimental results with the numerical predictions at ambient temperature. A satisfactory agreement is observed, indicating that the model calibration adequately represents the overall response of the slab. The experimental results show a slight non-linear behavior, which may be attributed to material effects such as micro-cracking of the concrete and local stiffness degradation. In contrast, the numerical model assumes linear elastic material properties, resulting in a predominantly linear response. Despite this simplification, the model captures the main trend and magnitude of the experimental response with acceptable accuracy.

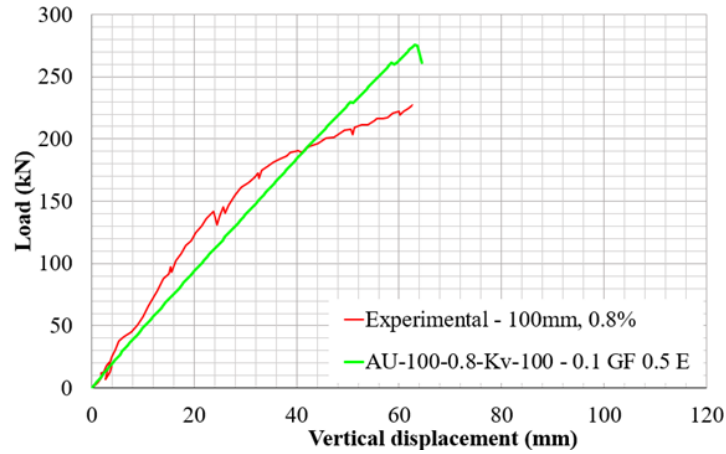


Figure 6. Load-displacement curve for ambient temperature

3.4 Thermomechanical model

The load applied to the heated specimen was factored by taking Muttoni's CSCT (Critical Shear Crack Theory) predictions into consideration and is presented in Table 2. It was taken as 70% of the ambient capacity BS EN 1992-1-2:2023 [10]. The slabs were loaded at a displacement rate of 2 mm/min. Table 2 compares the Muttoni-designed failure loads with the experimentally measured values. The percentage differences between CSCT predictions and experimental results were reasonably consistent, given the limited test sample.

Table 2. Ambient experimental failure load and calculated applied load for heated test

SPECIMEN ID	Experimental failure load (kN)	Muttoni Design Failure Load (kN)	Failure load difference (kN)	Factored Muttoni design load (kN)	Applied load for heated test (kN)
AU-100/0.8	226.3	144	57.2	242	174.6

$$\text{failure load difference} = 100 \cdot \frac{(\text{experimental failure load} - \text{Muttoni design failure load})}{\text{Muttoni design failure load}} \quad (1)$$

$$\text{factored Muttoni design load} = \text{Muttoni design failure load} \cdot \left(1 + \frac{(\text{failure load difference})}{100}\right) \quad (2)$$

$$\text{applied load for heated test} = 0,7 \cdot \text{Factored Muttoni design load} \quad (3)$$

The thermo-mechanical behaviour of the slab was simulated using a sequentially coupled thermal–structural finite element analysis. First, a transient heat transfer analysis was performed to determine the temperature distribution within the slab during fire exposure. The fire-exposed surface was subjected to the ISO 834 standard fire curve, while heat transfer at the boundary

was modeled considering both convection and radiation. A convective heat transfer coefficient of $25 \text{ W/m}^2\text{K}$ and a surface emissivity of 0.7 were adopted, which are commonly used values in fire engineering analyses. The remaining surfaces were assumed to exchange heat with the ambient environment at room temperature. The temperature field obtained from the thermal analysis was subsequently applied to the structural model to evaluate the thermo-mechanical response of the slab. In this approach, the thermal and mechanical analyses were performed using an uncoupled procedure, which is widely adopted in fire resistance simulations of structural elements.

A thermal flux of $40,000 \text{ W/m}^2$ was applied as a Neumann boundary condition on the upper (compression) surface. The effects of moisture were included through the variation in the concrete specific heat with temperature. To allow the heat to be applied after initial load, 2 interval data were created. Interval data 1: 100 load-steps, ambient temperature; Interval data 2: 100 load-steps, heated. Initial thermal properties were computed, and nodal temperatures were generated. Figure 7 presents the resulting temperature contours.

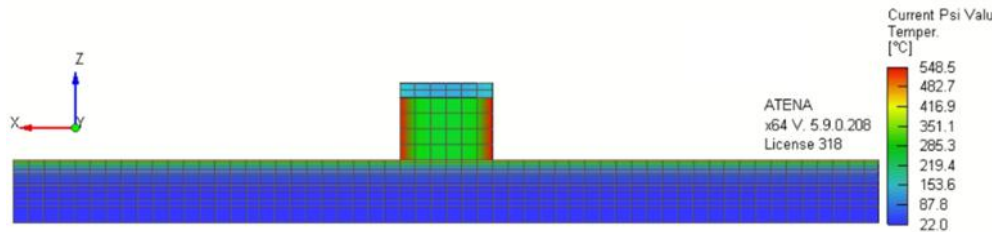


Figure 7. Temperature contours in the slab cross section for thermal results at time 600s.

Smith [1] conducted the heated test at 77% of the ambient-temperature failure load. In the thermomechanical analysis, thermal results were imported into the static model. Figure 8 compares the experimental and numerical load-displacement curves.

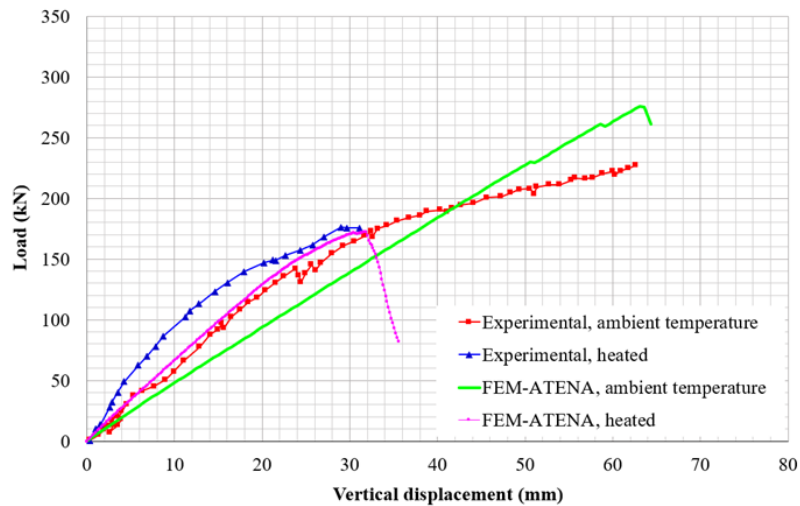


Figure 8. Load-displacement curve for heated condition

Figure 9 shows the failure cross-sectional crack patterns of the HU-100/0.8 slab and the finite element slab, obtained from ATENA analysis. The blue arrows indicate the reaction forces acting on the slabs. The load applied is shown with black arrows.

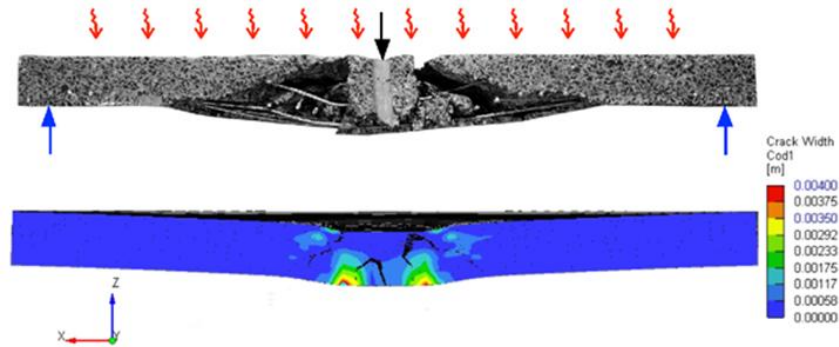


Figure 8. Cross-sections of HU-100/0.8 slab with the post-failure crack patterns – applied load 174.6 kN (Smith [1]) and FE slab.

4. RESULTS

The calibration model was loaded using the condition “displacement for surface” of 0,2mm/min. It was distributed in 200 load steps. The applied load was varied to enable a comparative analysis of crack patterns and crack propagation rates in the heated slab. Displacement rates were incrementally increased in steps of 0.1 mm/min, while maintaining a constant number of load steps. Figure 9 shows the load-displacement curves for different load levels.

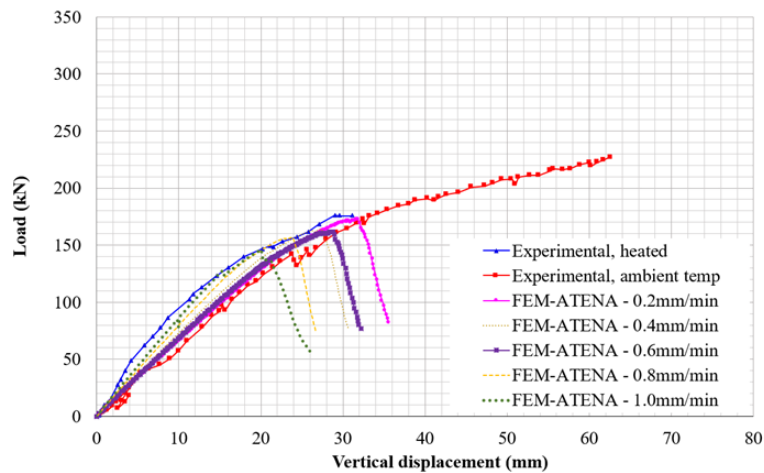


Figure 9. Load-displacement curve for HU-100-0.8 slab.

During fire exposure, concrete cracks when tensile strength is exceeded due to thermal expansion and dehydration. Surface cracking allows direct heating of reinforcement, increasing thermal stress. Crack width was calculated as crack spacing multiplied by crack-inducing strain.

Before failure, crack widths reached 3.19mm at 1.0mm/s, 2.81mm at 0.6mm/s, and 1.85mm at 0.2mm/min loading rates. Figure 10 shows the crack widths for the thermomechanical models.

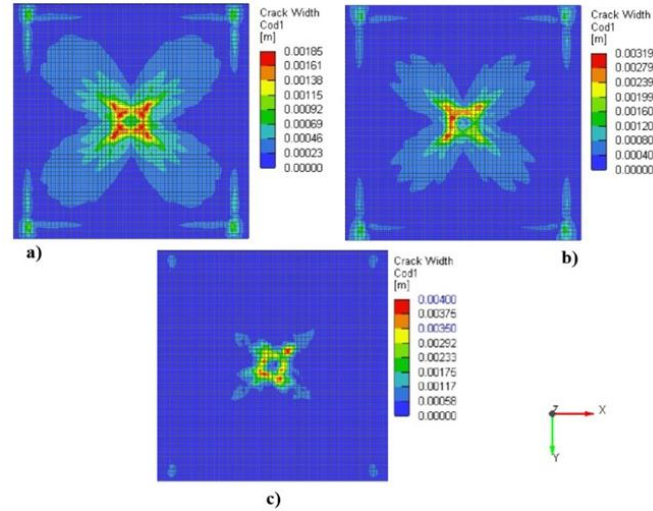


Figure 9. Load-displacement curve for HU-100-0.8 slab.

Figure 10-a represents the HU-100/0.8 slab loaded of 1.0mm/min. Figure 10-b represents the HU-100/0.8 slab loaded of 0.6mm/min. Figure 10-c represents the HU-100/0.8 slab loaded of 0.2mm/min.

5. CONCLUSIONS

The FE analysis indicates a rapid and unstable increase in slab deflection shortly after heating begins, caused by accelerated plastic strain development and early tensile crack initiation. This response highlights the strong sensitivity of slab behaviour to thermally induced material degradation and the importance of accurately modelling nonlinear material behaviour and cracking in fire-exposed structures. This study focuses on the influence of applied load on crack opening in flat slabs under elevated temperatures, an area with limited existing research. Heating was applied to the top surface to represent bottom-surface fire exposure in practice. No shear reinforcement was considered as it has small effect on the fire resistance of a slab, as presented by the literature. The displacement rates were the parametric focus. The findings of this study are as follows.

- During calibration, the ATENA model was loaded at a rate of 0.2mm/min over 200 load steps. The loading rate influences both slab displacement and fire resistance. The slab tested experimentally by Smith [1] was subjected to the same loading rate and failed by catastrophic punching shear, providing a consistent basis for comparison with the numerical model;
- A significant difference was observed between the experimentally measured temperature (approximately 130°C) and the value predicted by the numerical model (323.6°C). This discrepancy is likely related to limitations associated with the

temperature measurements during the experimental test. In practice, thermocouples may be affected by factors such as their exact positioning within the slab, incomplete thermal contact with the surrounding material, and the thermal inertia of the sensor, which can lead to lower recorded temperatures compared to the actual temperature in the structural element;

- Additionally, local heterogeneities in the material and possible shielding effects may influence the measured values. In contrast, the numerical model calculates the temperature field assuming idealized heat transfer conditions and homogeneous material properties. Although the numerical model predicts higher temperatures than those measured experimentally, this represents a conservative condition for the structural analysis, since higher temperatures generally lead to greater degradation of mechanical properties. The discrepancy highlights the inherent uncertainties in experimental temperature measurements but does not compromise the overall reliability of the numerical approach used in this study;
- It should be noted that heating applied to the top surface represents bottom-surface fire exposure in real conditions. Shear reinforcement was not included, as previous studies indicate it has a negligible influence on slab fire resistance;
- Analysis of the models showed that the slab loaded at 1.0mm/min developed crack widths of 3.19mm immediately before failure, compared with 2.81mm at 0.6mm/min and 1.85mm at 0.2mm/min. These results demonstrate that the displacement rate has a direct and significant influence on the cracking behaviour of fire-exposed flat slabs;
- Higher displacement rates led to larger crack widths prior to failure, indicating a more brittle response, while lower rates resulted in smaller cracks and a more gradual progression to collapse. These findings highlight the need for accurate spring stiffness calibration and careful selection of loading parameters in numerical models, as both strongly influence the predicted structural response under fire conditions;

The main contribution of the parametric analysis was in filling a niche gap in load influence for the crack opening of flat slabs in fire since the different load rate analysis with full description of the parameters is not frequently presented in literature. Future research is recommended to further develop and validate the proposed thermo-mechanical modelling approach. In particular, the following aspects should be investigated:

- Experimental and numerical studies considering different reinforcement ratios to evaluate their influence on the structural response under fire conditions.
- The influence of alternative fire scenarios, including non-standard fire curves and localized fire exposure.
- The implementation of more advanced material models, including temperature-dependent nonlinear behaviour of concrete and reinforcement.

These investigations would contribute to improving the understanding of the structural performance of reinforced concrete elements exposed to fire and enhance the reliability of numerical models used for fire resistance assessment.

6. ACKNOWLEDGMENTS

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PROPOSAL OF ANALYTICAL FORMULAE FOR THE CALCULATION OF THE FIRE RESISTANCE OF DOUBLE-TUBE AND DOUBLE-SKIN SQUARE SECTIONS



Ruben Lopes
Phd Candidate
UC - Coimbra
Portugal



António Correia*
Coordinator
Professor
ISEC-IPC, SUSCITA
Portugal



João Rodrigues
Associate Professor
UC - Coimbra
Portugal

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1. INTRODUCTION

For this study, the fire resistance of composite steel and concrete double-tube and double-skin square cross-section columns has been previously evaluated through experimental tests carried out at the University of Coimbra. The results of these experimental tests were used to calibrate a finite element numerical model. This numerical model allowed a parametric study for developing new simplified fire design formulae for these types of columns [1].

Following an extensive programme of experimental and numerical tests, the aim of this work is to provide analytical formulae to allow the evaluation of the fire resistance of double-tube and double-skin square composite steel-concrete columns, under mechanical load and fire actions.

2. EXPERIMENTAL PROGRAMME

2.1 Specimens

In order to maintain uniformity in the specimens, all tested columns were manufactured with the same steel sections, with a height of 3.00 m [2]. The three double-skin (CFDSHS) and seven double-tube (CFDTHS) tested columns, in a total of ten, were composed of two square hollow sections (SHS), an outer SHS 220 section, with a width (b_o) of 220 mm and wall thickness (t_o) of 8 mm, and an inner SHS 110 section, with a width (b_i) of 110 mm and 6 mm of wall thickness (t_i).

* Corresponding Author — Instituto Superior de Engenharia de Coimbra. Rua Pedro Nunes, Alto de S. João, 3030-199 Coimbra (Portugal).

Telef.: +351 239 790 200, Fax: +351 239 790 200, E-mail: antonio.correia@isec.pt

The inner section was exactly half the width of the outer steel section. The outer steel section was S355 steel grade and the inner steel section was S275 steel grade. The reference concrete-filled hollow section (CFHS) composite and hollow columns were manufactured with SHS 220 sections with S355 steel grade.

To fill the columns, three types of concrete were used: class C30/37 plain concrete (PC), class C55/67 high strength concrete (HSC) and class LC30/33 lightweight expanded clay aggregate concrete (LWC). Figure 1a) shows a schematic with the six combinations of tested cross-sections, and the positioning of the glass braiding insulated K-type thermocouples used to measure the temperatures in the cross-sections. Thermocouple T1 was placed in the centre of the concrete core. Thermocouple T2 was welded in the middle of the width of the inner steel section. Thermocouple T3 was in the middle of the concrete ring thickness. Thermocouples T4 and T5 were welded in the middle of the width and corner of the outer steel section, respectively. For the SHS columns, a reduced number of thermocouples was used. It is also possible to observe which types of concrete were used in each part of the cross sections. Figure 1b) shows the sections in height where the temperatures were measured. Thermocouples were placed in five different cross-sections, with an equal spacing of 700mm each.

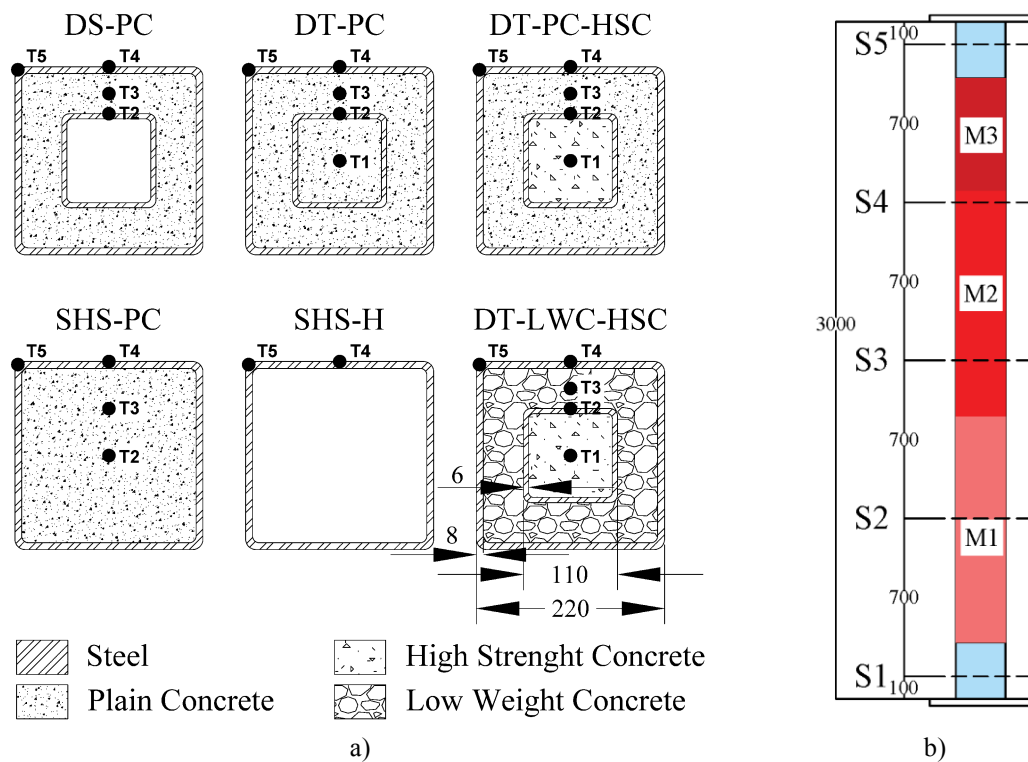


Figure 1 – a) Cross-sections of the testing columns and thermocouple location; b) Thermocouple sections along the height of the column and furnace heating sections.

2.2 Experimental Plan

The load values applied to the columns were 30% and 50% of the design value of the buckling resistance of a compression member at ambient temperature ($N_{b,Rd}$) calculated according to the clause 6.3.7.5 method from EN 1994-1-1:2005 [3]. The inner steel section in the cross-section was considered in the calculation as an equivalent reinforcing steel area. These loading levels were used, as they are commonly used in the structural fire design of concrete filled hollow section composite columns filled with concrete. The ISO 834 standard fire curve was adopted for fire action on the columns. Two restraining levels of the surrounding structure were adopted during the tests. For the tests with K_1 minimum restraining level, an axial restraint K_a of 30 kN/mm and rotational restraint in the two directions K_r of 94 615 kN.m/rad were adopted. In testing with K_2 maximum restraining level, an axial restraint K_a of 110 kN/mm and rotational restraint on the two directions K_r of 131 340 kN.m/rad was used.

In order to differentiate the tested columns, they were identified using a combination of labels, as presented in table 1: T_{XX} (where XX is the column reference number); DS, DT or SHS (DS, for double-skin columns, DT for double-tube columns and SHS for square steel hollow section columns; PC, HSC, LWC and H, to differentiate the type of column filling (PC for class C30/37 concrete, HSC for class C55/67 high strength concrete, LWC for class LC 30/33 expanded clay aggregate lightweight concrete and H for hollow section); K_1 or K_2 to identify the type of restraining level applied; 30% or 50% for the loading level. Table 1 also presents the values of the axial restraining level α_k of the columns, calculated with equation 1. The calculations used a Young modulus for steel of 210 GPa, 30 GPa for PC and LWC concretes, and 33 GPa for HSC concrete.

$$\alpha_k = \frac{K_a \cdot l}{(A_c \cdot E_c + A_a \cdot E_s)} \quad (1)$$

The columns were placed in the surrounding restraining frame using the bridge crane in the laboratory and centred in the lower cross of beams. After the columns were attached to the lower cross using M24 8.8 class threaded steel rods, the upper cross beams was lowered and connected to the top of the column using the same bolts. After this moment, the specimen mainly supported the upper cross until the end of the service load application. This was due to the nuts in the threaded rods that bolted the upper cross to the restraining frame's columns being loosened to allow the movement of the upper cross during service load application. After the intended loading level for service load measured in the special device was achieved, the nuts in the M27 10.7 class threaded rods were tightened, creating a rigid connection between the upper cross and the restraining frame's columns. Then, the restraining frame's columns were bolted to the lower cross and from this moment on, the column was under axial and rotational restraint from the surrounding frame. The electric furnace was turned on, and the fire resistance test started, keeping the service load measured in the load cell between the upper cross and the hydraulic jack constant as a real load from the column on the floor above where the fire was occurring. Restraining forces, axial and lateral displacements and cross-section temperatures on the column and furnace temperatures were measured and acquired using a datalogger.

Table 1 – Test Plan

Column	Type of filling	b_o (mm)	t_o (mm)	b_i (mm)	t_i (mm)	K_a (kN/mm)	K_r (kN.m/rad)	α_k	P_o (kN)	$N_{b,Rd}$ (%)
T1-DS-PC-K1-30	Ring: PC Core: Hollow	220	8	110	6	30	94 615	0.032	1009	30
T2-DS-PC-K1-50	Ring: PC Core: Hollow	220	8	110	6	30	94 615	0.032	1525	50
T3-DS-PC-K2-30	Ring: PC Core: Hollow	220	8	110	6	110	131 340	0.116	1009	30
T4-DT-PC-K1-30	Ring: PC Core: PC	220	8	110	6	30	94 615	0.029	1053	30
T5-DT-PC-K1-50	Ring: PC Core: PC	220	8	110	6	30	94 615	0.029	1546	50
T6-DT-PC-K2-30	Ring: PC Core: PC	220	8	110	6	110	131 340	0.106	1053	30
T7-DT-PC-HSC-K1-30	Ring: PC Core: HSC	220	8	110	6	30	94 615	0.029	1091	30
T8-DT-PC-HSC-K2-30	Ring: PC Core: HSC	220	8	110	6	110	131 340	0.105	1091	30
T9-DT-LWC-HSC-K1-30	Ring: LWC Core: HSC	220	8	110	6	30	94 615	0.029	1091	30
T10-DT-LWC-HSC-K2-30	Ring: LWC Core: HSC	220	8	110	6	110	131 340	0.105	1091	30
T11-SHS-PC-K1-30	Core: PC	220	8	-	-	30	94 615	0.034	919	30
T12-SHS-H-K1-30	Hollow	220	8	-	-	30	94 615	0.063	493	30

2.3 Numerical models

Following the experimental testing presented in the previous chapter, a numerical study was conducted using a computer aided finite element analysis. The numerical study was carried out with the finite element software Abaqus [4], using homogeneous 3D extruded elements.

The numerical model uses a sequentially coupled thermomechanical analysis. It was validated with the experimental results from CFDTHS and CFDSHS columns only filled with PC obtained in the tests carried out by Camargo [1]. The numerical analysis was carried out with the finite element software [3], using homogeneous 3D extruded elements.

The columns were longitudinally modelled, dividing into five sections (Figure 2b). Two indirectly heated longitudinal sections corresponding to the column's ends were considered (in blue in Figure 2b), with a height of 0.25 m, as well as three heated longitudinal sections, each with the same height as the furnace modules (two with 1 m and one with 0.5 m height).

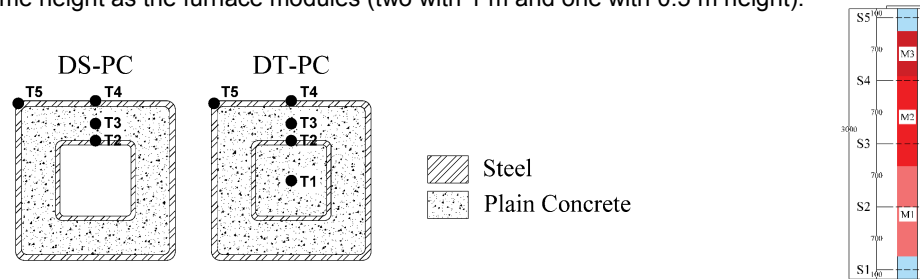


Figure 2 – Data for the numerical study: a) Numerically modeled cross-sections and location of the thermocouples; thermocouple location in the cross-section b) Thermocouple cross-sections and heated sections along the column's height.

The interactions between steel and concrete surfaces were considered as surface-to-surface, which, depending on the type of analysis performed, heat transfer or thermomechanical, had their properties as described in the following two sub-sections. The interactions between steel elements, that is, between the outer or inner square hollow steel sections and the supporting plates, were defined as tie-type constraints. This type of constraint provides a perfect connection in both analyses regarding heat transfer and transition of forces and displacements.

In the cross-sections, a mesh, as shown in Figure 3, was modelled to ensure the existence of mesh regularity for symmetry reasons and to improve interaction between the nodes of the different elements, thus minimizing convergence problems in the boundaries, during the fire simulations.

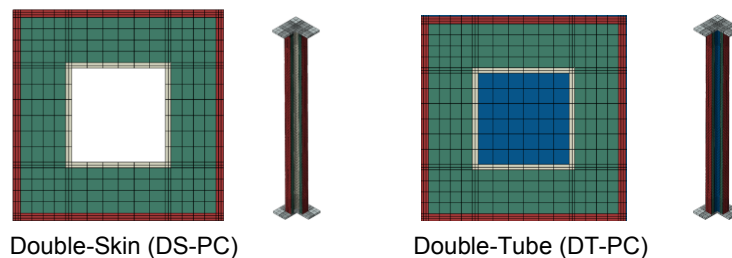


Figure 3: Cross-section and longitudinal mesh detailing for the composite columns.

3. PROPOSAL OF FORMULAE FOR THE ASSESSMENT OF THE FIRE RESISTANCE

In order to create simplified methods to calculate the fire resistance of square CFDTHS and CFDSHS columns, subject to axial and rotational restraining to thermal elongation, based in time, the results of the parametric study for each relative slenderness at recovery or critical (P/P_0 , rec or cr) and ultimate collapse (P/P_0 , ult) instants were plotted in graphics. Each method presents four graphics for each cross-section, one for each load level-restraining level combination (30 LL-K₁, 30 LL-K₂, 50 LL-K₁, 50 LL-K₂). Recovery and critical instants were combined in the same plot due to these two instants marking a particular point in the fire resistance of the columns, which is the ability of the concrete's ring and core and the inner steel section to carry the applied load on the columns after the outer steel section lost its strength to do it. The plotted results were approximated with third-degree polynomial regression curves, as a function of the columns' relative slenderness, resulting in the equations presented in each graphic. This type of polynomial regression curve was used because it presented a good trade-off between using polynomial equations with the lowest number of constants and the obtained coefficient of determination (R^2), for each situation (type of cross-section, instant and loading level-restraining level combination). An analysis of the equations is presented in the following subsections.

3.1 Analysis of results

Figures 4 to figure 7 present the produced graphics and formulas for predicting the fire resistance of square DT-PC and DS-PC column cross-sections in terms of time, subject to four load level-restraining level combinations.

Recovery or critical equations for the time method (P/P_0 , rec or cr) presented a coefficient of determination ranging from 0.6615 (30 LL-K₂) to 0.9983 (50 LL-K₂) for the DS-PC cross-section, as for the DT-PC cross-section it ranged from 0.7995 (30 LL-K₂) to 0.9921 (30 LL-K₁). For the ultimate collapse (P/P_0 , ult) time method equations, the coefficient of determination ranged from 0.8421 (50 LL-K₂) to 0.9961 (30 LL-K₁) for the DS-PC cross-section and from 0.9952 (50 LL-K₂) to 0.9999 (30 LL-K₂). Despite the good coefficient of determination for some of the equations presented in Figures 4 to Figure 7, these equations should be only used between the minimum and maximum relative slenderness values used in the parametric study to predict the time values. This is due to inversions of the curves of the equations outside the minimum and maximum relative slenderness values, which could lead to higher fire resistance values for relative slenderness values exceeding the maximum values used in the parametric study. For the DS-PC cross-sections, the minimum relative slenderness value to be used is 0.172, and the maximum value is 0.795. To the DT-PC cross-sections, the relative slenderness values to be used are between 0.175 and 0.812. This is considered the valid range of relative slenderness, for the application of this method.

The following charts present the formulae obtained using the parametric study, in fire situation, as function of the slenderness of the column. For each formula presented in Figures 4 to Figure 7, fire resistance time values were calculated at each of the relative slenderness values used in the parametric study. The obtained values (Form.) are present in Tables 2 to Table 5, next to respective values (Par.) from the parametric study. For each pairing, the respective relative error was calculated.

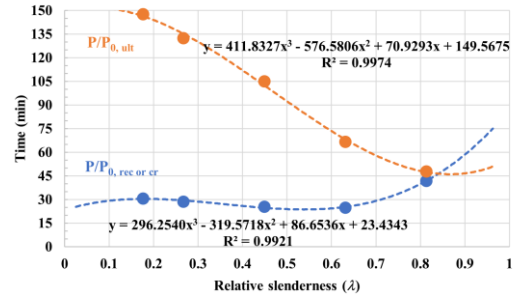
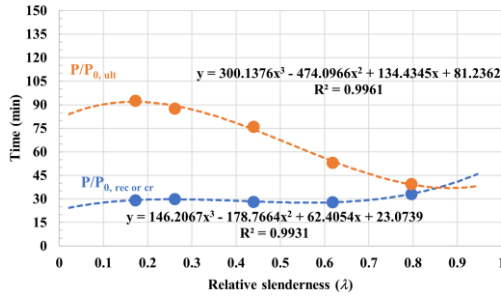


Figure 4 – Formulae to calculate the fire resistance time values for DS-PC and DT-PC columns subject to 30LL-K1 combination, as function of the slenderness of the column.

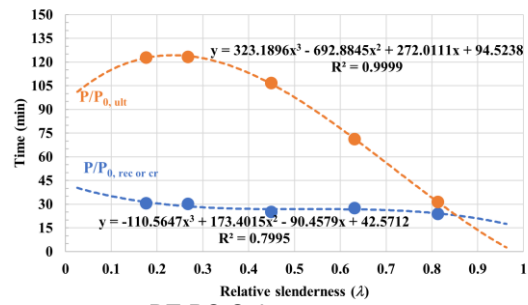
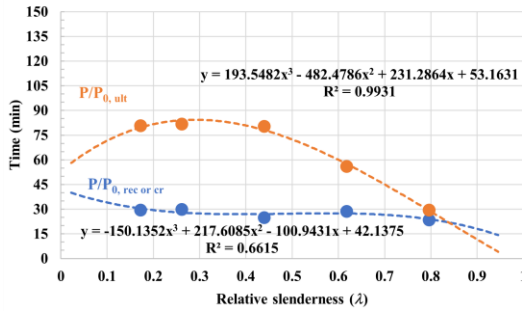


Figure 5 – Formulae to calculate the fire resistance time values for DS-PC and DT-PC columns subject to 30LL-K2 combination, as function of the slenderness of the column.

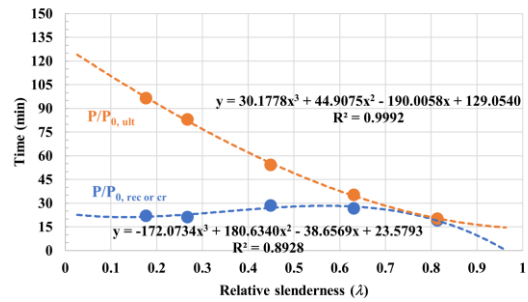
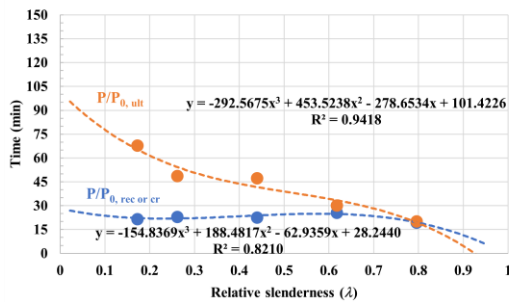


Figure 6 – Formulae to calculate the fire resistance time values for DS-PC and DT-PC columns subject to 50LL-K1 combination, as function of the slenderness of the column.

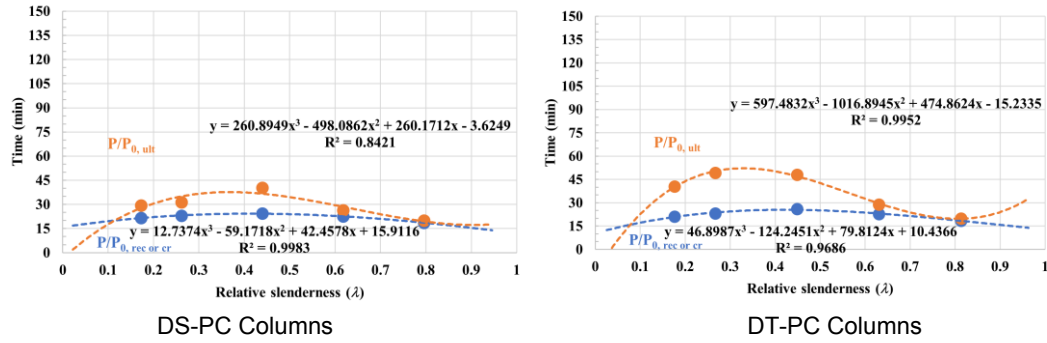


Figure 7 – Formulae to calculate the fire resistance time values for DS-PC and DT-PC columns subject to 50LL-K₂ combination, as function of the slenderness of the column.

3.2 Analysis of results

Analysing the fire resistance time values for DS-PC and DT-PC columns at recovery or critical instants from the equations, presented in Table 2 and Table 3, the equations that present the least amount of error are the ones for the 30 LL-K₁ and 50 LL-K₂ combinations for both cross-sections, with the 30 LL-K₂ and 50 LL-K₁ combination equations being the ones that present the highest error. For the DS-PC equations, the lowest error value was found for a relative slenderness of 0.795 with the 30 LL-K₁ equation (0.09%) and the highest one was found for a relative slenderness of 0.439 with the 30 LL-K₂ equation (8.24%). In the DT-PC equations, the lowest value was for the 0.812 relative slenderness value with the 30 LL-K₁ equation (-0.26%), and the highest value was with the 0.266 relative slenderness value with the 50 LL-K₁ equation (7.57%). The error with these equations tends to be lower towards the limits of them, being higher in the three middle relative slenderness values.

Table 2 – Comparison of time values obtained from the equations with the values from the parametric study for DS-PC cross-sections at P/P₀, rec or cr instant and the respective relative error.

Combination	0.172188			0.261251			0.439377			0.617503			0.795629		
	Form. (min)	Par. (min)	Error (%)	Form. (min)	Par. (min)	Error (%)	Form. (min)	Par. (min)	Error (%)	Form. (min)	Par. (min)	Error (%)	Form. (min)	Par. (min)	Error (%)
30 LL-K1	29.3	29.2	0.34	29.8	30.0	-0.72	28.4	28.2	0.77	27.9	28.0	-0.46	33.2	33.2	0.09
30 LL-K2	30.4	29.5	3.19	27.9	30.0	-6.87	27.1	25.0	8.24	27.4	28.7	-4.31	24.0	23.7	1.24
50 LL-K1	22.2	21.7	2.48	21.9	23.1	-5.10	23.8	22.7	5.20	24.8	25.5	-2.77	19.5	19.3	0.87
50 LL-K2	21.5	21.6	-0.23	23.2	23.1	0.47	24.2	24.3	-0.45	22.6	22.5	0.29	18.7	18.7	-0.08

Table 3 – Comparison of time values obtained from the equations with the values from the parametric study for DT-PC cross-sections at P/P₀, rec or cr instant and the respective relative error.

Combination	0.175881			0.266854			0.448800			0.630745			0.812691		
	Form. (min)	Par. (min)	Error (%)	Form. (min)	Par. (min)	Error (%)	Form. (min)	Par. (min)	Error (%)	Form. (min)	Par. (min)	Error (%)	Form. (min)	Par. (min)	Error (%)
30 LL-K1	30.4	30.8	-1.13	29.4	28.7	2.66	24.7	25.5	-2.99	25.3	24.8	1.84	41.8	41.9	-0.26
30 LL-K2	31.4	30.7	2.47	28.7	30.3	-5.46	26.9	25.3	6.56	26.8	27.8	-3.58	24.2	24.0	0.98
50 LL-K1	21.4	22.2	-3.31	22.9	21.3	7.57	27.1	28.7	-5.61	27.9	26.9	3.58	19.1	19.3	-1.19
50 LL-K2	20.9	21.2	-1.32	23.8	23.2	2.65	25.5	26.1	-2.35	23.1	22.8	1.62	18.4	18.5	-0.47

In the fire resistance values for DS-PC and DT-PC columns at ultimate collapse instant from the equations, presented in Table 4 and Table 5, the 30 LL-K₁ and 30 LL-K₂ combination equations are the ones that present the lower error for the DS-PC columns, with lower error being on DT-PC columns for the 30 LL-K₂ and 50 LL-K₁ combination equations. For the DS-PC equations, the lowest error value was found for a relative slenderness of 0.795 with the 30 LL-K₁ equation (- 0.64%) and the highest one was found for a relative slenderness of 0.439 with the 50 LL-K₁ equation (- 11.69%). In the DT-PC equations, the lowest error value was for the 0.175 relative slenderness value with the 30 LL-K₂ equation (- 0.18%), and the highest value was with the 0.448 relative slenderness value with the 30 LL-K₁ equation (- 2.54%). As seen in the equations for the recovery or critical instants, the error for ultimate collapse instants also tends to be lower on their limits, being higher in the three middle relative slenderness values.

Table 4 – Comparison of time values obtained from the equations with the values from the parametric study for DS-PC cross-sections at P/P₀, ult instant and the respective relative error.

Combination	0.172188			0.261251			0.439377			0.617503			0.795629		
	Form. (min)	Par. (min)	Error (%)	Form. (min)	Par. (min)	Error (%)	Form. (min)	Par. (min)	Error (%)	Form. (min)	Par. (min)	Error (%)	Form. (min)	Par. (min)	Error (%)
30 LL-K1	91.9	92.7	-0.87	89.3	87.6	2.02	74.2	76.0	-2.32	54.1	53.1	2.00	39.2	39.5	-0.64
30 LL-K2	79.7	80.8	-1.33	84.1	81.8	2.89	78.1	80.4	-2.93	57.6	56.2	2.52	29.2	29.6	-1.14
50 LL-K1	65.4	67.9	-3.72	54.4	48.8	11.31	41.7	47.3	-11.69	33.4	30.1	11.02	19.5	20.3	-3.90
50 LL-K2	27.7	29.4	-5.70	35.0	31.3	11.72	36.7	40.3	-9.11	28.5	26.3	8.37	19.5	20.0	-2.62

Only in one case, the cubic polynomial fit is not so accurate, with an R²=0,66, so in this case, the design reliability is a little bit compromised. In all the remaining cases the R² is bigger than 0,799, which perfectly acceptable.

Table 5 – Comparison of time values obtained from the equations with the values from the parametric study for DT-PC cross-sections at P/P, ult instant and the respective relative error.

Combination	0.175881			0.266854			0.448800			0.630745			0.812691		
	Form. (min)	Par. (min)	Error (%)	Form. (min)	Par. (min)	Error (%)	Form. (min)	Par. (min)	Error (%)	Form. (min)	Par. (min)	Error (%)	Form. (min)	Par. (min)	Error (%)
30 LL-K1	146.4	147.7	-0.83	135.3	132.6	2.02	102.5	105.2	-2.54	68.3	66.7	2.41	47.5	47.8	-0.80
30 LL-K2	122.7	122.9	-0.18	123.9	123.4	0.40	106.3	106.8	-0.46	71.5	71.3	0.42	31.4	31.5	-0.22
50 LL-K1	97.2	96.7	0.54	82.1	83.3	-1.36	55.6	54.4	2.09	34.7	35.3	-1.93	20.5	20.3	0.80
50 LL-K2	40.1	40.6	-1.24	50.4	49.3	2.21	47.1	48.2	-2.31	29.6	29.0	2.14	19.7	19.9	-1.08

4. CONCLUSIONS

A detailed mathematical analysis, is possible to the wide variety of cases analysed in the present study, allowing the definition of several formulae, for the two types of columns, in the time domain. These formulae are very easy-to-use. The input data to apply the method is the relative slenderness of the column, considering the type of the column, the axial and rotational stiffness of the column, and the load level assumed for the relevant combination of actions. It was proved that these formulae have scientific accuracy, since they were derived from very detailed experimental tests, and after that, a parametric study, based on an extensive programme of numerical simulations.

It was observed that these formulae can be used with a considerable level of accuracy, which can be observed by comparing the differences between the values obtained in the parametric study, and the ones obtained with the formulae. The valid range of the method is for values of the relative slenderness between 0.175 and 0.800. Due to the limitations of the cubic polynomial regression, no extrapolation should be accepted outside this range. Moreover, no sensitive analysis was carried out regarding the type of concrete and grade of steel, meaning that this study is not validated for columns made of material with much different properties than the ones described in the text.

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POST- FIRE STRUCTURAL ASSESSMENT ASSISTED WITH BIM AND AI



Luana Maris*
PhD student
UFMG – Brazil
Professor
UNA - Brazil



João P. C. Rodrigues
Professor
UC – Portugal and
UFMG - Brazil

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1. INTRODUCTION

Decision-making regarding structural repair and rehabilitation after a fire involves a high degree of uncertainty, especially due to constructive heterogeneity and the limitation of consistent data. In this context, Artificial Intelligence (AI) emerges as a strategic tool to support damage assessment, pathology diagnosis, and the definition of intervention strategies. [1].

With the development of Artificial Intelligence (AI) systems, new possibilities may emerge for services related to identifying pathologies and repairing structures after fire. Based on the premise that fires can irreversibly compromise structures due to the loss of their integrity, the assessment of buildings subjected to fire becomes fundamental. In this context, this study proposes some discussions that should be held given the increasing introduction of AI systems in the field of structural rehabilitation, in order to contribute to the creation of a database and to identify and classify structural pathologies after fire in buildings. This will make it possible to predict the most effective techniques for recovering structures with variations in their residual load-bearing capacity.

In this respect, two operational fields of AI deserve to be highlighted: one is analytics, referred to algorithms that analyze data and their cross-referencing; the other is the machine learning system, whose algorithms are capable of predicting or generalizing patterns learned from a set of data used to train the system [1]. The emergence of artificial intelligence (AI) has revolutionized SHM (Structural health monitoring), that has become a crucial aspect of infrastructure management. It provides information on the condition and safety of critical assets such as tunnels, dams, buildings, and bridges (Aktan, 2024) [2]. SHM involves a periodic

*
Autor correspondente — UFMG. Belo Horizonte (Brazil).
Telef.: +55 3199102-1649. E-mail: luanampe@hotmail.com

assessment of a structure's health through data collected from various sensors embedded in or located within the infrastructure.

The study proposes the analysis of an integrated methodology that combines SHM, Building Information Modeling (BIM), and Artificial Intelligence (AI) for the assessment of residual load-bearing capacity and the management of the rehabilitation process of reinforced concrete structures after fire. The main objective of SHM is to prevent damage or disruptions prematurely, ensuring timely maintenance interventions and reducing risk, such as the spread of fire in buildings. Given the above, fire is a major threat to the preservation of buildings, since it causes notable fires in buildings with devastating effects [3].

This study discusses the state of the art in the application of AI to the decision-making process in fire-related structural repair, based on a critical literature review. It proposes a conceptual framework integrating qualitative data related to machine learning techniques and structural rehabilitation. The results indicate that AI contributes to reducing subjectivity, increasing diagnostic reliability, and supporting more consistent decisions, provided it is integrated with specialized technical judgment.

2. POST-FIRE DAMAGE ASSESSMENT

Structural health monitoring (SHM) has the main objective to detect damage or deterioration early, ensuring timely maintenance interventions and reducing the risk of catastrophic failures [4]. By improving the ability to monitor the structural integrity of infrastructure, SHM plays a key role in extending the lifespan of assets, increasing their safety, and optimizing their maintenance costs. Furthermore, the rise in drone-based inspections, according to Torzonni (2023) [5], has revolutionized access to hard-to-reach areas, allowing for detailed visual and thermal assessments. According to the author, the development of Digital Twins (DTs) — virtual replicas of physical structures updated with real-time data — has further enabled predictive maintenance and dynamic analysis, offering a holistic view of structural behavior [5].

These emerging technologies are reshaping SHM practices, providing more comprehensive, efficient, and accurate monitoring solutions. The rise of artificial intelligence (AI) has revolutionized SHM, along with several other fields related to civil engineering and structural engineering in particular, including structural modeling, structural optimization, structural reliability analysis, emission reduction in construction, earthquake engineering, and many others. In SHM, AI introduces innovative approaches to data processing, damage detection, and predictive maintenance. Its ability to handle large amounts of data, learn from patterns, and make accurate predictions has paved the way for more efficient and automated SHM systems.

This paper proposes the application of BIM (Building Information Modeling) associated with Artificial Intelligence (AI) in the structural rehabilitation process of reinforced concrete buildings after fires. The basic concept of the BIM methodology identifies an idealization of the building in a virtual way, organized in a way that allows representing the elaboration, construction and management of the construction project, and consequently, eliminating or reducing the failures and errors normally associated with the development of the project, in stages and with the intervention of several technicians [6].

Reinforced concrete structures after a fire exhibit characteristic that, once determined, allow the classification of damage. Coloration, cracking and "spalling", in addition to the deformation of the elements, among others (such as the chemical attack of chlorides), are fundamental in the identification and evaluation of damage. Thus, the colors of the concrete, for example, as a qualitative parameter after a fire situation, contribute to the evaluation of the temperatures that were reached during this situation.

According to the specialized literature, spalling manifests itself in different forms, varying according to the predominant mechanism and the imposed thermal conditions. As systematized by [7] and [8], the phenomenon can be classified as: spalling in aggregates, characterized by surface damage resulting from the thermal deterioration of aggregates; spalling at corners and edges, of a gradual and non-violent nature, mainly associated with rising temperatures; surface spalling, marked by the progressive and violent detachment of fragments, with possible exposure of the reinforcement, typical of high-strength concretes; spalling during cooling, related to the rehydration of calcium oxide and the absorption of moisture; and, finally, complete spalling of the structural element, of an extremely violent nature, more likely in dense and low-porosity concretes.

Spalling is a phenomenon that can occur in concrete or rock, during a fire, with the unpredictable, violent or non-violent fragmentation or spalling of pieces or layers of the element's surface. Spalling occurs most frequently between temperatures of 250 to 400 °C. Figure 1 shows the spalling that occurred in a reinforced concrete ceiling and in a rock [9].



Figure 1 – Spalling: (a) in reinforced concrete slab and (b) in rock
Source: [9].

The loss of adhesion between steel and concrete generates cracks and can lead the structural element to collapse [9]. The author explains that the action of a fire on a reinforced concrete structure is normally characterized by the appearance of the “spalling” phenomenon. There are fundamentally two types of “spalling”: layered separation and explosive. Explosive “spalling” normally occurs in columns, beams and grids, characterized by the abrupt separation accompanied by a bang of parts of the concrete. Layered “spalling” normally occurs at the edges of beams and columns, showing gradual development. Regarding the first color change, to pink or red, it will depend essentially on the nature of the concrete aggregate. The intensity of this color is associated with the oxidation of iron ions, present in greater quantity in siliceous aggregates. Figure 2 shows the color change of concrete elements as a function of temperature [10].

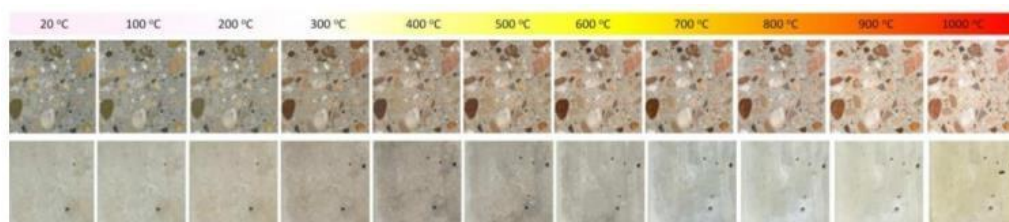


Figure 2 – Change in color as a function of temperature
Source: [10].

Thus, according to Oliveira et al. (2009) [10], the steel of the reinforced concrete reinforcement is a good thermal conductor, which, when exposed to a high temperature, absorbs heat better than the mass of concrete, propagating the heat rapidly along the reinforcements that are closer to the faces of the piece exposed to the heat source. The steel will then undergo greater thermal expansion than concrete (a poor thermal conductor), resulting in buckling of the steel bars, causing loss of adhesion with the concrete and possibility of detachment of concrete cover, accentuating the effect.

Boccacci et. al. (2023) [11] present an overview of NDT (Non-Destructive Testing) techniques for in situ detection and monitoring of reinforced concrete degradation in buildings. It is worth noting that among the techniques used in the evaluation of damage evolution, Ultrasound Pulse Velocity (UPV) and Acoustic Emission (AE) were the most explored, being economical and sensitive techniques capable of detecting and locating active defects, and having a large depth of penetration useful for estimating the size, shape and nature of the damage to the concrete. Ultrasonic tomography follows the two techniques, since tomographic maps are considered a valid tool in the case of evaluating the degradation of heritage buildings (used mainly to detect internal flaws and defects in concrete, as well as to assess the corrosion of reinforcing bars).

Timber structures behave relatively well in the face of a fire, with the external charred layer that forms at this time protecting the core of the elements. In more severe fires, timber elements may present an external charred appearance, verifying that the residual resistant sections are often insufficient to withstand service loads [1]. Current developments and challenges in improving the fire performance of timber and timber-based composites treated with fire-retardant materials are important to be verified, as shown by the behavior of timber during combustion in Figure 3.

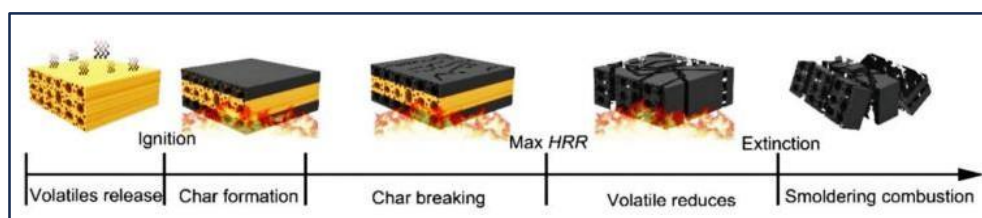


Figure 3 - Schematic visualization of the behavior of timber during combustion
Source: Adapted from [12].

At this level, the improvements to be introduced are limited and can only focus on: - facade cladding elements; - opening closure elements, for which it is possible to act by incorporating materials that have a more favorable fire reaction. Therefore, it is vital to address the gaps in our understanding and discover innovative approaches to improve fire safety and reduce risks by improving the fire performance of timber and timber-based composites. There are several types of fire protection treatments, including coatings, impregnation and surface treatments [12].

As an alternative to testing, non-destructive testing has emerged, offering lower costs and greater ease of execution. Non-destructive evaluation (Non-destructive testing - NDE) consists of using methods to evaluate properties without compromising the final use of the material [13]. The tests performed using non-destructive techniques provide the dynamic modulus of elasticity. Equipment such as stress wave, ultrasound, and transverse vibration are used in this type of test.

Regarding masonry, brick masonry has a relatively satisfactory behavior in relation to fire, suffering minor damage when exposed, mainly at the mortar joints. The fact that the bricks have

been subjected to higher temperatures than when exposed to fire during their manufacturing process demonstrates that the masonry has a relatively good behavior in this situation [1]. In relation to stone masonry, it suffers greater damage, since the thermal gradients generated during a fire cause a state of differential displacement that generates cracking of the elements both internally and superficially, promoting a reduction in compressive strength. In situations where, compressive stresses are very high, they cause possible ruptures.

If the damage is more significant, it is advisable to carry out compression tests with test specimens. According to Rodrigues (1994) [1], in the case of collapsed walls, exceeding the maximum allowable stresses, replacement may be the most economical option. Possible cracks resulting from the expansion of structural elements, produced by the expansion of horizontal elements, should be treated with epoxy resin in order to give the element a monolithic appearance and also prevent future infiltration, as shown in Figure 4.



Figure 4 - Degraded masonry walls
Source: [1].

Croitoru (2021) [14] presents the following categories of intervention that are distinguished in the rehabilitation of masonry constructions: 1) repair, reintegration or joining of new constructive elements or organs with a different operational purpose; 2) consolidation interventions by replacing structural components and/or consolidating and reintegrating existing structural components: - an individual consolidation; - a global consolidation.

Repair consists of the localized correction of pathological problems. Reinforcement implies the correction of such problems with an increase in the resistance or load-bearing capacity of the structure, while structural recovery aims to restore – fully or partially – the original performance of the elements for which they were designed. Rehabilitation (or intervention) encompasses both simple repair and recovery and reinforcement. Therefore, it can be seen as a necessary action to enable the structure to once again fulfill its original function or to meet new conditions of use different from those initially foreseen in the design phase [1].

Recovery must meet the ultimate and service capacities of the structure before the event. There is a possibility that the damage caused by the fire may be irreversible, making any recovery measures unfeasible and unnecessary, with demolition and reconstruction being the most appropriate course of action.

3. BIM AND AI IN THE DECISION-MAKING PROCESS OF POST-FIRE REPAIRS

The construction industry, characterized by manual processes and a lack of technological integration, has been experiencing a growing transformation with the introduction of new

technologies, including Artificial Intelligence (AI). In recent years, AI has shown promise in improving efficiency and productivity in the construction sector, from planning and managing projects to automating construction processes. However, despite the advances, the adoption of AI-based solutions in construction still faces significant challenges that need to be analyzed to determine if it is actually applicable in specific cases, such as the repair and maintenance process of structural elements.

In this direction, the engineering technical reports produced by on-site inspections are fundamental instruments in shaping the State of the Art. Aligned with the principle of equality, a prerequisite for public bidding processes, the BIM system includes the delivery of the bid products in digital format as open BIM files titled by buildingSmart (bsl) as Industry Foundation Classes (IFC) (Building, 2022) [15]. In addition to native software formats. In this direction, the professionals involved in the project practice multidisciplinary collaboration and the exchange of information in an integrated and interoperable way.

BIM systems must therefore allow for effective communication between programs and a high level of confidence in the digital data transferred between project stages. The systems must therefore incorporate a high level of interoperability. Interoperability is an inherent capability of the programs to allow users to transfer information between stages. The level of interoperability between systems must be high so that the transferred data remains correct, without omissions or incorrect interpretation, and to avoid manual data re-entry (Queiróz et al., 2019) [16].

As Antunes (2022) [17] points out, due to these particularities, the bidding process is supported by a BIM Execution Plan (BEP), which has the general objective of explaining the guidelines that will guide the development of the use of BIM in bidding, in addition to relating the professionals and tools involved in the rehabilitation project to achieve the expected result(s). The Modeling of Existing Conditions is the use of BIM foreseen in the BEP that allows the connection of the Built Environment to the BIM system, preliminarily (Planning phase). However, the new solutions demanded by the rehabilitation works foreseen in the Design phase depend on the analyses of the State of the Art of the structure, a product of the engineering report made possible through technical inspections. This gap is solved by inserting the collected pathological data and other relevant information into the IFC model of the object under study [17].

The relationship between Civil Engineering, BIM and AI has generated a scenario of significant transformation in different areas of the industry. Civil Engineering and BIM, responsible for transforming the built environment, is undergoing a revolution driven by the advancement of AI and its applications. As technology penetrates traditional engineering operations, from design and planning to construction and maintenance, it increases the possibilities and innovations achieved in this scenario.

Artificial Intelligence (AI) stands out as one of the most impactful innovations of recent decades, revolutionizing various fields, including engineering. With the rapid advancement of technologies such as Machine Learning and Deep Learning, AI is transforming the way engineers work, creating challenges and opportunities. By automating processes, optimizing data analysis, and offering innovative solutions, AI is significantly altering the skills and competencies demanded of these professionals.

Zhu et al. [18] use machine learning to solve eigenvalue problems for linear and semi linear second-order differential operators in high-dimensional spaces, eliminating the need for gradient information in other methods [18]. Beck et al. use machine learning to address uncertainty quantification in high-dimensional inverse problems. The results show that machine learning is superior in approximately sampling high dimensional posterior distributions [19].

In 2021, a machine learning paradigm for SHM was proposed, which advocates using big monitoring data, including vibrations, wind, acceleration, displacement, cable force, strain, images, videos, etc., to diagnose the structure status [20]. This paradigm introduces a new perspective on structural health diagnosis, garnering considerable interest in recent research. In recent years, numerous new methods have been developed and successfully applied to practical engineering structures, such as data cleaning methods for anomaly data, machine learning-based identification methods for structural modal parameters, structural damage identification methods, digital twin techniques, and machine learning methods for structural reliability assessment.

Aktan et al. (2024) [4] carried out a proposal for a predictive digital twin approach for monitoring the health, maintenance, and management planning of civil engineering structures, promoting real-time updating of the structural state and predictive maintenance planning. The active twin coupled dynamic system is coded using a probabilistic graphical model, which allows all relevant sources of uncertainty to be considered.

In particular, the flow of observations for decisions, which repeats over time, is modeled using a dynamic Bayesian network. Real-time structural health diagnostics are provided by assimilating sensed data with deep learning models. The state of the digital twin is continuously updated through sequential Bayesian inference. This is then exploited to inform the optimal planning of maintenance and management actions within a dynamic decision-making framework.

Regarding machine learning and neural networks, different models can be adopted, such as Supervised Models and Probabilistic Models. Supervised Models (such as MLP - multilayer perceptron, CNN for images - Convolutional Neural Network, RNN - Recurrent Neural Network, for time series) are trained with inputs that may include dynamic responses (accelerations), deformation measurements, NDE results (ultrasound, sclerometer), surface images (cracks), etc., as pointed out by Torzoni et al. (2023) [5]. Furthermore, in the case of structures studied after a fire situation, the model can provide an initial safety assessment based on evidence from inspections and operational data.

The convolutional neural network (CNN) called FFDNet (Fast and Flexible Denoising Network) is a deep learning-based fire detection system that encompasses the AI model (convolutional neural network and classical pattern recognition algorithms), states [21]. Through a supervised learning process, where it identifies the presence of fire and has decision logic, it analyzes the results and triggers an alarm or not, for example. The system is trained with thousands of images and recordings labeled as "real fire" or "false alarm," such as: shower steam (false); electric welding (false); real flame (true) and light reflections (false). The model learns patterns of texture, brightness, dispersion, and smoke movement, creating a unique digital signature of the real fire.

Recent research explores the use of supervised machine learning algorithms (such as SVM, Random Forest, AdaBoost, and LightGBM) to classify and predict the degree of spalling and fire resistance of reinforced concrete columns after thermal testing. These models have shown high accuracy rates and statistical performance, demonstrating that AI can outperform traditional design equations by capturing complex relationships between material properties, geometry, and fire response.

Naser and Kodur (2022) [22] developed an explainable machine learning approach for rapid assessment of fire resistance and fire-induced spalling in reinforced concrete columns. The study combines three learning algorithms (random forest, gradient boosted trees, and deep

networks) with a large dataset of real and synthetic thermal tests to estimate the fire performance of concrete columns with different strength and load conditions. The methodology also emphasizes the interpretability of the predictions, overcoming the common criticism of “black box” in AI, and can analyze thousands of structural members in seconds for different fire scenarios.

The recent development of models as computer vision frameworks with Transformers demonstrates that AI can classify multiple categories of structural damage, going beyond simple binarization (damaged/injured), and deliver damage typologies — which has strong potential to guide more precise structural repair interventions after extreme events.

Following research in national and international literature, a synthesis was carried out of the main research attributed to approaches that integrate data processing, structural inspection and monitoring, thermal data capture, among others. Thus, in addition to the authors already cited here, a table was produced with the main existing AI methodologies, whose models can contribute to decision-making for a coherent proposal for structural rehabilitation after a fire (Table 1).

Table 1 - AI models and techniques discussed and their respective applications

Author(s)	AI Model / Technique	Brief Description	Application / Context
Plevris (2023, 2024) [23]	AI in SHM (general overview); ML; DL	Data processing approaches, damage detection, and predictive maintenance.	Structural monitoring, intelligent maintenance, automation.
Bremer (2016) [24]	Fiber optic sensors (non-AI)	Support for SHM using continuous data acquisition.	Strain, vibration, and temperature measurements.
Fayyad (2025) [25]	Drones for inspection	Image capture and thermal data acquisition.	Structural inspection.
Hosamo (2022) [26]	Digital Twins (DT)	Digital models with real-time updates.	Predictive maintenance and structural analysis.
Balageas, Fritzen & Güemes (2006) [27]	SHM for diagnostics	Assessment of global structural integrity.	Life-cycle management.
Lazzeroni et al. (2025) [28]	AI for technical condition assessment	Service life evaluation and decision support.	Bridges and structural components.

Source: Author (2025).

The results indicate that AI contributes to reducing subjectivity, increasing diagnostic reliability, and supporting more consistent decisions, provided it is integrated with specialized technical judgment.

4. METHODOLOGY STRUCTURE FOR THE USE OF AI IN THE REHABILITATION OF STRUCTURES AFTER FIRE

The cataloged models of pathology types and their respective rehabilitations after a fire situation were adopted, developing a parametric simulation pipeline based on this data. The purpose is to generate virtual structures from various pathology parameters, identifying the methodologies for evaluating structural capacity and thus producing data for the strategic choice of intervention.

The objective is to contribute to the decision-making process for repairs to be carried out on structures after a fire, where BIM will read the information generated from simplified methods, integrating it with AI models, defining the most appropriate rehabilitation technique for the corresponding situations. Through tests and literature research on the subject of this research, the creation of a database of pathologies and mechanical and residual properties of structures after fire and rehabilitation techniques is proposed. A BIM methodology will be developed to manage the rehabilitation process and assess the structure's resistance capacity. From this data, the residual resistance capacity will then be determined by simplified methods, simulating the evolution of temperature in the structure, adopting the CFAST model, FDS or parametric curves of Natural Fire (Figure 5).

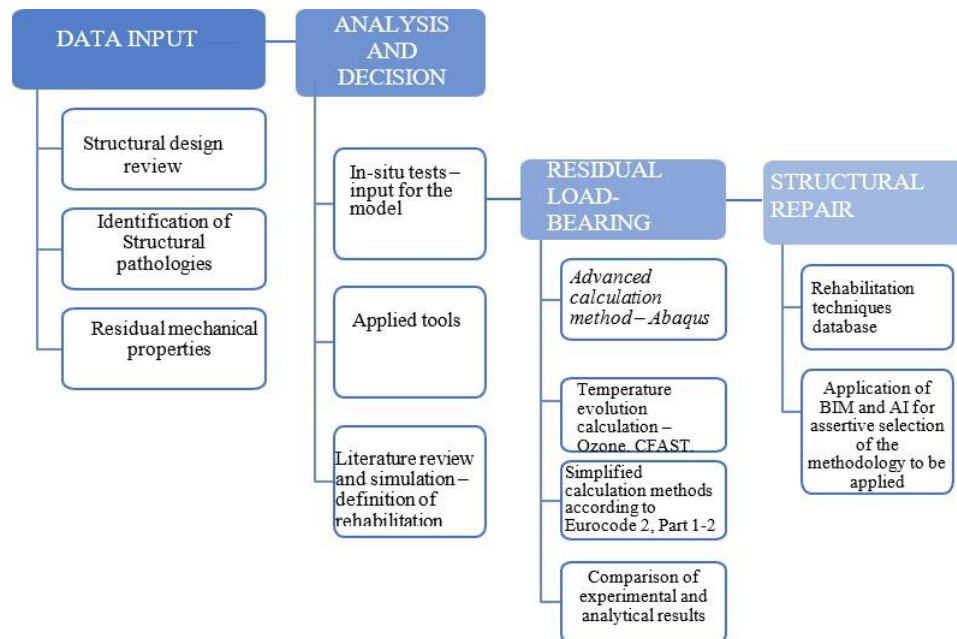


Figure 5 – Schematic illustration of the process of creating the Reinforced Concrete Structural Rehabilitation methodology after fire
Source: Author (2025).

5. CONCLUSIONS

The assessment and rehabilitation of structures subjected to fire involves high complexity, marked by uncertainties associated with constructive heterogeneity and thermal degradation mechanisms. This article discussed the state of the art of the application of AI and BIM as tools to support decision-making in post-fire structural repairs.

The results indicate that the integration of machine learning techniques, neural networks, digital twins, and probabilistic systems with data from visual inspections, non-destructive testing, and simplified thermal models can significantly contribute to reducing subjectivity and increasing diagnostic reliability. Such approaches allow the identification of damage patterns, estimation of residual resistance capacities, and guidance in choosing more coherent and well-founded intervention strategies.

Future research directions highlight the potential of generative AI, through models such as GANs (Generative Adversarial Networks), to simulate damage and pathological scenarios of historical structures after fire, expanding the diversity and robustness of training datasets. AI-coupled drones reduce inspection time and eliminate risks to worker safety, with significant gains in both diagnostic accuracy and operational safety.

However, the application of AI should be understood as a complementary tool to specialized technical judgment, since its effectiveness depends on the quality of the available data and the proper interpretation of the results. The proposed methodological framework, integrating BIM, pathology databases, and AI models, presents itself as a promising approach to systematize and qualify the structural rehabilitation process after fire, with potential application in different construction typologies and intervention contexts.

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MÓDULOS DE ELASTICIDADE ESTÁTICO E DINÂMICO RESIDUAIS DE ARGAMASSAS MISTAS COM AREIA DESCARTADA DE FUNDIÇÃO EXPOSTAS A ALTAS TEMPERATURAS

Camila Moura

Doutoranda
UNICAMP -
Campinas
Brasil

Daniel Massola

Doutorando
UNICAMP -
Campinas
Brasil

***Gisleiva Ferreira**

Professor
UNICAMP -
Campinas
Brasil

Michelle Rodrigues

Doutorando
UNICAMP -
Campinas
Brasil

**Armando Moreno
Jr.**

UNICAMP -
Campinas
Brasil

Marta Pires

Doutorando
UNICAMP -
Campinas
Brasil

Palavras-chave: desempenho, constantes elásticas, resíduos industriais, incêndio.

1. INTRODUÇÃO

Os objetivos de desenvolvimento sustentável (ODS), indicados pela ONU, têm impulsionado os diversos setores produtivos a buscarem tecnologias e inovações para atingi-los. Neste sentido, a construção civil tem se unido a outros setores para buscar soluções conjuntas com foco na gestão de resíduos sólidos, tanto para reduzir a geração como para usá-los como coproduto. Sendo assim, destaca-se a areia descartada de fundição (ADF), resíduo gerado pelo setor metalúrgico durante a moldagem de peças metálicas. Os estudos se concentram no uso da ADF como agregado miúdo em materiais cimentícios (concretos, artefatos de concreto e argamassas), devido suas características físico-químicas e disponibilidade em grandes centros urbanos [1]. Em relação ao uso da ADF em argamassas, há alguns estudos com resultados promissores, principalmente em relação à trabalhabilidade e propriedades mecânicas, considerando diversos teores de substituição da areia comum por ADF.

Entretanto, esses estudos ainda são preliminares, exigindo mais conhecimento principalmente em relação ao desempenho das argamassas com ADF, quando comparadas com argamassas convencionais. Ao considerar que as argamassas de revestimento desempenham funções de estanqueidade da edificação, além da proteção dos elementos construtivos, verifica-se uma lacuna de conhecimento em relação às propriedades mecânicas residuais destas argamassas, quando expostas às condições de incêndio. Uma das principais propriedades mecânicas das argamassas de revestimento é o módulo de elasticidade, parâmetro que explica a sua rigidez e capacidade de deformação em situações extremas como altas temperaturas. Portanto, o objetivo desse trabalho foi obter os módulos de elasticidade dinâmico (E_d) e estático (E) de argamassas com ADF, submetidas a altas temperaturas. Para obter o E_d , foram realizados ensaios de ultrassom, conforme NBR 15630 [3].

2. MATERIAIS E MÉTODOS

O cimento utilizado nas argamassas foi o CP II-E-40 RS, composto por silicato de cálcio, alumínio, ferro, sulfato de cálcio, filler carbonático e pozolana. A cal hidratada é de classe III, a areia comum é quartzosa e foi fornecida por uma construtora brasileira, e a ADF foi fornecida de uma empresa do setor de fundição, é proveniente da moldagem de peças metálicas, fornecida pela indústria de fundição.

A massa específica da areia comum (AC), ADF, cimento Portland (CP) e cal hidratada (CH) são 2,56 g/cm³, 2,48 g/cm³, 3,09 g/cm³ e 2,50 g/cm³, respectivamente. A composição química dos materiais, foi obtida a partir de análises de Fluorescência de Raios X – FRX, e estão apresentadas na Tabela 1

Tabela 1 - Composição química dos materiais utilizados na produção das argamassas, obtidos a partir de análises de Fluorescência de Raios X – FRX.

Óxidos	ADF	AC	CP	CH
SiO ₂	90,3	95	20	4,04
Al ₂ O ₃	2,76	1,89	5,4	0,54
Fe ₂ O ₃	1,36	0,67	2,31	0,55
MnO	<0,1	0,15	0,16	0,07
MgO	0,42	0,05	4,65	25,9
CaO	0,19	0,09	57,4	36,9
Na ₂ O	0,3	0,17	0,11	-
K ₂ O	0,18	0,92	0,85	0,17
TiO ₂	0,15	0,32	0,3	0,08
P ₂ O ₅	<0,10	<0,05	0,17	0,02
SO ₃	-	<0,01	3,47	0,04
PF	4,61	0,6	5,36	31,6

2.1 Métodos

Ao verificar que ainda não há normas específicas para avaliar as propriedades de argamassas expostas a altas temperaturas, adaptou-se normas utilizadas para a caracterização de concretos [2]. Sendo assim, foram adotadas as diretrizes da RILEM TC 200-HTC partes 1 e 2 (RILEM, 2007) [2,3] e da RILEM 129-MHT parte 5 (RILEM, 2004) [6] para determinar parâmetros como os corpos de prova, metodologia de aquecimento e arrefecimento. Ao todo, foram moldados 120 corpos de prova cilíndricos (53 mm × 159 mm), respeitando a relação altura/diâmetro igual a 3 e utilizando 6 repetições por condição analisada, conforme indicações de normas para concreto.

Após o período de cura de 90 dias, os corpos de prova tiveram as faces da seção transversal retificadas (necessário para garantir a planicidade durante o ensaio de compressão axial). Após 48 h, realizou-se os ensaios de ultrassom para se obter a Velocidade do pulso ultrassônico

(VPU), além do peso (gramas) e respectivas dimensões (altura e diâmetro). Os ensaios de ultrassom foram realizados conforme NBR 15630 (ABNT, 2008)[3], utilizando o equipamento USLab (Agricef, Brasil), com transdutores exponenciais de 45 kHz de frequência. O tempo de propagação do pulso ultrassônico foi registrado após a estabilização do sinal do equipamento. Com isso, foi possível calcular o módulo de elasticidade dinâmico residual (Ed), conforme a equação 1.

$$E_d = v^2 \rho ((1+\mu)(1-2\mu)/(1+\mu)) \quad (1)$$

Onde:

v: velocidade do pulso ultrassônico (mm/μs)

ρ: densidade da argamassa (kg/m³)

μ: Coeficiente de Poisson (0,2)

Em seguida, os corpos de prova foram posicionados (12 por ciclo) e submetidos ao aquecimento em um forno elétrico de 32 kW, localizado no Laboratório de Estruturas da FECFAU/Unicamp, com capacidade máxima de 1300 °C e volume de 60 litros. A taxa de aquecimento e resfriamento adotada foi de 1 °C/min, com permanência de 60 minutos no patamar, conforme orientações da RILEM 129-MHT parte 3 (RILEM, 1996) [6], que recomenda taxas iguais ou inferiores a 4 °C/min para corpos de prova com 50 mm de diâmetro. Os testes foram realizados em cinco temperaturas: 20 °C (controle), 200 °C, 400 °C, 600 °C e 800 °C.

Após a exposição às altas temperaturas e imediatamente após o resfriamento, os corpos de prova foram novamente pesados e submetidos ao ensaio de ultrassom, para determinação da VPU e cálculo do Ed. Destaca-se que se buscou realizar as análises logo após o resfriamento (quando foi possível manusear os corpos de prova), para assim evitar o aumento da fissuração decorrente da reidratação da cal.

4. RESULTADOS E DISCUSSÕES

4.1. Módulo de elasticidade dinâmico e estático

A Tabela 2 e Figuras 1 e 2 apresentam valores médios de Ed (GPa) e E (GPa) das argamassas, obtidos em temperatura ambiente (20 °C) e após a exposição as altas temperaturas pré-definidas (200 °C; 400 °C; 600 °C; 800 °C). Além disso, estão apresentados os respectivos valores de coeficiente de variação (CV) e desvio padrão (DP), conforme análise estatística descritiva. Em primeira análise, destaca-se a diferença entre os valores de Ed e E, o que é justificado pela microestrutura das argamassas ainda intacta durante a obtenção da VPU. Já durante a determinação do E, quando há a aplicação de carga e proporcional microfissuração da matriz, resulta valores menores do que Ed. Portanto, esse comportamento indica que os valores de Ed são mais representativos da rigidez das argamassas. Entretanto, vale ressaltar que essa variação entre Ed e E pode alterar em função da temperatura que as argamassas são expostas, pois as microfissuras causadas por esse tipo de degradação que uma matriz cimentícia é submetida pode ser identificada pelo ensaio de ultrassom e não por ensaio destrutivo (compressão axial).

Tabela 2 - Valores nominais de Ed e E das argamassas mistas com ADF e seus respectivos valores de desvio padrão e coeficiente de variação.

Temperatura (°C)	Series	Ed nominal (GPa)			E nominal (GPa)		
		Média	DP	CV	Média	DP	CV
20	REF	17,92	0,88	5	14,46	0,17	1
	T30	12,96	1,85	15	11,9	1,38	12
	T50	13,69	0,48	4	3,73	0,29	8
	T70	9,51	1	11	3,16	0,55	17
200	REF	12,77	0,46	4	10,42	1,13	11
	T30	9,48	0,31	3	7,16	0,69	10
	T50	6,87	0,79	11	2,43	0,45	18
	T70	4,78	0,35	7	1,59	0,14	9
400	REF	4,53	0,44	10	3,55	0,73	21
	T30	3,38	0,29	9	2,77	0,24	8
	T50	2,31	0,09	4	1,01	0,06	6
	T70	1,65	0,15	9	0,65	0,04	6
600	REF	1,72	0,19	11	1,65	0,17	10
	T30	1,07	0,13	13	1,3	0,1	8
	T50	0,52	0,01	2	0,51	0,03	6
	T70	0,33	0,01	4	0,22	0,01	2
800	REF	0,58	0,02	4	0,56	0,05	8
	T30	0,31	0,06	21	0,47	0,03	7
	T50	0,15	9,17E-4	1	0,07	0,01	7
	T70	0,18	0,03	17	0,09	0,01	9

DV: Desvio Padrão

CV: Coeficiente de variação

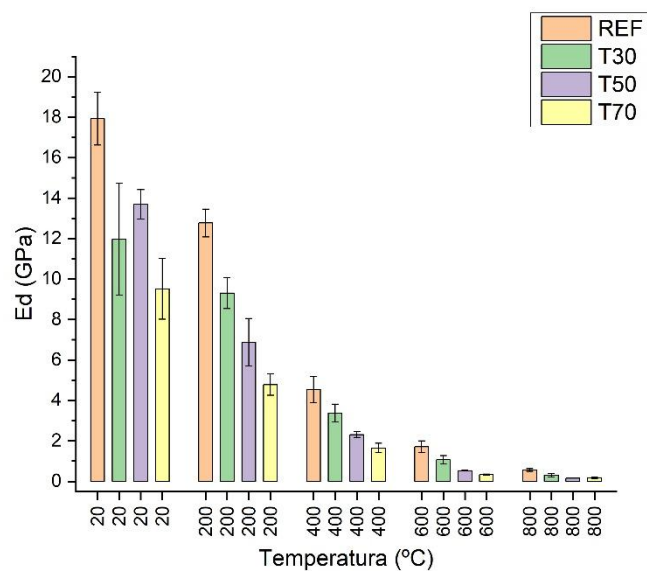


Figura 1: Ed nominal das argamassas expostas a diferentes temperaturas seus respectivos DP

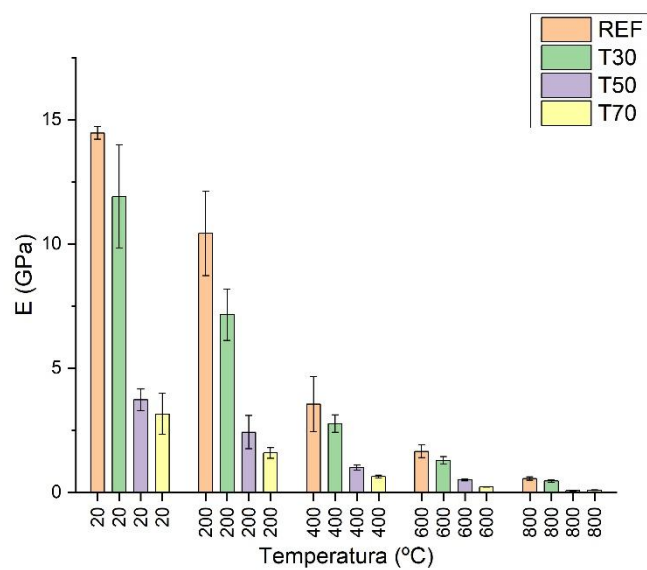


Figura 2: Módulo de elasticidade estático (E) nominal das argamassas expostas a diferentes temperaturas e seus respectivos DP.

Ao analisar as Figuras 1 e 2, observa-se que os valores médios de Ed e E apresentaram comportamento linear, ou seja, reduziram com o aumento do teor de ADF nas argamassas. Além

disso, os valores de E_d e E reduziram com o aumento da temperatura de exposição, conforme o esperado de acordo com a literatura [7]. Vale ressaltar que os resultados em temperatura ambiente foram diferentes, pois a argamassa T50 apresentou valor médio de E_d maior do que a T30. Isso pode ser explicado pela maior variação dos resultados dos corpos de prova ensaiados na temperatura ambiente.

Ao comparar os valores de E_d e E em relação às temperaturas, aos 200°C, todas as argamassas apresentaram reduções significativas em relação à REF. Entretanto, aos 400°C e 600°C, a T30 apresentou valores estatisticamente iguais à REF, o que pode indicar 30% como um teor ideal de ADF, ao avaliar o desempenho em relação a estas temperaturas de exposição. Vale ressaltar que a literatura indica a temperatura de 300 °C como máxima para identificar elementos estruturais de concreto em estado crítico de degradação. Entretanto, há poucos dados na literatura referentes às argamassas, o que justifica ainda mais a importância desse estudo (tanto em relação às argamassas tradicionais como daquelas com a presença da ADF). Aos 800 °C, a inclusão de ADF não influenciou o comportamento do E_d nominal de argamassas mistas, com exceção da T70, que apresentou redução drástica em relação à REF (80%). Esse comportamento identificado pela análise estatística descritiva demonstra a degradação da matriz com o aumento da temperatura, justificado por alterações físicas (aumento da microfissuração e da porosidade), além da química (compostos químicos como C-S-H e CaOH_2), reduzindo a capacidade de suportar tensões e deformações. Autores que avaliaram o E_d em concreto exposto a 400 °C explicam que impurezas presentes na ADF geram reações em argamassas expostas a altas temperaturas, ocasionando maior volume de poros e fissuras na zona de transição [8], o que pode ter ocorrido nas amostras desta pesquisa, mesmo que para argamassas.

As Figuras 3 e 4 ilustram os valores residuais de E_d e E , respectivamente, ou seja, relativos à temperatura ambiente, conforme teor de ADF. Além disso, foram incluídos dados obtidos na literatura para argamassas mistas (CP+cal), já que ainda não há dados disponíveis sobre argamassas mistas com ADF.

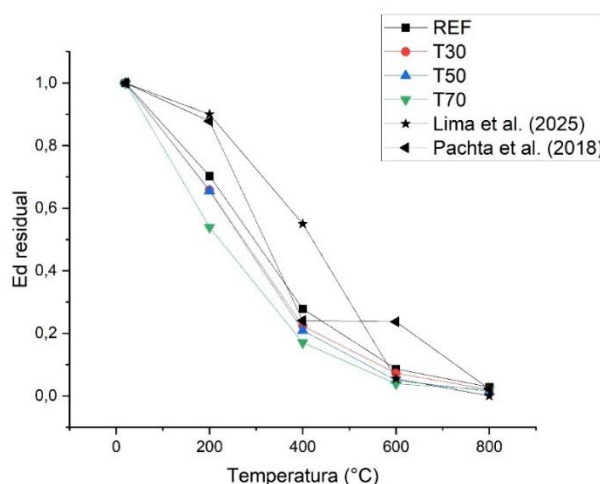


Figura 3: Módulo de elasticidade dinâmico (E_d) residual das argamassas expostas a diferentes temperaturas

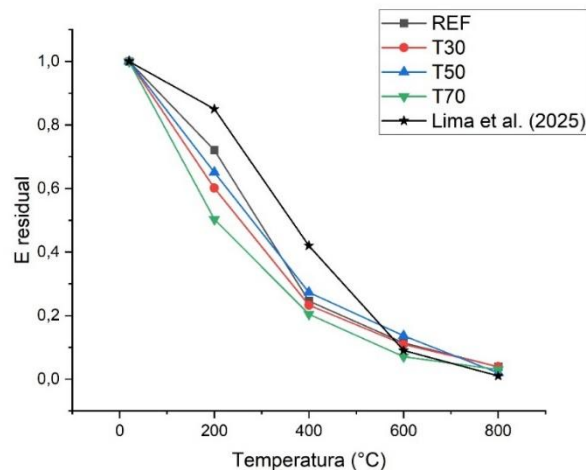


Figura 4: Módulo de elasticidade estático (E) residual das argamassas expostas a diferentes temperaturas.

Ao analisar o E e E_d residual (Figura 3) das argamassas, observa-se que ocorreram reduções significativas em todas as argamassas avaliadas, conforme o aumento da temperatura. É importante ressaltar que o E_d , assim como a VPU, é um parâmetro mais sensível às alterações físico-químicas e microestruturais relacionadas às altas temperaturas de exposição [7]. Isso ocorre porque essas alterações (microfissuras, retração, variações de densidade e umidade, além da degradação dos compostos químicos) alteram o percurso do pulso ultrassônico, resultando em variações da VPU.

Através das análises estatísticas, foi possível identificar que aos 200 °C, a composição com 70% de ADF foi a única argamassa com perda significativa do E_d residual (23%), quando comparada ao traço de referência. Já quando comparamos com valores de E residual, tanto o T70 quanto o T30 reduziram significativamente em relação ao REF. Portanto, argamassas com teores de adição de ADF de até 50% mantêm essa propriedade residual após a exposição a diferentes temperaturas.

Já em relação às temperaturas de 400 °C, os valores de E_d residual de todas as argamassas com ADF, reduziram significativamente em relação ao REF, enquanto isso não ocorreu para os valores de E residuais. Esse resultado indica que os ensaios destrutivos foram menos precisos do que a técnica não destrutiva, uma vez que não conseguem avaliar adequadamente as microfissuras presentes na microestrutura. Ainda assim, ambas as propriedades exibiram comportamento semelhante, com redução progressiva dos valores à medida que a temperatura aumentou, indicando a existência de uma relação entre E_d e E residuais em argamassas mistas com adição de ADF.

Ainda aos 400 °C e 600 °C, o Ed das argamassas com e sem ADF reduziram de maneira similar, indicando a maior interferência dos efeitos físico-químicos e microestruturais das temperaturas avaliadas, anulando o efeito positivo da ADF, obtido até 200 °C.

Ao comparar os valores residuais de Ed obtidos nesta pesquisa com os de outros estudos sobre argamassas mistas expostas a altas temperaturas, observa-se que houve reduções mais acentuadas entre as exposições de 200 °C e 600 °C [7,9]. Dessa forma, as argamassas mistas estudadas por Lima et al. (2025) [7] apresentaram valores residuais de Ed superiores aos desta pesquisa, nas temperaturas de 200 °C e 400 °C devido ao maior tamanho de suas amostras que foram duas vezes maiores e, consequentemente, tiveram um tempo de exposição efetivo menor durante o aquecimento, contribuindo para uma menor degradação do material.

Já ao comparar com Pachta; Triantafyllaki; Stefanidou (2018) [9], houve diferenças no Ed residual aos 200 °C e 600 °C. Assim, os valores residuais desses autores foram superiores ao desta pesquisa nessas faixas de temperatura, indicando que a suas amostras sofreram menores degradações durante o aquecimento, portanto o menor valor de Rc (4,36 MPa) indica uma matriz de maior coeficiente de capilaridade, que reduz as tensões internas causadas pela pressão da evaporação das águas livres e adsorvidas presentes na matriz. Além disso, outras variáveis podem ter influenciado os resultados como a maior taxa de aquecimento (5 °C/min), tempo de exposição à temperatura máxima atingida (2h), formatos dos corpos de prova (prismáticos) e tipo de cimento (cimento branco), que esses autores adotaram.

Para os valores do E residuais desta pesquisa com os da pesquisa de Lima et al. (2025) [7] percebe-se que assim como no Ed residual, os valores deles foram superiores a 200 °C e 400 °C, o que pode estar em função do tamanho dos corpos de prova desses autores, conforme relatado anteriormente, na parte de Ed residual.

5. CONCLUSÕES

Para atingir o objetivo principal desta pesquisa, foram realizados ensaios para determinar as propriedades mecânicas residuais de argamassas com substituição parcial da areia comum por ADF, expostas a altas temperaturas. Para isso, as argamassas foram expostas às temperaturas de 200 °C, 400 °C, 600 °C e 800 °C, em uma taxa de aquecimento e resfriamento de 1 °C/min, com patamar de 60 minutos. Antes e após tal exposição, foram realizados ensaios de ultrassom e compressão axial, para determinar o Ed e E residuais. A partir das análises dos resultados, foi possível concluir que:

- Os dois tipos de módulo de elasticidade estudados nesta pesquisa (E e Ed) apresentaram variações em função do teor de ADF e da temperatura de exposição
- O teor ótimo de ADF é 50%, em que as variações dos resultados não foram significativas.
- O ensaio com ultrassom foi mais sensível em relação ao estático, apontando reduções significativas de valores residuais em situações que o ensaio destrutivo não identificou.

Também deve-se acrescentar que é melhor considerar o E ou Ed para analisar o comportamento de argamassas com ADF expostas a altas temperaturas, pois são propriedades com maior

sensibilidade aos efeitos oriundos deste tipo de agressividade accidental (deformações, fissuração e alterações químicas).

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Session 3

Sesión 3

Sessão 3

**PROPOSAL FOR A METHOD OF EVALUATING FIRE SAFETY
CONDITIONS IN BUILDINGS OF HISTORICAL AND CULTURAL INTEREST
THAT HOUSE COLLECTIONS**



Rosaria Ono*
Professor
USP - São Paulo
Brazil

Keywords: fire protection; historical and cultural heritage; museums; cultural collections; evaluation method.

1. INTRODUCTION

In Brazil, fire safety in buildings is still not widely recognized as an area of knowledge, and in building construction and architecture practice, it has mostly been limited to meeting legal requirements (State fire departments' regulations and Municipal building codes). On the other hand, current Brazilian States' Fire Safety Regulations essentially aimed at protecting buildings and occupants in order to avoid significant losses. Indeed, there has been a significant evolution in these regulations over the last two decades in several Brazilian states, especially focusing on the safety of new buildings. However, ensuring fire safety in existing buildings is a major challenge, mainly for those built more than 50 years ago, as there were no legal requirements at the time of their construction. This issue becomes even more worrying when considering buildings of historical and cultural value, where architectural characteristics are to be preserved. In these cases, interventions to adapt conditions to ensure the safety of the building and its users may conflict with preservation issues. Additionally, there are serious situations where listed buildings house activities that may increase the risk of fire and potential losses in the event of a fire. This is the case of museums, libraries and archives housed in historic buildings.

* Corresponding author — Faculdade de Arquitetura e Urbanismo e de Design da Universidade de São Paulo. Rua do Lago, 876 – Cidade Universitária – Butantão, São Paulo – SP (Brasil). Telef.: +55 11 3019-4571, E-mail: rosaria@usp.br

Despite the lessons that society could have learned from the various disasters suffered by listed buildings, in Brazil, in the last decades, the most significant tragedy occurred on September 2nd, 2018. On that date, a fire broke out at the National Museum of the Federal University of Rio de Janeiro that completely destroyed the building, which had housed the Imperial Palace until the Proclamation of the Republic (1889) and the National Museum since 1892. This institution held the richest and oldest scientific collection in the country, started by King John, the Sixth, of Portugal in 1818, continued by Emperor Peter, the First, of Brazil and it was greatly expanded by Emperor Peter, the Second. About 90% of the collection housed in the building was lost in the fire, including indigenous ethnology objects, Egyptian mummies, dinosaur fossils, and 537,000 books of a library[†]. In addition, several research laboratories were burn down, with the loss of materials and on-going research data.

The lack of human and material resources to improve fire safety conditions in institutions that house collections in historic buildings is an important issue in Brazil. In addition, the technical parameters set out in fire safety regulations are frequently insufficient to meet the needs and specific characteristics of listed buildings, and do not always cover the protection of the collection, beyond the building itself and its occupants.

2. OBJECTIVES

This paper aims to present a method for assessing the fire safety conditions of buildings of historical and cultural interest which house collections, taking into account the protection of the collection, the building itself, and its occupants. This objective stems from the hypothesis that proposing a systemic and comprehensive approach to the fire safety conditions of buildings listed by heritage protection agencies is capable of identifying risks that cannot be verified when addressing the issues of collection preservation, life safety, and building preservation separately.

3. RESEARCH METHOD

Initially, a theoretical approach was carried out, based on an analysis of the literature on the various aspects to be considered in the evaluation method, followed by a stage of integrating the information obtained to develop a proposed method, which was tested for effectiveness through a pilot application.

The literature review took the traditional approach of seeking information on various aspects of safety in museum buildings individually, as well as on methods for integrated multipurpose assessment. This process included a comprehensive survey and an analysis on topics related to fire protection in historic buildings and museums, and also on subjects related to risk analysis and risk assessment methods in general and, specifically, their application in fire risk assessment in historic buildings.

[†] Source: <https://vestibular.uol.com.br/resumo-das-disciplinas/atualidades/ciencia-o-que-o-brasil-perdeu-com-o-incendio-do-museu-nacional.htm>

After a critical analysis of the methods found, considering their applicability to Brazilian historic buildings, procedures and systems for addressing the issue were proposed. Then, several buildings were selected for pre-testing and their information on the specific characteristics of the building and its collection were gathered, in order to assess the suitability of the proposed procedures. Finally, the application in a study case was carried out as well as a critical analysis of the proposed assessment method.

4. LITERATURE REVIEW

Some guidelines for fire protection of historic buildings in Europe such as those from the Confederation of Fire Protection Associations in Europe (CFPA-E) [1], London Fire Brigade [2] and Historic Environment Scotland [3, 4] aim to guide listed buildings managers on how to keep buildings safe from fire, as well as their contents and occupants. This is an important issue, as fire-safety management of those assets are essential to prevent the occurrence of fires and the mitigation of losses.

Efforts to develop a technical guidance document by the Conseil International du Bâtiment (CIB) in the CIB W 15 Fire Commission, between the 1980's and the year 2000 are also found [5, 6]. However, since the early 2000's, the adoption of the performance-based approach to fire safety design of historic buildings are presented as a potential solution [7, 8]. In the U.S.A., two documents issued by the National Fire Protection Association – NFPA deal with the fire protection of *historic structures* in general [9] and the *cultural resources properties* (museums, libraries and places of worship), particularly [10]. These codes are technical documents firstly issued as recommended practices or guides, in the 1940's, evolved to codes (mandatory) in its 2001 edition. In addition to prescriptive approach, in this edition, those codes introduced the performance-based approach to achieve acceptable levels of fire protection. The NFPA 909's 2005 edition also added several aspects related to the management of the daily and emergency situations involving fire and other emergencies. Those two codes are constantly revised and gradually improved.

Concerning the topic of fire safety of historic buildings, a very consistent and thorough literature review is presented in 2023 by Garcia-Castillo, Paya-Zaforteza and Hopitaler [8] and, particularly, a special issue of Fire Technology published in 2025 entitled “Fire Safety of Informal Settlements and Historic Buildings” [11] presents an interesting article, based on a fire case in Japan [12]. In both cases, the future challenges to this topic are discussed. In Brazil, a document was issued in 2023, as Recommended Practice [13] by the Brazilian Association of Technical Standards (ABNT) as consequence of several fire losses in historic structures and collections in recent years in the country as well as abroad. Most of the recommendation are based on prescriptive technical standards, as the performance-based approach is not yet regulated in Brazil.

However, even the adoption of a performance-based approach to improve fire safety of historic buildings is challenging, as conceptually, codes and regulations have focus on life safety, rather than the protection of buildings and its contents [8, 12].

5. THE PROPOSAL

Regarding the initial procedures, a qualitative fire safety assessment was proposed, as an approach to check the basic issues for existing buildings, as follows:

- Codes, regulations and standards: Identify whether the minimum fire safety requirements in force are met;
- Hazards and unsafe conditions: Identify likely vulnerabilities based on regulations and the construction characteristics of the building;
- Potential paths for internal and external flame spread: Analyze the spatial characteristics of the building to identify the potential for fire growth with the spread of flames, heat, smoke, and hot gases;
- Emergency exits: Understand spatial issues and analyze escape routes and exits from the building, considering its construction and spatial characteristics, as well as the profile of its occupants and, in particular, the safety of the most vulnerable population (children, the elderly, and people with physical or cognitive disabilities).

Then, the following procedures were proposed in the method, for improving fire safety, which are resumed in the Flowchart presented in figure 1:

- Fire risk classification of historic buildings based on their architectural and construction characteristics (type of construction system and its fire resistance; types of finishing and coating materials and their reaction to fire; architectural configuration—dimensions of rooms and openings; etc.);
- Fire risk classification of the collections housed in the buildings, based on their physical characteristics (documentation - on paper or digitized, paintings, sculptures, objects such as clothing and furniture, etc.) and type of storage, based on their support material (paper, wood, stone, metal, plastic, fabric, etc.), as well as the ways of exhibition;
- Fire risk analysis based on the different complementary activities carried out inside the listed buildings that house collections, such as administration, maintenance, conservation and restoration laboratories, cafeteria/snack bar/restaurant services, souvenir shop, conference rooms, library, etc.;
- Analysis of the conditions for evacuating the building by its different occupant profiles, using the emergency exits provided;
- Analysis of the conditions for safeguarding the collections and the institutional emergency plan.

The details of each step of the Method are presented together with the results of its application in a case study in this paper. It should be emphasized that an important activity prior to analyzing the building fire-safety is to gather information about its registration, such as original floor plans, cross-sections, elevations, and information about interventions carried out over the years.

Most of the existing frameworks such as NFPA's [9,10] and the one proposed by Watts [6] do not consider issues concerning the collections and how to safeguard them, or even the effectiveness of the management system/ emergency plan, as factors to be evaluated as fire safety components in historical buildings.

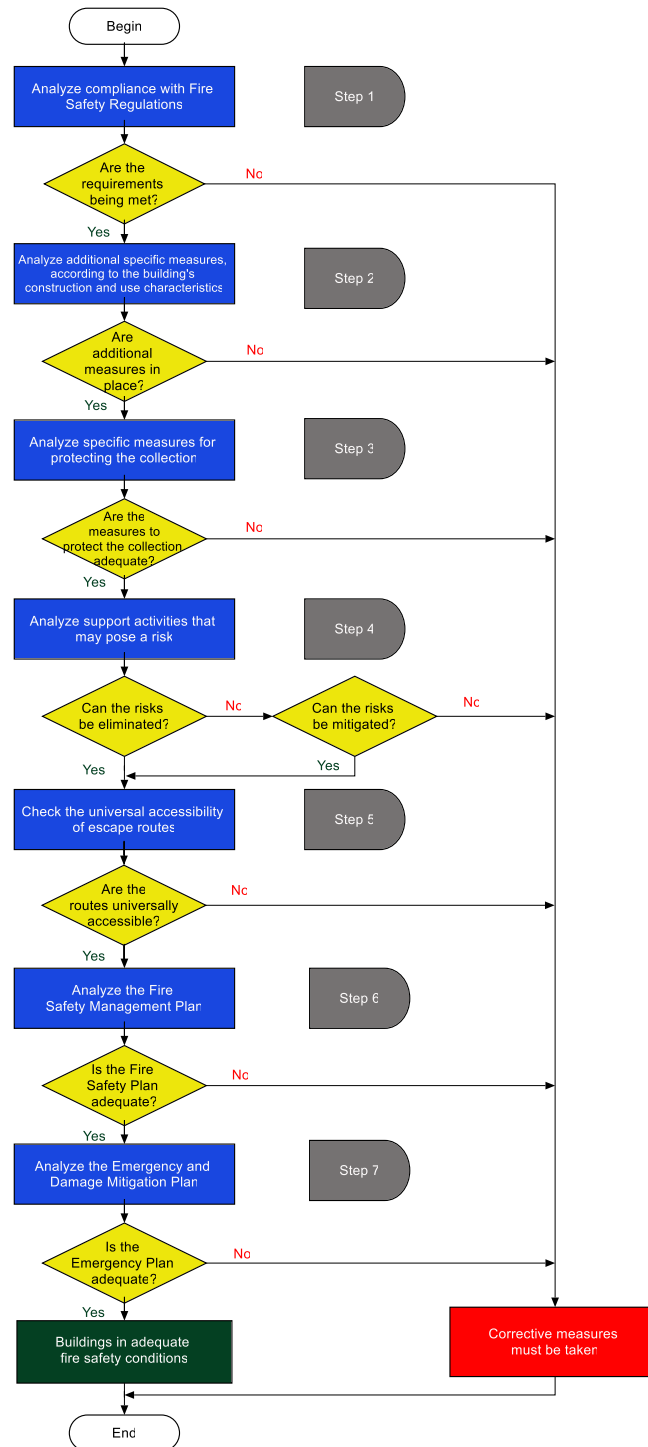


Figure 1: Flowchart of the proposed method.

6. TESTING OF THE METHOD

6.1 Preliminary testing

This research is based on the hypothesis that fire safety can be analyzed based on the characterization of the construction systems of historic buildings. Thus, an important step was to understand the construction characteristics of buildings that house museums, with an initial geographical limitation to the city of São Paulo, and the construction period up to the first half of the 20th century. A group of six public museums belonging to the São Paulo State Department of Culture was selected, as well as five cultural institutions belonging to the University of São Paulo. An extensive bibliographic survey of documentation describing the architectural and construction characteristics of selected historic buildings was conducted, as about the interventions carried out throughout time. These documents included original architectural designs in libraries and historical archives, studies carried out in academic research and by heritage bodies, renovation or restoration projects, among others. The survey covered: a) Information on the architectural, construction, and historical-cultural characteristics that led to the building's listing; b) Relevance of architectural features and exterior finishes; c) Relevance of architectural features and interior finishes; and d) The special construction features of the building. Several publications were found that shed light on the history of these buildings. However, few documents presented or described in detail the original construction systems and interventions carried out over time, as well as the transformations that these buildings have undergone, concerning spatial modifications, finishing and coating materials (floor plans, sections, details, and specifications for restoration processes or surveys of the existing "as built"). The lack of documentation hinders decision-making, both in restoration works and in adapting these historical buildings to adequate fire safety conditions.

6.2 The Study Case

The following criteria were used to select the case study:

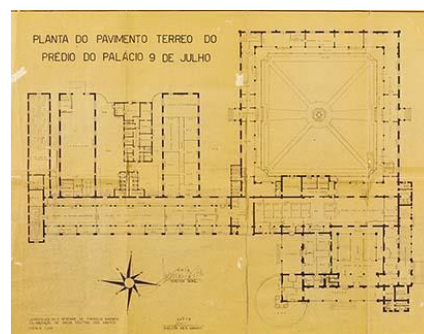
- a) Availability and ease of access to historical documentation and recent archives related to the building;
- b) Little perceived difficulty in the museum adaptation or in the observations commented on during visits;
- c) Few or no fire compartmentation in floors and rooms (vertical and horizontal);
- d) No sharing of the building with other owners;
- e) Few changes in the layout of the rooms comparing to the original plan;
- f) Few changes in the buildings materials and elements comparing to the original design; and
- g) The availability of information about the building's components and materials.

Among the buildings analyzed, three stood out based on the criteria presented above, and one was selected for the application of the method, as it was possible to obtain access to most of the information about the building, as well as authorization to visit restricted areas, such as the roof, machine rooms, and the collection storage space, among others. The study case selected

was the Catavento Museum, open to the public in 2009. The building, originally called *Palácio das Indústrias* (Palace of Industries), an exhibition pavilion, with eclectic architecture, opened in 1924, has undergone various occupancies by the public administration over time and it was adapted to a museum in 2007. For this purpose, it was necessary to add light structures suitable for exhibition areas inside the building, in addition to making adjustments to welcome visitors. The building was listed as a historic landmark in 1982. Figure 2 presents an overview of the Catavento Museum and table 1, the availability of information required by the method.



Source: <https://vejasp.abril.com.br/estabelecimento/palacio-das-industrias/>



Source: FAUUSP Library

Figure 2: Façade and floor plan of ground floor of Catavento Museum (c.1950's)

Table 1: Checklist of information / documentation availability – Catavento Museum

Factors to be considered	
Construction characteristics	
Location in the urban context (analysis of the surroundings and existing risks);	Yes
Building dimensions (height and area);	Yes
Dimensions of rooms and their openings;	Yes
Type(s) of building construction system(s);	Yes
Fire resistance of the structure(s);	Yes
Fire resistance of barriers (walls, floors, ceilings, roofing, etc.);	Yes
Fire behavior of the main finishing and coating materials;	
Type and quantity of combustible materials in the rooms;	No
Characteristics of the collection	
Physical characteristics of the collection (documentation, paintings, sculptures, objects such as clothing and furniture, etc.);	Yes
Storage location (in technical reserves or exhibition areas)	
Characteristics of the enclosure near the storage location (walls, floors, ceilings);	
Support material (paper, wood, stone, metal, plastic, fabric, etc.);	
Fire resistance of collection storage (display cases, shelves, cabinets, etc.)	
Risk of secondary activities	
Secondary activities that may increase the risk of fire inside the building	Yes
Emergency exits	
Horizontal escape routes;	Yes
Vertical escape routes;	Yes
Final exits (discharges).	Yes

7. RESULTS

7.1 Step 1 - Analyze compliance with Fire Safety Regulations.

The Catavento Museum has a Fire Department Inspection Certificate (AVCB) that proves the building complies with the safety conditions required by São Paulo State fire safety regulation. The AVCB was issued, considering the existing and listed building, by the installation of non-invasive fire protection systems in order to preserve the architectural characteristics of the building. However, it became clear during the inspection that some issues had not been resolved, such as the horizontal and vertical fire compartmentation, and, in the event of a fire, the building could be at risk of property loss, and its visitors may encounter difficulties in evacuating the building.

7.2 Step 2 - Analyze additional specific measures, according to the building's construction and occupancy

Based on the information collected during the research, combined with observations made during inspections of the building, it was possible to analyze the structural conditions and risks involved in a possible fire in the building. Thus, a qualitative analysis was performed, assigning a "risk level", as shown in table 2. The classification of risk level into "high", "medium" and "low" was adopted, based on the experience and knowledge of the professionals involved in the evaluation. The classification criteria considered aspects such as "ease of ignition," "ease of fire spread," "probability of structural collapse," and "difficulty of external intervention," based on the available information about the characteristics of the building and its components. One of the major challenges in this case is to ensure horizontal and vertical compartmentation of large spaces. It is equally important to ensure adequate and protected emergency exits. In addition, if the fire reaches the roofs of this building, which are made of mixed metal and wood structures or wood-frame alone, it could cause structural collapse, damaging the rest of the building below. There was no fire protection (active or passive) installed inside the attic under the roof.

7.3 Step 3 - Analyze specific measures for protecting the collection

The available data about the collection characteristics as well as its surroundings were analyzed and the results are presented in table 3 below. Again, the classification of risk level into "high", "medium" and "low" was suggested, based on the experience and knowledge of the professionals involved in the evaluation and the criteria explained previously. The Collection Storage Area is located in the "basement" floor, which is actually semi-underground with windows. This floor has a large area and allows for the installation of an adequate fire safe Storage Area, if improved with fire resistant cabinets and doors. The difficulty of improving fire safety of collections lies in the exhibition areas, due to its spatial characteristics, as well as the materials that make up the exhibition design.

7.4 Step 4 - Analyze other activities that may pose risks

Other activities are not always avoidable in museums, leading to the need for coexistence, always requiring the reduction of the fire risk. They were identified and are presented in table 4.

Table 2: Specific and additional fire-safety measures

Building characteristics	Risks	Risk Level
Location in the urban context (analysis of the surroundings and existing risks)	• Spread of fire between buildings (dense areas with buildings close together/no setbacks)	Low
	• Spread of fire between different blocks of the same building	Medium
	• Difficulty of access for fire department vehicles to the site (urban areas with rugged topography and land without setbacks or access and vehicle maneuvering areas)	Low
Building dimensions (height and area)	• Difficulty of external access to upper floors via the façade	High
	• Difficulty of access upper floors from inside the building	High
Dimensions of rooms and their openings	• Ease of fire spread (flames, heat, and smoke) between rooms on the same floor;	
	• Ease of fire spread (flames, heat, and smoke) between floors from the inside;	High
	• Ease of fire spread (flames, heat, and smoke) between floors through openings in the facade.	Low
Type(s) of building construction system(s)	• Ease of ignition of building materials, when combustible	High
	• Ease of fire spread, when combustible	High
Fire resistance of structural elements throughout the building	• Risk of structural collapse, if the materials constituting the structure are susceptible to heat and flames (wooden or steel structures, or mixed structures, for example)	Medium
Fire resistance of barriers in all rooms	• Risk of horizontal and vertical compartmentalization failure, due to the fragility of the constituent elements (combustible or low fire resistance)	High
Fire behavior of main finishing and coating materials	• Ease of ignition of constituent materials;	High
	• Ease of fire spread.	High
Type and quantity of combustible materials inside the rooms	• Contribution to fire growth	High
	• Contribution to fire intensity and duration	High

Table 3: Specific measures for protecting the collection – Catavento Museum

Collection	Risks	Risk Level
Physical characteristics	• Total or partial loss of the collection due to the effects of fire	Medium
Location	• Storage in the basement can be affected by fire	Medium
	• Exhibition areas can be affected by fire	High
Characteristics of the enclosure near the storage area and collections	• Risk of fire compartmentation failure due to the fragility of the constituent elements (combustible or low fire resistance) in the vicinity of the Collection Storage area)	Medium
	• Risk of horizontal and vertical compartmentation failure due to the fragility of the constituent elements (combustible or low fire resistance) in the Exhibition areas	High

Table 4: Secondary activities that may generate risk – Catavento Museum

Risky activities	Where / Type of potential risk	Risk Level
Identify areas where risky activities are carried out (educational and cultural services, food services, gift shops, etc.)	• Coffeshop: use of heat sources for preparing and heating food and drinks	Medium
	• Assembly rooms (crowds) – auditorium/recording studio	Medium

7.5 Step 5 - Check the universal accessibility of escape routes

This historic building has restrictions and requirements that conflict with compliance with regulatory standards for accessibility and fire safety in escape routes. Through analysis of the design plans and the inspections, it was clear that the escape routes are currently insufficiently accessible, as disabled people are not able to leave the building safely on their own. The challenge in this case is to provide accessible conditions that allow people with disabilities to be independent. Adaptations to existing buildings often end up offering solutions in which people with disabilities need assistance to move around in both normal and emergency situations.

7.6 Steps 6 and 7- Analyze the Fire Safety Management Plan and the Emergency Plan

The institution stated that there is a Building Safety Management Plan, but the research team did not have access to the document. The Emergency Plan is also required by the Fire Department, but this document was also not available to the research team for analysis. Those steps are crucial for firesafety of historical buildings, as vulnerabilities and weaknesses to fire are more evident in this type of construction.

7.7 The Building's Overall Fire Safety Profile

The overall fire safety profile of this building is not satisfactory, with the need of several improvements to reduce the consequences of a fire incident, as there is a high risk of internal fire spread due to the lack of horizontal and vertical compartmentation as well as the lack of control of finishing and coating materials. The installation of a automatic fire suppression system, for instance, could reduce the risk of firespread. The non-availability of the Fire Safety Management Plan and the Emergency Plan did not help on the evaluation of this building.

7.8 Final Considerations Regarding the Proposed Method

Based on the analysis of Steps 1 to 7, by applying the proposed method, it was noted that some aspects could be improved to provide better fire safety conditions in Museums housed in historic buildings, as follows:

- In Steps 2 and 3, with the application of the proposed method, it was observed that many additional measures would be necessary, requiring the development of specific design solutions to improve fire safety, in order to protecting the building and its collection properly from fires;

- Step 4, in turn, the method highlighted the need for more information to confirm the existing condition, in order to assure that the risk, apparently perceived as “medium” or “low” is indeed in one of these categories;
- Step 5, concerning emergency exits to the public, the method points to the need of developing more appropriate solutions that could take into account the safety of people in wheelchairs or with reduced mobility in an emergency situation - which goes beyond the minimum measures established in the Brazilian accessibility standard.
- The evaluation of Steps 6 and 7 was not possible due to lack of access to documentation. However, it is clear that they also consist of dynamic conditions that must always be updated and renewed towards a constant improvement. In fact, such measures are crucial for the proper management of fire prevention and protection systems on a day-to-day basis, as well as for dealing with emergency situations. In historic buildings, where building fire safety can not always be satisfactorily provided by the design and construction solutions, Management and Emergency Plans are essential pieces to achieve the completeness of the assessment and to the assurance of a safer building for occupants and collections.

8. CONCLUSIONS

A comprehensive method has been developed and proposed for assessing fire safety in museums housed in historic buildings, with the aim of improving the fire safety of the building, the collection and people. Its application is based on “lists of requirements,” many of which can be analyzed by qualified professionals, such as civil engineers or architects who are familiar with the subject. Its application to the case study demonstrated its effectiveness, enabling the desired comprehensive fire safety approach.

This method is based on a document analysis (basic and executive projects; history of interventions; descriptive reports with technical characteristics of materials and products; Emergency Plans; Fire Safety Management Plan; Active system maintenance records; Training activity records; etc.) complemented by technical field inspections. However, without full access to technical documents, plans and data, the consistent application of this method is severely hampered, or would require invasive technical inspections involving openings in walls, floors, and ceilings; performance of facility operation tests; and even removal of materials for laboratory testing.

A broader applicability of this method is possible with further improvements, including a semi-quantitative scoring, to the situations where a performance-based approach are not yet implemented due to the lack of regulations as well as of qualified professionals.

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ON THE FIRE RISK ASSESSMENT OF HISTORICAL BUILDINGS IN MINAS GERAIS- BRAZIL



Luana Maris¹
PhD student
UFMG- Brazil
Professor UNA -
Brazil



João Paulo C. R.
Professor
UC - Portugal and
UFMG - Brazil

Keywords: fire risk; historic building, safety, regulation.

1 INTRODUCTION

The preservation of cultural heritage is a necessary and highly relevant measure, essentially due to the need of guaranteeing its conceptual, symbolic and representative dimension to future generations. Certainly, preservation is included in the field of important issues in the escalation of sustainable development undertaken by the government, society and institutions.

It is necessary to understand issues related to fire safety as an approach for conserving built historical heritage, since it guarantees the longevity of these cultural assets through conscious interventions and adequate maintenance [1]. Combined with knowledge of fire risk, this approach aims not only to preserve the heritage itself, but also to ensure the continuity of various sociocultural and economic practices for future generations, although it is necessary to pay attention to the actual fire safety regulation.

It is necessary for both designers and fire safety inspection departments to verify the implementation of safety measures deemed appropriate for each type of use and occupation of buildings under their jurisdiction. Furthermore, it is of fundamental importance for the agencies involved in the design, execution, inspection and maintenance of fire safety in historic buildings to work together [2].

Specific analysis model for existing buildings allows not only the assessment of current fire safety conditions but can also help the designer to quantify the improvements introduced and, consequently, limit the intervention required to ensure the safe use of the building [3].

¹ Autor correspondente — UFMG. Belo Horizonte (Brasil). Telef.: +55 3199102-1649 , E-mail: luanampe@hotmail.com

Fire risk analysis methods can be divided into three basic types, according to the level of demand for available information and the quality and quantity of details of the expected results: a) Regulations and questionnaires lists, or qualitative methods; b) Ordering or semi-quantitative methods; c) Quantitative methods [4].

The present study aimed to address the material consolidation of built cultural heritage as a component of the structural rehabilitation process after fire, which increasingly threaten a diverse range of historical remains. In Brazil, discussions are needed regarding the analysis of these buildings in light of the potential fire risk. The main objective of the work was to analyze historical buildings in terms of fire risk, using assessment methodologies relevant to the topic and the regulatory field of safety.

The state of Minas Gerais (MG), in Brazil, is very rich in cultural heritage, requiring attention to the fire risk in historic buildings. To achieve the general objective proposed in the research, the potential fire risk in public and listed buildings in Mariana, Minas Gerais - MG (Church of Nossa Senhora do Carmo and the Mariana/MG Town Hall and Jail) has been evaluated. The selected buildings are justified by the fact that they are public buildings, ancient and located in a historic urban center where the fire risk is very high. Three semi-quantitative analysis methods were used: Gretener Method, Global Fire Risk Method and ARICA Method.

2 FIRE RISK ANALYSIS METHODS

2.1 Gretener Method

This method was created in 1960 by the Swiss Fire Protection Association [5]. It can be used to assess fire risk in buildings for collective use with high population density. Its use assumes that the building complies with all fire safety rules, since such measures cannot be replaced in this assessment.

Applying the Gretener Method, three assessment phases must be completed: survey of the building's characteristics (identifying potential hazards and fire safety measures), assigning values to the identify parameters; and, finally, calculating the actual fire risk [5]. The value of fire risk (γ), called the fire safety coefficient (or overall safety factor), is calculated as the ratio between the Permissible Fire Risk (R_u) and the Effective Fire Risk (R).

The Gretener Method analysis considers the type of building, the potential hazard of the building and its contents, and the measures against fire development (normal, special and construction). These factors are the basis for determining the actual fire risk. Therefore, when analyzing an entire building, the floor or compartment with the highest fire risk must be chosen to base the analysis on.

2.2 Global Risk Analysis Method

This method was proposed with the aim of analyzing fire risk in old and/or historic buildings in Brazil, focusing on the balance between risk parameters and safety measures present in the building [6]. The Global Risk Analysis Method considers that there are no means of structurally intervening in old buildings to increase fire safety or install fire prevention systems.

For the Global Fire Risk analysis, the building safety coefficient γ that expresses the ratio between the coefficient of safety measures and factors and the overall fire risk [7]. The value of the building safety coefficient must be greater than or equal to the minimum established safety coefficient: $\gamma = S / R \geq \gamma_{\min}$. Considering that this coefficient is the ratio between safety and the overall risk, the method understands the value of $\gamma = 1$ as being the minimum acceptable, that is, when the safety conditions are equivalent to the risk.

2.3 ARICA Method

The Fire Risk Analysis Method for Old Urban Centers – ARICA, version of 2019, will be used in this study allowing the analysis of design solutions for safety systems in existing buildings [7]. The original version of the ARICA method, (developed in 2005 for application in historic centers of Portugal), had a more limited focus and was designed to assess minimum fire safety conditions in historic urban centers, with restricted application to simpler scenarios. The 2019 version significantly expanded the method's scope by incorporating new technical parameters, providing greater detail in risk factors, and allowing for the evaluation of the impact of interventions in existing buildings. This makes it more suitable for analyses of historical buildings with cultural and heritage value.

The ARICA Method results in the evaluation of the Fire Safety Index (I_{SI}), which refers to the safety level of a building or part of it, aiming to analyze the result of interventions in the degree of fire safety, outlining minimum parameters for this type of project [3]. The method itself provides that its application should not be carried out: 1) In risk areas with more than 199 people (which excludes application in large auditoriums, for example); 2) In areas with horizontal evacuation routes for more than 500 people or vertical evacuation routes for more than 1000 people; and 3) in reconstruction sites preceded by complete demolition of the pre-existing building, even if the exterior walls have been maintained.

2.4- Comparative analysis of methods

The Gretener method, although originally intended for industrial buildings and not including evacuation criteria, was adopted because it is widely recognized in the technical literature and allows the objective identification of risk parameters in buildings with a high fire load, such as the Casa da Câmara, in Mariana, Minas Gerais (MG), Brazil. Gretener method is a classification method that was originally developed for Industrial Buildings and does not prioritize evacuation. It has the advantage of being able to be used to evaluate only a part of the building or the entire building, assessing the fire risk by comparing the fire load. The analysis considers the type of building, the potential danger of the building and its contents, and the measures against the development of fire (normal, special and construction).

The Global Fire Risk Method, in turn, was chosen because it was developed specifically for the Brazilian context and for historic buildings, based on the premise of non-structural interference (a common limitation in listed properties). It considers that there are no means of structurally intervening in buildings of historical value to increase fire safety or install fire prevention systems. The method considers the probability of a fire occurring and its consequences (human, material and financial).

Despite this, its applicability is debatable in cases where discrete interventions are possible or necessary. ARICA was selected because it is a consolidated method for historic urban centers in Portugal, and because it offers a detailed approach adapted to heritage buildings, although its direct application in the Brazilian context still faces challenges, such as parameter calibration and local regulatory restrictions. The joint use

of these methodologies thus sought to build a more robust analysis that is sensitive to the specificities of the buildings analyzed, allowing for data triangulation and greater technical support for the proposed recommendations. Thus, ARICA method, as the others presented, may show difficulties in direct use in Brazilian buildings, that resulted in inconsistent values for the factors considered and for the result of the fire safety index – ISI.

3 CASE STUDIES

3.1 Casa da Câmara (Mariana/MG)

The “Casa da Câmara” - current headquarters of the City Council of the city of Mariana/MG, was built in 1798. Together with the Carmo and São Francisco Churches, it forms the architectural complex of João Pinheiro Square. The building has two floors, with a rectangular floor plan, a stone and lime masonry structure, and a hipped roof (Figure 1).

Figure 1- Mariana/MG - Casa da Câmara



Source: IPHAN (2020) [8].

As pointed out by Souza (2024) [9], the blue soapstone façade forms a contrast with the white lime of the walls. Internally, the ground floor has a slab floor, thick walls, and the internal walls are built with the adobe applied directly to the installation site.

The electrical project does not involve intervention in the basement and the maintenance was carried out on the electrical part of the building's walls. After the restoration was completed, measurements and graphic drawings were made of all the projects: architectural, electrical, lighting, sound, accessibility, among others.

The ground floor was assessed for fire risk, as it has internal walls and doors with low fire resistance. Attributing this to the lack of physical separation of the space from the first floor in its entirety, this promotes a possible horizontal and vertical fire spread, as there are no separation compartments.

3.2 Church “Nossa Senhora do Carmo”

The Church “Nossa Senhora do Carmo” is a typical example of the Minas Gerais Baroque style. In 1759, construction began on a temporary chapel, and work on the final church began in 1784. It is a Rococo-style building made of stone masonry, lime mortar and wood (Figure 2).

Figure 2- Church of Our Lady of Mount Carmel - Mariana /MG



Source: Iphan (2020) [8].

In April 1999, the Church suffered a fire, losing much of its collection, affecting the entire Main Nave. The historic building was in the final stages of restoration when a welding spark set fire to the kerosene used to disinfect the wood. According to Gouveia (2005) [6], the Church of Carmo was mainly affected by the vital elements of its artistic expression, represented by the painted ceilings, altars, images and stone ornaments. Only the main altar was preserved and a large part of the Church was destroyed.

The new structural consolidation project and new intervention were carried out in 2000, configuring the physical space of the building as it is currently located, reconstructing the elements lost in the fire.

4 - RESULTS AND DISCUSSIONS

This section presents the results of the application of the fire risk methods to the buildings in analysis:

- Building 1: Casa da Câmara: critical compartment location: Ground floor (428.50 m²);
- Building 2: Church of "Nossa Senhora do Carmo": critical compartment: total area of the building's ground floor (1100 m²).

4.1 – Gretener Method

The results of the Gretener Method are in Table 1:

Table 1- Application of the Gretener Method

GRETENER Method					
Factors and Subfactors –				Build 1	Build 2
length (bigger dimension, m)		<i>l</i>		28.01	65.00
width (smaller dimension)		<i>b</i>		15.29	21.00
relationship length width		<i>l/b</i>		2:1	3:1
area (m ²)		<i>area</i>		428.50	1100
Fire load (MJ/m ²)		<i>Qm</i>		1660.46	507.8
Danger potential	<i>q</i>	Fire load mobiliary	<i>q</i>	1.6	1.6
	<i>c</i>	Combustibility	<i>c</i>	1.6	1.4
	<i>r</i>	Smoke	<i>r</i>	1.1	1
	<i>k</i>	Corrosion / toxicity	<i>k</i>	1.2	1.2
	<i>i</i>	Fire load building elements	<i>i</i>	1.2	1.1

	Factors and Subfactors		Build 1	Build 2	
	e	Level of the floor	e	1.3	1.0
	g	Amplitude of the surface	g	0.4	0.6
Total of danger potential			P	2.109	1.774
Normal Measures	Portable fire extinguishers		n 1	1	0.9
	Internal hydrants		n 2	0.8	0.8
	Water supply		n 3	1	0.9
	Supplying system		n 4	1	0.9
	Instructed personel		n 5	0.8	0.8
Total of normal measures			N	0.64	0.467
Special Measures	Fire detection		s 1	1.2	1.1
	Transmission and alert		s 2	1.05	1.1
	Firemen and fire brigades		s 3	1	1
	Time of intervention: firemen		s 4	1	1
	Extinguishing instalations		s 5	1	1
	Heat/smoke exhausting instalations		s 6	1	1
Total of special measures			S	1.260	1.210
Construction Measures	Structure fire resistance		f 1	1.0	1.0
	Facade fire resistance		f2	1.10	1
	Slab fire resistance		f 3	1.05	1
	Firebreak cells		f 4	1.10	1.12
Total of construction measures			F	1.271	1.200
Factor of danger exposition			B	2.050	2.610
Danger activation			A	1.00	1.00
Effective fire risk			R	2.050	2.610
Correction factor			PHE	1.00	1
Accepted fire risk			Ru	1.54	1.54
GLOBAL FIRE SAFETY FACTOR			□	0.750	0.589

Source: Authors (2025).

What quantifies the acceptable fire risk for building occupants is the result of the product between the correction factor and a constant that represents the normal fire risk, which is fixed at 1,3. The PH,E factor deals with the exposure of building occupants to the hazard and their mobility capacity in case of fire. This correction factor must be applied according to the number of building occupants and the category of exposure to the hazard to which these people are subjected. The effective fire risk is the result of the product of the activation hazard (A) and the exposure factor to this hazard (B). In this way, the fire safety

coefficient (or overall safety factor) is calculated by the quotient between the Acceptable Fire Risk (R_u) and the Effective Fire Risk (R).

The application of Gretener 's method showed that, identifying the potential hazards and fire safety measures, in addition to factors such as constituent materials (potential hazards related to the construction characteristics of the building and its contents) and the absence of a fire brigade, it was found that these data contributed to both buildings presenting a high fire risk result. With the Fire Safety Coefficients γ , associated with the fire risk values (calculated by the quotient between the Allowable Fire Risk (R_u) and the Effective Fire Risk being high, γ less than 1 attributed an unsafe fire risk value to the building.

4.3 Global Fire Risk method

The results of the application of the Global Fire Risk method are in Table 2:

Table 2- Global Fire Risk Analysis Method

Global Risk Analysis			Build 1	Build 2
For exposure to fire risk (E):			V	V
Classification of the edification				
Fire load density			f_1 1.60	1.3
Height of compartment floor			f_2 3.0	1.5
Distance from the fire department			f_3 1.00	1.00
Conditions of access			f_4 1.00	1.00
Generalization of the danger			f_5 2.00	2.00
Specific importance from the edification			f_6 1.70	1.70
Coefficient of fire risk exposition			E 10.88	6.63
Signaling measures	Alarm of fire manual	s_1	1.5	1.5
	Detector of heat/smoke	s_2	2.00	2.00
	Detector of heat/smoke automatic	s_3	3.00	-
Extinguishing measures	Fire extinguishers	s_4	1.00	1.00
	Fixed gase extinguishing system	s_5	-	-
	Fire brigade - on call/working hours	s_6	-	-
	Fire brigade - on call/permanent	s_7	-	-
	Internal sprinklers	s_{8a}	-	-
	External sprinklers	s_{8b}	-	-
Infrastructure measures	Hydrants - public reservoir	s_9	-	-
	Hydrants - private reservoir	s_{10}	-	-
	Water reservoir	s_{11}	-	1.00
Structural measures	Fire resistance ≥ 30 min	s_{12}	1.00	1.00
	Fire resistance ≥ 60 min	s_{13}	-	-
	Fire resistance ≥ 90 min	s_{14}	-	-
	Fire resistance ≥ 120 min	s_{15}	-	-

Global Risk Analysis			Build 1	Build 2
political measures	Plant of risk	s 16	1.00	-
	Flat of prevention	s 17	1.20	-
	Escape plan	s 18	-	-
	Signaling of the exits	s 19	1.00	-
Safety coefficient		S	10.8	3.00
Risk of activation for the nature from the occupati		A 1	1.5	1.00
Risk of activation due to human error		A 2	1.00	1.75
Risks arising from the facilities		A 3	1.00	1.25
Risk due to natural phenomena		A 4	1.00	1.50
Risk of activation		A	1.5	1.00
Global Fire Risk		R	16.32	6.63
Y			0.66	0.45

Source: Authors (2025).

The application of Method of Global Fire Risk in the studied buildings, from the observation in the application of $R = E \times A$, and $A = A_1 \times A_k$, considering:

- A1 (Risk based on Nature of Occupancy): evaluates the specific, continuous risks inherent to the building's use;
- Ak (Accidental Risks): represents transient risks that can occur, such as human error, electrical faults, or natural hazards. It showed that the balance between risk parameters and safety measures present in the building resulted in an unsatisfactory result with a safety coefficient γ less than 1.

4.4 ARICA method

The results of the application of the ARICA method, considering the risk location (RL) are in Table 3:

Table 3- ARICA Method

ARICA Method		Build 1	Build 2
Anomalies that can originate from a fire	F_{CE}	0.90	0.90
Electrical facilities	F_{IE}	0.70	0.70
Gas facilities	F_{IG}	1.00	1.00
Heating - central thermals	F_{CT}	-	-
Heating - equipment	F_{AA}	-	-
Preparation/preservation of food	F_{EIS}	-	-
Evacuation of combustion effluents	F_{IEC}	-	-

ARICA Method		Build 1	Build 2
Ventilation and conditioning of air	$IVCA F$	1.00	-
	Minimum	0.70	0.70
	Sum	2.70	1.70
Partial Factor- Gas Installations	$F IT$	0.66	0.69
Global Factor- technical facilities	$FG II$	0.85	0.80
Covering of walls and ceilings	F MRPT	1.00	1.00
Covering of floors	F MRP	1.00	0.85
Materials for covering of RL	F MRRL	1.00	0.85
Materials of covering evacuation paths	F MRVE	1.00	1.00
Insulation and protection of RL	F IPLR	1.00	1.00
General compartmentation	F CGAI	-	-
Insolation of the Use Type	F IPUT	-	-
Safety teams	F ES	0.5	0.00
Detection, alert and alarm	F DAAI	2.00	1.00
External coating of RL	F RE	1.00	1.00
Removal of gaps and facades	F AV	1.00	1.00
Propagation to the exterior	F PPE	1.20	1.00
Global Factor- Fire development and spread	$FG DPI$	1.20	1.00
Number of exits of RL	F NSL	1.00	1.00
Total width of the exits of RL	F SLL	1.29	1.00
Subfactor relating to the widths of openings and horizontal evacuation routes	FL VHE	1.8	1.8
Walk distance in the horizontal evacuation path	FD VHE	1.48	1.48
Dimensions of the horizontal evacuation path	F VHE	-	-
Number of vertical ways of evacuation	FN VVE	1.15	1.15
Width of vertical ways of evacuation	FL VVE	1.00	1.00
Slope of the vertical ways of evacuation	FI VVE	-	-
Flooring of RL	F P	1.00	1.00
Dimensions of the vertical path of evacuation	F VVE	1.00	1.14
Insolation of the evacuation paths	F IPVE	-	-
Smoke control node RL	F CFRL	1.00	-

ARICA Method		Build 1	Build 2
Smoke control: ways of evacuation	F CFVE	-	-
Smoke control node RL	F CF	1.00	1.00
Signaling node RL	F SIRL	0.65	0.65
Signaling in the ways of evacuation	F SIVE	0.65	0.65
Signaling of emergency in RL	F SIN	0.65	0.30
Lighting node RL	FIERL	0.60	0.60
Lighting in the ways of evacuation	FIVE	0.60	0.60
Emergency Lighting	F IE	0.60	0.60
Safety teams	F ES	0.50	0.00
Fire detection, alert and alarm	F DAAI	1.00	1.00
Fire drills	F SE	0.00	0.00
	F PROT	0.55	0.20
	FG EE	0.71	0.95
Accessibility to the building	F AE	1.00	1.00
External hydrants	F HE	-	-
Subfactor relating to dry or wet networks	F CS/CH	0.60	0.00
Fire extinguishers	F EXT	1.00	1.00
Armed fire networks	COLD	0.75	0.75
Accessibility and intervention	F MINE	0.90	0.90
Automatic means of extinguishing	F MEA	1.00	-
Safety teams	F ES	0.50	0.00
	FG CI	0.80	0.90
I SI		0.89	0.91

Source: Authors (2025).

The ARICA Method should always be applied considering two situations: initial conditions (CI): where existing safety conditions are evaluated, resulting in the fire safety index in initial conditions (ISICI) and project conditions (CP): where the safety conditions that will be present in the unit of analysis after the intervention are evaluated (ISICP). The final calculation of the Fire Safety Index (ISI) is done by averaging the following factors: FGII – global factor related to the start of the fire; FGDPPI – global factor related to the development and spread of the fire; FGEE – global factor related to evacuation in case of fire and FGCI – global factor related to fire fighting. When analyzing the value found for the fire safety index, $ISI < 1$ was identified, that is, a result less than one means that the building has a level of fire safety lower than what is legally required.

The application of the ARICA Method in the buildings showed that the Fire Safety Index (ISI) assessment, which refers to the safety level of a building or part of it, was not satisfactory, not meeting the minimum parameters for this type of project. Data such as

the overall fire initiation factor and fire development and spread do not satisfy the ideal safety condition.

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5. CONCLUSIONS

Since the state of Minas Gerais/MG is very rich in cultural heritage in Brazil, it is essential to pay attention to the fire risk of its historic buildings. Thus, the application of the Gretener, Global Fire Risk and ARICA methods to the historic buildings Casa da Câmara and “Igreja Nossa Senhora do Carmo”, in Mariana/MG, showed that neither of them meet the minimum fire safety requirements.

In the Gretener Method, the variables with the greatest influence on the fire safety coefficient (γ) were the fire load density (Q_m), combustibility of materials (c) and the exposure factor (B), reflecting the presence of combustible historical materials and the absence of compartmentation. These aspects significantly increased the effective fire risk in the analyzed buildings.

For the Global Fire Risk Method, the most influential parameters were related to the exposure coefficient (E), particularly the generalization of danger and the specific importance of the building. As well as the limited availability of fire protection measures, such as detection systems and firefighting teams, reduced the safety coefficient (γ). In the ARICA Method, the variables with the greatest impact on the Fire Safety Index (ISI) were associated with fire initiation conditions, especially the state of electrical installations, detection and alarm systems, and factors related to evacuation and firefighting capacity.

The Gretener method, although useful, does not consider evacuation strategies and was originally developed for industrial buildings, which limits its suitability for heritage assets. The Global Fire Risk method, in turn, assumes the impossibility of structural interventions, which makes it insensitive to alternative technical solutions. ARICA, although aimed at historic centers, has application restrictions and generated inconsistent values when used in the Brazilian context.

It is possible to determine the set of appropriate measures for reducing the fire risk to a maximum acceptable value. The comparative analysis showed that, despite their individual limitations, such as the rigidity of the Gretener method or the low adaptability of the Global Fire Risk, the combined use of the three methodologies broadens the understanding of fire risk in heritage contexts. This integrated approach stands out to allow the identification of critical points from different perspectives, although it requires caution in interpreting the results given local specificities.

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SEQUÊNCIA INCÊNDIO-EXPLOÇÃO OU VICE-VERSA NUM ACIDENTE



Jorge Saraiva
Eng. Mecânico
Director da Dinâmica
Aplicada - Lisboa
Portugal

Palavras chave: Fogo, “Back-Draught”, Explosão.

1. RESUMO

Uma explosão, ocorrida ao princípio de uma manhã de um sábado, numa grande unidade industrial, localizada nos arredores de Lisboa, provocou danos muito significativos (avaliados, pelas seguradoras, em 1,2 M€), além de um ferido grave com cerca de 30% do corpo apresentando queimaduras de 2º e 3º grau [1].

As questões de responsabilidade e indemnizações acabaram por conduzir à necessidade de identificar a sucessão dos acontecimentos já que a primeira hipótese levantada (explosão de uma máquina de lavar de alta pressão com aquecimento de água (MLAP)) foi abandonada praticamente logo após a sua inspecção.

As teses sobre o que realmente se passaram tornaram-se mais complexas:

- Para uns, a MLAP incendiara-se; O incêndio ter-se-ia propagado ao combustível (ruptura do depósito), criando condições para a ocorrência de um fenómeno de “back-draught”, desencadeado quando o operário que operava máquina e se encontrava no local, não conseguindo controlar o incêndio, abandonou a sala, abrindo a porta desta (o que permitiu o acesso de ar novo).
- Para outros, a sala apresentaria na altura do acidente uma atmosfera ATEX, sem que existisse qualquer aviso/alarme. Este tipo de atmosfera teria sido criado pela lavagem, no fim da tarde da sexta-feira, como era usual, das paredes e de uma máquina existente na sala para lavagem de peças (MLP) com solventes orgânicos, sendo essa a verdadeira origem do acidente (explosão).

O artigo apresenta o trabalho levado a cabo para determinar a sucessão de acontecimentos: incêndio – explosão, ou explosão-incêndio.

2. A ENVOLVENTE

Entende-se por envolvente a sala onde se verificou o incidente/acidente. Pode ser descrita como um volume paralelepipedico com dimensões em planta de (referidos em documentos diferentes como 6 m e 8 m) 6x5 mxm ($A_p \sim 30 \text{ m}^2$) e com cerca de 5 m (estimado das fotografias) de pé-direito, ou seja, um volume estimado (mínimo) de $\sim 180 \text{ m}^3$ (poderia existir – referido no relatório do acidente, mas não visível nas fotos de registo disponibilizadas - um tecto falso, sob os elementos de suporte da cobertura, pois as fotografias mostram que o sistema de ventilação forçada ficava colocado um pouco abaixo daqueles elementos).

Havia apenas uma entrada para pessoas e equipamentos a partir de um corredor interior. O acesso era constituído por uma porta, na parede de separação para esse corredor (parede de topo da sala), com duas folhas, que apenas abriam para o interior da sala, e que ocupava uma área significativa dessa parede.

As paredes laterais da sala e a parede do fundo não tinham qualquer abertura à excepção da que permitia a passagem da conduta de ventilação e a ligação do “esgoto”.

A parte inferior da parede do fundo e pelo menos um par de metros das paredes laterais eram revestidos com azulejos, pois era nessa zona que se situava a área de lavagem. Esta ocupava toda a largura da sala e era dotada, no chão, de grelhas, admite-se que com cerca de 1,25 m de dimensão transversal (área de lavagem em planta de 5x1,25 mxm), por baixo da qual existia um colector (o esgoto) que recolhia os líquidos de lavagem e os encaminhava subterraneamente para o exterior do edifício, onde existia um reservatório com um separador de hidrocarbonetos (encostado à parede de fundo que é também a parede exterior do edifício).

As paredes eram constituídas por elementos de betão vazado, com pelo menos 15 cm de espessura, ligados por argamassa e que preenchiam o espaço entre perfis metálicos, que constituíam a estrutura base.

O sistema de ventilação da sala (designada por de “lavagem de peças”) visível (ver figura 2) era constituído por um tubo, tipo Spiro, que penetrava na sala, a um nível elevado, vindo da parede do lado esquerdo (vista da parede de topo para a parede de fundo) e desenvolvia-se na perpendicular a esta, percorrendo um pouco mais de metade da sala. O tubo estava tamponado na extremidade do lado da sala, mas dispunha de uma grelha cobrindo, na zona inferior e perto da extremidade, uma abertura rectangular (solução correntemente utilizada para este tipo de tubagem). O sistema, que deveria operar em extracção, merece duas críticas:

1) revela, do ponto de vista técnico, uma concepção defeituosa; o ar poluído para ser removido precisa que ar novo o venha substituir o que só é possível, como se deduz do já descrito sobre a sala, pela porta, que se encontraria normalmente fechada e, como tal, limitadora da capacidade de renovação do ar;

2) o sistema, na altura do acidente, nunca funcionaria pois a conduta de ventilação tinha sido interrompida (removida) assim que atravessava a parede, estando completamente obstruída por elementos de uma estrutura metálica existente na sala ao lado.

Por outras palavras, se a ventilação já seria deficiente por condições de operação (dificuldade de admissão de ar novo), pode afirmar-se que, na realidade, era inexistente nas condições que se verificavam aquando do acidente.

A figura 1 (preparada com suporte nas fotografias efectuadas após o acidente) ilustra a descrição feita e mostra todos os equipamentos existentes, na sala, na altura do acidente, bem como a sua posição aproximada. As folhas da porta apenas abriam para dentro,

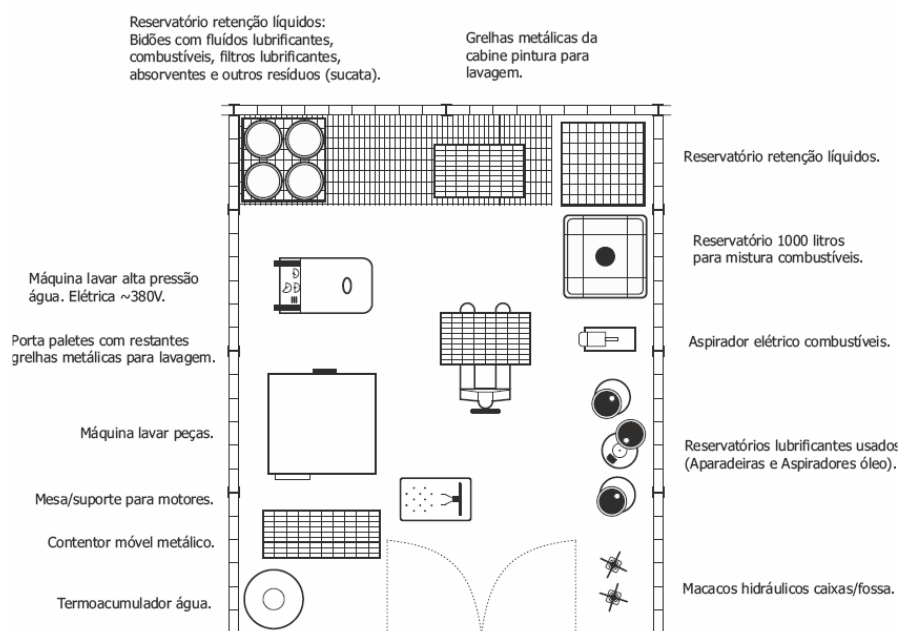


Figura 1: Planta da sala (6x5x6 m³) e localização (aproximada) dos equipamentos ali existentes

Merecem destaque dois equipamentos: o reservatório de 1000 l do lado direito, pois continha uma quantidade significativa (não existem referências ao nível) de uma mistura de gasolina e gasóleo (em proporção desconhecida); a chamada MLP (que dava o nome à sala) que utilizaria para essa finalidade soluções aquosas, ao lado da qual se pode ver a MLAP, que terá estado na origem do acidente.

3. CONSEQUÊNCIAS DO ACIDENTE

O conjunto de imagens seguintes (2 a 5) ilustram o aspecto da sala depois do acidente.

A figura 2 merece uma referência particular por 3 razões:

- 1 – Foi tirada sobre os escombros da parede de entrada, que ruiu completamente (vêm-se do lado direito da imagem os blocos do canto desta parede);
- 2 – Permite identificar o tubo de ventilação e a posição do tecto falso (destruído);
- 3 – Mostra a queda dos azulejos que revestiam a parte inferior das paredes, bem como a deformação e fissuração destas.



Figura 2: Vista para a parede de fundo

As figuras 3 e 4 correspondem, respectivamente, às imagens das paredes direita e esquerda. Os danos nas paredes são visíveis, mas a figura 5 permite verificar, em particular, os danos significativos (incluindo deslocamento) da parede do fundo. Mostram também o estado em que ficaram os equipamentos existentes na sala depois do incidente. Há 2 pontos que se destacam:

- 1 – Do lado direito vê-se o reservatório de combustíveis que rebentou (certamente derramando o conteúdo pelo chão da sala) verificando-se que a parte de trás não foi destruída nem ardeu; o derramamento desse combustível para o chão, inclusive ao longo da parede, o que justifica o aspecto, após o incêndio) dos equipamentos visíveis na imagem;
- 2 – Do lado esquerdo vêem-se as duas máquinas de lavagem: a de peças (sensivelmente um cubo de grandes dimensões) e o que ficou da MLAP, chamando-se, desde já, a atenção para o seu aspecto (estrutura metálica) que não apresenta sinais de deformação.

Nas figuras 2 e 5 vêem-se as grelhas que iam ser lavadas e nas figuras 3 e 4 o porta-palettes utilizado para as transportar do seu local de origem (oficina de pintura) para a sala de lavagem. Na figura 2 pode ver-se uma placa branca do lado direito, não tendo sido possível confirmar se provinha do tecto falso da sala ou do espaço vizinho, do lado da entrada; os cabos soltos visíveis estavam instalados no exterior da sala, no corredor de acesso.



Figura 3: Vista para a parede do lado direito



Figura 4: Vista para a parede do lado esquerdo

4. A ORIGEM DO ACIDENTE

Quando se analisa o acidente, a primeira conclusão é que estando desligados, na altura, todos os equipamentos correntemente presentes na sala (a unidade industrial estava fechada nos fins de semana) estes não podem ser a causa/origem da ignição. Resta, pois, a hipótese de a operação da máquina de lavagem de alta pressão ter causado o acidente (independentemente da sequência dos eventos).



Figura 5: Vista dos danos na parede do fundo

4.1 A máquina de lavagem de água quente e alta pressão (MLAP) [2]

A MLAP é constituída, essencialmente, por um motor eléctrico (blindado) que acciona vários componentes (uma bomba de pressurização da água (bomba hidropressora de pistões); a bomba de combustível (gasóleo para queima); e o ventilador (alimentação da câmara de combustão)), uma pequena caldeira a gasóleo, onde a água é aquecida em tempo real, um depósito de gasóleo de 25 litros para alimentar o queimador; um painel de comando, (órgãos de comando e controlo) e, ainda, um depósito de detergente e outro de anti-calcário, para além de mangueiras, acessórios e um chassis que suporta os diversos componentes.

A figura 6 mostra diferentes aspectos da MLAP (marca KARCHER, modelo HDS895, pressão máxima 30-180 bar, temperatura máxima da água 98 °C, consumo máximo de combustível do queimador 6,9 Kg/h ~2 g/s), sendo visíveis todos os elementos descritos. A imagem em corte da caldeira dá uma ideia clara da sua estrutura. A operação é descrita seguidamente:

- 1 - Liga-se a mangueira com a pistola de lavagem pretendida e estabelece-se a alimentação em água e em energia eléctrica;
- 2 - Regula-se a pressão da água no manípulo existente na bomba hidropressora, selecciona-se a temperatura desejada no interruptor termostático existente no painel de comando e roda-se interruptor ON/OFF para a posição "I" (ON);
- 3 - De imediato, o motor eléctrico arranca, a pressão aumenta até activar o interruptor manométrico de segurança que automaticamente desliga o motor, permanecendo a máquina em modo "stand by";
- 4 - Antes de iniciar a utilização deve ser efectuada a verificação do sentido de rotação do motor eléctrico, dado tratar-se de uma ligação trifásica; essa verificação é feita de forma simples descrita no manual: um breve accionamento da pistola com uma mão colocada sobre a "chaminé" da caldeira, um pouco afastada desta. Se o sentido de rotação for o devido deve sentir-se, de forma quase imediata, o escoamento na mão, se não for deve ser invertida a ligação e repetido o procedimento como confirmação antes de iniciar a operação;

5 - Pega-se, então, no manípulo da pistola, dirige-se para o local pretendido e prime-se o gatilho (a pistola dispõe de um dispositivo de segurança de bloqueio do gatilho);



Figura 6: Máquina de lavar de alta pressão com aquecimento de água

6 - O acto de “premir o gatilho” desencadeia na máquina, de forma automática, as seguintes acções: liga as bombas de pressurização da água e de fornecimento de gasóleo ao queimador, o ventilador de ar de combustão do gasóleo e o sistema de ignição (faíscas) da mistura de ar com gasóleo pulverizado; mais em pormenor, ao premir o gatilho abre-se a saída da água para o bico de pulverização, a pressão diminui, o interruptor manométrico liga o motor (o qual acciona simultaneamente as bombas hidropressora e de combustível e o ventilador de ar de combustão), a passagem de caudal de água é detectada por um sensor electromagnético que actua sobre a electroválvula da bomba de combustível, permitindo a passagem do combustível para o queimador, no qual é iniciada a combustão pelo sistema de ignição;

7 - Quando se “liberta o gatilho” são desligados todos os elementos referidos na alínea anterior, ficando a máquina em modo “stand by”;

8 - De salientar que, durante o funcionamento normal, o interruptor termostático regula (pode mesmo cortar) o fornecimento de gasóleo ao queimador em função da temperatura da água, mas o sistema de ignição mantém-se sempre activo (mesmo na condição de “água fria”), assegurando que, se surgir gasóleo no queimador, tem condições para ser queimado;

9 - O sensor electromagnético de caudal de água atrás referido garante que, na ausência de água é cortada a alimentação eléctrica à electroválvula da bomba de gasóleo e, mesmo que o motor se mantenha em funcionamento, o gasóleo faz “by-pass” para o reservatório e não segue para o queimador.

4.2 Incêndio – Explosão

A sequência incêndio explosão, neste caso “back-draught” [3], foi defendida da seguinte forma:

1 – O incêndio iniciou-se no interior da MLAP devido a uma fuga de combustível, possivelmente a partir do injector no topo de caldeira; a fonte de ignição teria sido a temperatura dessa superfície;

2 – Esse incêndio inicial teria provocado a ruptura do depósito de combustível que, uma vez derramado, permitiu a constituição de um “pool-fire” que consumiu praticamente todo o oxigénio da sala;

3 – O operador da máquina (única pessoa presente) não conseguiu extinguir o incêndio (teria removido a cobertura da mesma para o fazer, sendo então sofreu as queimaduras) e saiu da sala, abrindo a porta, dando origem à entrada de ar novo que proporcionou a ocorrência de um fenómeno de “back-draught”, dado o tipo de atmosfera entretanto formado.

4 – Após esta situação o incêndio pôde progredir.

A figura 7 apresenta o estado geral da máquina após o acidente; a simples observação permite, efectivamente, refutar de imediato a tese inicial da sua explosão, mas permite, igualmente, verificar que todos os polímeros (reservatórios, cobertura, painel dos comandos) arderam completamente. É igualmente possível verificar que parte do combustível formou um pool fire a nível do chão e outra parte terá ardido no tabuleiro formado pelo chassis.



Figura 7: Máquina de lavar de alta pressão e zona vizinha após o acidente

De facto, pode observar-se que a caldeira está montada no chassis numa plataforma mais elevada e, ainda que só seja visível um furo de drenagem junto ao suporte da consola, o facto é que existe um furo em cada canto, estando os da frente da máquina, como se pode verificar, completamente obstruídos por material carbonizado

Assim, deve ser analisada a dupla ocorrência: fuga de gasóleo em quantidade significativa e presença de uma superfície quente.

Para a fuga de gasóleo podem-se levantar duas hipóteses:

1 - Fuga do depósito por ruptura neste, o que significaria o escorrimento do gasóleo para a parte inferior do chassis e o posterior vazamento para o chão. Uma fuga importante, nestas condições, devia deixar um rasto de gasóleo ao longo do trajecto em que a máquina foi deslocada e, mesmo, no interior do veículo em que foi transportada. Não há qualquer indicação/relato de uma ocorrência deste tipo. Uma pequena fuga deveria ter um comportamento semelhante, mas menos visível (note-se que não foi detectado qualquer mancha no veículo em que, por sinal, a máquina tinha sido carregada na véspera). Em qualquer dos casos o gasóleo correria abaixo do nível a que encontra a caldeira e sempre para o chão.

2 – Fuga de gasóleo pelo tubo de ligação da bomba de combustível ao injector (interior da caldeira). Se a fuga se verificasse ao nível da bomba a situação seria semelhante à relatada acima, podendo acontecer que a fuga se verificasse no próprio tubo em si ou na ligação na entrada na parte superior da caldeira antes de atingir o injector. Repare-se que este tipo de fuga, a ocorrer, exigiria que a bomba de combustível estivesse a trabalhar ou, equivalentemente, que a máquina estivesse em uso. Dado que a máquina consome, no máximo, cerca de 2 ml de gasóleo por segundo isto significa que dispor de uma quantidade significativa de gasóleo para um incêndio de alguma dimensão exigiria (largos) minutos de operação o que não é compatível, como se verá, com a escala de tempos do que aconteceu. Acresce que quando foi possível observar a máquina acidentada se verificou, por ensaio, com ar comprimido, que não havia qualquer ruptura no tubo de alimentação de combustível e que os anéis cónicos de vedação dos dois lados deste (da bomba e do injector) estavam intactos permitindo o aperto da porca de fixação no topo da caldeira garantir a vedação.

Em resumo, nem a observação visual para o caso referido em 1, nem o ensaio, nem a escala de tempos envolvida, referida em 2, justificam a existência de uma fuga de gasóleo que pudesse dar origem a uma poça de combustível que viesse a incendiar-se gerando um “pool-fire”, mesmo de pequena dimensão.

Como atrás referido, há ainda uma questão adicional, se por qualquer razão, que não se consegue identificar, ocorresse uma situação deste tipo (quantidade significativa de combustível derramado), seria preciso uma fonte que promovesse a ignição. Ora, o sistema de ignição no interior da MLAP é completamente isolado do exterior pelo que resta a possibilidade de contacto com uma superfície quente, tipicamente acima dos 200 °C. No interior da máquina apenas a caldeira pode proporcionar temperaturas elevadas, mas, mesmo em operação, limitadas pela própria constituição da caldeira: parede interior constituída pela serpentina de aquecimento e uma (dupla) parede exterior (com câmara de ar). No topo da caldeira, onde se situa o queimador, há também uma parede dupla, sendo o combustível injectado na zona de aquecimento a partir do topo a velocidade elevada (ver figura 6).

Por outro lado, a ocorrência em si tem uma escala de tempos (segundos) que complementa a informação apresentada e que permite abandonar a teoria.

A descrição e testemunho do pessoal envolvido e os registos de entrada nas instalações da viatura que transportava a máquina de lavagem indicam o início da manhã, por volta das 9

horas. A máquina de lavagem foi retirada do carro e os dois trabalhadores da empresa de lavagem deslocaram-se à instalação da unidade industrial onde se encontravam as grelhas, removendo uma primeira série que foi carregada no porta-palettes. Dirigiram-se com este e com a MLAP para a sala de lavagem (cerca de meia centena de metros) e um deles ficou a descarregar as grelhas e a pôr em funcionamento a máquina de lavagem, enquanto outro saía para desmontar a segunda série de grelhas.

As declarações recolhidas das (poucas) pessoas presentes (no exterior), que incluíam o segundo trabalhador, é que teriam decorrido cerca de 3 minutos desde a saída deste e a enorme explosão que ocorreu, na “sala de lavagem”.

Quando entraram nas instalações depararam-se com o cenário de destruição, apresentado nas figuras, com um incêndio intenso e com o trabalhador que tinha ficado na sala a trepar os escombros da parede de entrada “muito aturdido” e profundamente queimado.

Com esta escala de tempos é evidente que seria impossível ocorrerem, em qualquer ponto da máquina, temperaturas elevadas. No limite, mesmo que a MLAP tivesse trabalhado, apenas alguns gramas (muito poucos) de combustível poderiam ter sido injectados na caldeira o que significa, face ao volume de material a aquecer (água, serpentina, paredes de caldeira) um aumento de temperatura muitíssimo reduzido, ou seja, não havia possibilidade de qualquer peça estar significativamente acima da temperatura ambiente.

Admita-se, mesmo assim, que a situação poderia (por motivos que não se conseguem identificar, por exemplo, com a cobertura fechada a quantidade de ar novo que entra para o interior da máquina é basicamente o ar de queima aspirado pelo ventilador, pois o conjunto foi desenhado para ser praticamente estanque) ter ocorrido e que se desenvolveu rapidamente um incêndio de grandes proporções associada à queima do gasóleo do reservatório. No entanto, 3 hipóteses foram analisadas [4]: derramamento muito rápido (praticamente impossível); derramamento médio (dificilmente possível); e derramamento lento, abrangendo uma área típica da ordem de grandeza da área em planta da máquina.

Consideraram-se, respectivamente, as seguintes áreas para o “pool fire” formado para cada caso: 4 m²; 1 m²; e 0,25 m² (caso com tipicamente a dimensão em planta do tabuleiro inferior da máquina). A massa de combustível (gasóleo) queimada para um incêndio deste tipo é da ordem de 0,044 kg/(m²s) e o seu poder calorífico da ordem dos 44000 kJ/kg. Admitindo uma queima com proporção de ar sensivelmente estequiométrica (geradora de muito fumo no caso do gasóleo) pode assumir-se uma razão da ordem de 15 kg_{ar}/kg_{gasoleo}. A densidade do gasóleo é da ordem de 0,87 e admitiu-se que o volume de combustível em jogo é da ordem dos 20 l (~17,5 kg). Com base nestes dados é possível construir a tabela 1.

Como se pode verificar, o volume de ar na sala de “lavagens” não permite a combustão completa dos 20 litros de gasóleo. A última linha permite considerar (portas fechadas), para o “pool-fire” de 4 m², que pouco mais de meio minuto depois o oxigénio começa a ser escasso para continuar uma combustão livre, sendo esse tempo cerca de 3 minutos e de 7 minutos para as situações de áreas 1 e 0,25 m².

Tabela 1: Características de um “pool fire” de 20 l de gasóleo na sala de “lavagens”

Área do “pool fire”(m ²)	4	1	0,25
Potência total libertada (kW)	7700	2000	500
Componente de radiação	2600	700	330
Componente convectiva	5100	1300	170
Ar necessário para queima estequiométrica(kg)	262	262	262
Tempo de combustão (se for fornecido ar) (s)	100	400	1600
Tempo para consumir oxigénio existente na sala (s)	70	300	580

Isto significa que apenas na situação do cenário mais improvável (“pool-fire” de 4 m²) seria possível, ainda que muito pouco provável (até pelo tipo de combustível), considerar a fenómeno do “back-draught” induzido pela abertura da porta. Para os outros dois casos a probabilidade de ocorrência deste fenómeno, quando se considera a escala de tempos envolvida, parece (é) nula.

4.3 Explosão – Incêndio

Não sendo possível justificar a sequência incêndio – explosão (começando, desde logo, pela ausência de qualquer fonte de ignição) resta a sequência tratada neste parágrafo.

Comece-se por lembrar que pelo menos grandes áreas das paredes da sala e a MLP eram regularmente lavadas com um solvente (tolueno?, xileno?), nas tardes de sexta feira, e recorde-se, ainda, que a sala não era ventilada. Assim, os vapores desses solventes, sendo muito mais densos (mais de 3 vezes) que o ar, tiveram mais de 12 horas para se misturarem com a camada de ar aos níveis mais baixos criando potenciais condições para a formação de uma ATmosfera EXplosiva (ATEX)

As ATEX podem ser facilmente inflamáveis e têm características explosivas apenas quando a concentração de vapores se encontra entre dois limites bem definidos [5]: o limite inferior, designado por LEL (Lower Explosive Level) e o superior por UEL (Upper Explosive Level). Concentrações abaixo do nível LEL são ditas pobres (Lean) e acima do nível UEL são ditas ricas (Rich); em qualquer destas zonas o risco de explosão não existe. Os valores de LEL e UEL dependem do vapor/gás presente e são, em regra, apresentados, por produto, em tabelas.

Para o xileno e para o tolueno os valores são em % (1,1; 7) e para o xileno (3;7), o que significa que, com o valor de cerca de 1,2 l (líquido), é possível formar com qualquer deles uma ATEX numa camada junto ao chão (sobre toda a superfície da sala) com 1 m de espessura. Na realidade, os valores de líquido utilizado são proporcionais à altura da camada. A altura da camada ATEX devia ser baixa, pois, o operário que estava no exterior não referiu ter sentido qualquer cheiro, quando esteve na sala.

Recorde-se, agora, o processo de arranque da máquina descrito no §4.1 e o procedimento que terá sido seguido pelo trabalhador (experiente no seu uso): ligou a máquina à corrente e seguiu os procedimentos até ao ponto 4 (verificar o sentido de rotação do motor eléctrico) carregando no gatilho e desencadeando todas as operações automáticas. O ventilador aspirou ar ao nível

do chão (o tempo de renovação de ar na caldeira é da ordem (inferior a) de meio segundo). Mesmo não havendo injeção de gasóleo o dispositivo de ignição liga-se (ver nº8 do §4.1).

Se a mistura de ar com o vapor do solvente reunir condições de flamabilidade estão encontradas as razões da explosão. Chama-se mais uma vez a atenção para o facto desse nível de concentração não precisar de se estender a todo o espaço, basta existir nas camadas mais baixas. A escala de tempos para este processo é da ordem de 1 s.

5. CONCLUSÕES

Os resultados expressos ao longo do texto apontam, de forma inequívoca para que a sucessão de fenómenos no acidente tenha sido explosão – incêndio.

De facto, não se conseguiu identificar uma quantidade de combustível presente e uma fonte de ignição que levassem a um incêndio de dimensões suficientes para se poder tornar perigoso e dar origem ao fenómeno de “back draught”, sequência incêndio - explosão. A isto há que adicionar ser praticamente impossível que o fenómeno pudesse ter ocorrido sem que o operador da máquina disso tivesse tido qualquer percepção.

Em contrapartida, é credível e tecnicamente fundamentado construir uma justificação para a sequência explosão – incêndio que encaixe nos ferimentos sofridos pelo operador parte do corpo virada para a máquina - na destruição verificada após o acidente e na escala de tempos em que tudo decorreu. Complementarmente foi verificado que as pressões geradas pelo eventual “back-draught” (valores máximos da ordem dos 0,5 kPa) não seriam suficientemente elevadas para justificar os danos nas paredes e estrutura (pelo menos da ordem dos 2 kPa).

É claro que a máquina de lavar de alta pressão esteve na origem do que se passou, até por que era a única fonte de ignição presente na sala. O início da sua operação é a única forma de justificar a escala de tempos e o grau de destruição provocado pela explosão.

6. AGRADECIMENTOS

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FIRE FORENSICS AIDED BY COMPUTATIONAL TOOLS



**Rodrigo Almeida
Freitas ***

PhD student
UC - Portugal



**João Paulo C.
Rodrigues**

Professor
UC – Portugal, UFMG-
Brazil

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1. INTRODUCTION

Fire investigation is an inherently complex forensic discipline, frequently conducted in environments where critical evidence has been damaged, altered, or permanently destroyed by the fire itself. Consequently, investigators often rely on indirect information, reconstructed data, and technical examinations to support hypothesis development and verification.

In recent decades, advances in fire science, computational power, and numerical modeling have created new opportunities to analyze fire development, smoke movement, and human behavior during emergency situations. Within this technological and scientific evolution, computational fire simulation has emerged as a potentially valuable complementary tool to assist investigative processes, particularly in highly complex incidents.

Laboratory examinations and technical tests are traditionally employed to gather data and support hypothesis testing in fire investigation. Computational fluid dynamics (CFD), applied through fire simulation software, has progressively been used as one of these specialized investigative examinations. Visually compelling simulation results (such as animated smoke movement, thermal stratification, and gas flow visualization) can create the impression of precise fire “reconstruction.” However, as in any laboratory examination, the scientific reliability of simulations depends on methodological rigor, transparency of assumptions, and consistency between model outputs and the physical evidence of the incident under analysis.

Certainly, when viewing images of a fire simulated computationally, one may be captivated by the visual representations displayed on the screen. The movement of smoke and heat flow can even be rewound, effectively reversing the fire in time and generating striking illustrations. However, as

* Autor correspondente – Universidade de Coimbra, Departamento de Engenharia Civil, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal e-mail: rodrigo.almeida.freitas@gmail.com

with any laboratory examination, it is common to question the methodology applied and the validity of the results in relation to the case under analysis.

Within fire investigation, computational fluid dynamics must be framed as a hypothesis-support and scenario-evaluation tool rather than as a mechanism for determining cause or reconstructing an event in reverse. CFD simulations can assess whether defined fire scenarios are thermodynamically and physically consistent with documented evidence, allowing structured comparison of alternative conditions and testing of investigative hypotheses. However, conclusions derived from such models remain conditional upon stated assumptions, input data quality, and boundary definitions, and must always be interpreted in conjunction with physical evidence and other forensic examinations.

Several references^{[1],[2]} recognize computational simulation as a legitimate investigative examination tool. At the same time, the literature highlights important limitations that must be acknowledged if simulation outputs are to be interpreted correctly within a forensic context. These limitations concern, for example, uncertainties associated with input data; dependence on user expertise; simplifications inherent to numerical models; discrepancies between simulated outputs and real-scale fire performance; model validation constraints; and potential misinterpretation of visually persuasive, yet technically uncertain, results. Therefore, computational simulation should not be treated as unquestionable truth or as a standalone investigative solution. Rather, it should be used cautiously, critically, and within the framework of the scientific method of fire investigation.

It is important to remember that fire investigation always deals with limited or permanently lost information due to the fire itself. Therefore, every effort must be made to gather as much data and evidence as possible to support the investigation. The use of computational simulation is thus a reasonable opportunity to enhance fire investigations and should not be disregarded. On the other hand, its use must be deliberate and grounded in the Scientific Methodology to Fire Investigation.

Within this context, this article examines the role of computational fire simulation as a specialized analytical tool to support fire investigations. More specifically, the objectives of this work are: (i) to conceptually position computational simulation as a complementary investigative resource rather than a substitute for traditional methods; (ii) to establish methodological premises necessary for its responsible and scientifically grounded application; and (iii) to propose best-practice guidelines to support its systematic, transparent, and technically defensible use in investigation procedures.

Initially, a robust literature review on computational fire simulation was conducted. Subsequently, a theoretical framework addressing fire investigation was sought. Thus, the theoretical foundation of this article establishes a correlation between fire investigation and computational fire simulation. Next, reports and investigations of significant fire incidents involving computational fire simulations were reviewed.

The purpose of presenting these fire investigations is to build a practical framework for the use of computational simulations in fire investigations. The simulations discussed in this study begin with computational fire simulations spatially limited to the area of origin. Finally, more robust and complex simulations are presented, involving fire propagation and development.

Following this, the study presents, in the discussion section, proposed scopes, recommendations, possibilities, and best practices for the use of computational simulation in fire investigation. This work approaches computational simulation as a laboratory examination, as one procedure among

many within fire investigation, and as one stage among several in the investigative process. Finally, conclusions and suggestions for future research are provided. Given the advancement of CFD technology, its application in fire investigation will be further discussed in the following sections.

2. LITERATURE REVIEW

2.1 Computational Fire Analysis

Cox and Kumar^[4] state that as early as 1920 there were demonstrations of the equations governing fluid flow using numerical methods. However, it was only from the 1970s onward that computational fluid dynamics (CFD) analysis began to be used as a tool to study gas movement, especially related to combustion. Olenick and Carpenter^[5] observe that currently there is an increasing use of CFD due to the development of fire knowledge databases and the better availability of more sophisticated computers.^[5]

These same authors argue that the use of CFD fosters the development of performance-based codes rather than merely prescriptive fire safety codes. Yuen et al.^[6] state that computational fire simulation has become an important tool for fire reconstruction. Hypothetical models can be executed including fire suppression systems to assess their impact on the fire scene^[6].

Model validation and verification are only one stage of model evaluation. NFPA 921^[1] suggests that computational fire dynamics analyses can be classified into three categories: specialized fire dynamics analyses, zone models, and field models. Olenick and Carpenter^[5] prefer to categorize them as: zone models, field models, detector (or device) response, structural fire resistance, evacuation, and miscellaneous (mixed). Each model presents a degree of complexity and processing demand.

Furthermore, Cox and Kumar^[4] state that there are some essential components in the process of using a CFD program. First, the primary concern is a correct understanding of thermodynamic principles. That is, the user must understand the principles governing combustion and fluid dynamics, for example. Novice users may commit common errors such as insufficient openings or ventilation for ignition or combustion maintenance, use of inadequate combustion models, unrealistic combustion models (high temperatures, large flame lengths, extremely rapid propagation), among other unexpected behaviors.

2.2 Case Studies of using Fire Simulations in Fire Investigations

In each of the following case studies, the objective of the CFD modeling was explicitly bounded by defined investigative questions. The simulations were not conducted to determine ignition source or establish causation independently, but rather to evaluate fire dynamics, tenability conditions, time-dependent development, or scenario plausibility under documented assumptions. This distinction is essential to properly interpret the conclusions that can legitimately be drawn from the computational analyses presented.

2.2.1 Fire at The Station Nightclub, West Warwick, US

A fire investigation conducted by the National Institute of Standards and Technology (NIST) used various tests to analyze the fire that occurred at The Station nightclub in West Warwick, Rhode

Island, US, on February 20th, 2003. This tragic incident resulted in the deaths of 100 people and over 200 injuries [7],[8]. The fire began during the opening of a rock concert, when pyrotechnic devices ignited polyurethane foam insulation located on the walls and ceiling of the venue.

In the NIST investigation of the Station Nightclub fire, the objective of the CFD simulations was not to determine the origin or ignition mechanism of the fire. Rather, the modeling effort was undertaken to reconstruct the general fire and smoke development under documented conditions, evaluate tenability and available safe egress time, and compare the as-built configuration with counterfactual scenarios, including the presence of automatic sprinkler protection. The simulations were therefore designed to assess the plausibility and temporal progression of fire dynamics and occupant exposure, not to establish causation independently.

Despite the availability of video footage capturing much of the event before, during, and after ignition, the investigation remained crucial to understanding the incident in greater detail. Although the absence of automatic sprinkler systems was already known to be a contributing factor, investigators sought to determine how a fire in a single-story structure could result in such a high death toll.

NIST team had limited access to the fire scene, witnesses, and local authorities due to an ongoing criminal investigation. Furthermore, no physical evidence from the fire scene was collected, and NIST was denied access to any physical samples from the site. Nevertheless, sufficient photographic and video material was available to support the investigation.



Figure 1: Location of polyurethane foam [7.]

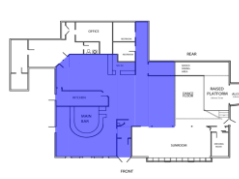


Figure 2: Location of mineral fiber acoustic tiles [7.]



Figure 3: Location of wood paneling [7.]



Figure 4: Location of carpet flooring [7.]

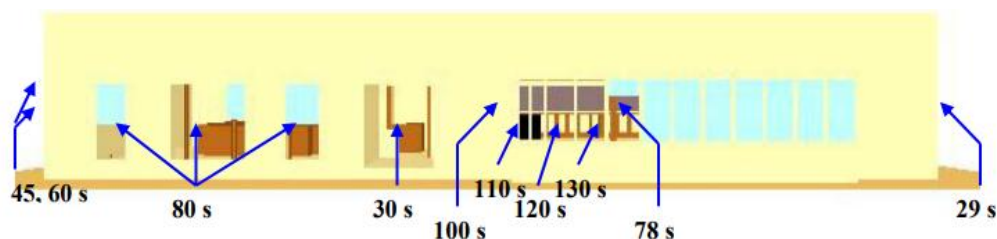


Figure 5: Timeline of door and window openings [11]

The finishing and lining materials (see Figure 1 to Figure 4) appeared to lack any form of fire-retardant treatment[7],[8]. Although the venue had portable fire extinguishers, it was not equipped with an automatic sprinkler system. The fire alarm was activated 41 seconds after the ignition. All

opening events (doors and windows) were mapped during the investigation, as shown in Figure 5.

NIST investigation concluded that simulation, “when appropriately applied, proved to be a valuable tool for supporting critical detail reconstruction of the fire incident and for demonstrating the effectiveness of alternative building designs and fire safety measures^[7.]” While the results showed strong visual similarity between real and simulated fires, there were also some discrepancies and limitations, as highlighted in Figure 6 and Figure 7.

This investigation employed the Fire Dynamics Simulator (FDS) to reproduce the fire development, smoke movement, thermal conditions, and tenability during The Station nightclub fire. The simulations were informed by extensive physical testing, including cone calorimeter experiments, full-scale mock-ups of the platform area, and characterization of polyurethane foam behavior under ignition, flame spread, and heat release conditions. The computational model assumed the ignition source to be the pyrotechnic devices directed toward non-fire-retarded polyurethane foam, incorporated material properties derived from laboratory testing, reproduced the nightclub geometry, and considered ventilation, fuel load, and boundary conditions representative of the actual incident.

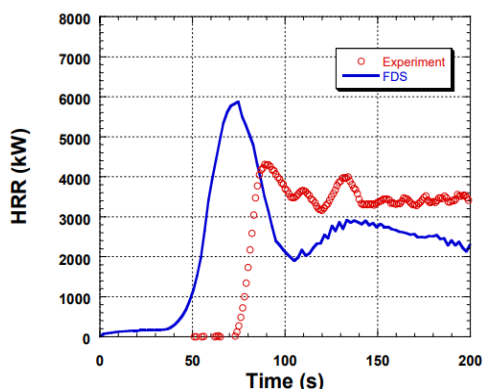


Figure 6: Comparison of heat release rate between real and simulated fires^[7.]

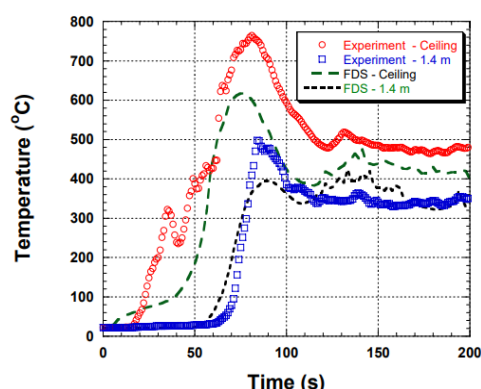


Figure 7: Temperature comparison between real and simulated fires (non-sprinklered scenario)^[7.]

Simulations were conducted both for the incident as it occurred and for alternative scenarios, including sprinklered configurations, enabling comparison of outcomes and assessment of life safety measures. Despite producing strong correspondence between predicted and observed phenomena, NIST acknowledged important limitations: lack of access to original physical evidence restricted direct validation of some material properties; uncertainties remained regarding local geometry alterations caused by renovations; and inherent uncertainties exist in CFD prediction of complex flame spread, smoke toxicity, and human behavior–coupled evacuation processes. Nevertheless, within these constraints, the investigation concluded that, when rigorously applied, the simulations were technically robust and highly valuable for reconstructing critical incident dynamics and evaluating alternative fire safety strategies

2.2.2 Grenfell Tower Fire, London, UK

Another major fire investigation that employed computational simulations was the Grenfell Tower fire, which broke out in the early hours of June 14th, 2017, in London, England. The incident resulted in 72 fatalities and was characterized by an exceptional rapid vertical and horizontal fire spread^[9]. Following the ignition of a refrigerator on the fourth floor, the building's aluminum composite material (ACM) façade served as the primary path for vertical flame propagation. A vast archive of images and videos documented the fire's spread.

Due to the fire's severity and devastating consequences, various individuals and organizations sought to better understand the causes and contributing factors. In particular, researchers such as Guillaume, Dréan, Girardin, Koohkan, and Fateh (among others)^{[9],[10],[11],[12]} investigated the incident to clarify events, mechanisms, and failures associated with the fire.

The investigation proceeded to conduct a computational simulation^[10] to assess how the kitchen fire spread to the façade through a window opening, how it propagated along the façade, and how it eventually reentered other apartments through additional windows. To support this simulation, data were collected on façade composition, spatial arrangement, construction layer thicknesses, and the physical and chemical properties of each material. The simulation modeled the building from the fourth to the twenty-third floor.

The simulation assumed that the fire originated in the kitchen's refrigerator. Two scenarios were tested: one involving a small refrigerator (with both limited and ample ventilation) and another involving a full-sized refrigerator (with ample ventilation only). For each hypothetical scenario, a heat release rate curve was generated over time. These curves were then aligned with actual fire development events and image evidence, with particular attention to the moment of window failure, as shown in Figure 8. All scenarios indicated that façade ignition occurred approximately 18 to 20 minutes after the initial fire outbreak.

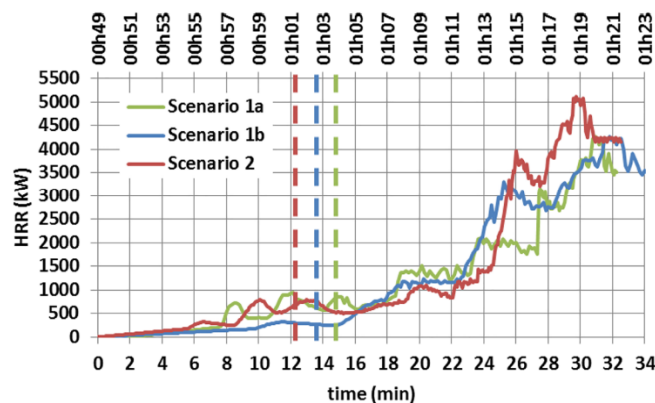


Figure 8: Estimated heat release rate for each hypothetical scenario^[10]

Based on the simulation^[10], the researchers concluded that regardless of the ignition source or degree of ventilation, sufficient thermal energy was present to ignite the PVC window frame,

trigger fire spread to the extractor panel at the window, and cause structural window failure. Even though the kitchen fire was extinguished at 1:20:48 AM, the fire had already reached the façade by that time. Furthermore, the simulation revealed that flashover did not occur in the kitchen, which was confirmed by the absence of flashover indicators in the actual post-fire scene.

Key variables (such as time, heat flux, and temperature) were prioritized in numerical analyses. Rather than focusing on isolated data points, the researchers relied on continuous data profiles to evaluate fire behavior across scenarios. In each test, only one component was replaced at a time to isolate the influence of each material on fire propagation.

2.2.3. Kiss Nightclub Fire, Santa Maria, Brazil

A computational case study was developed based on the Kiss Nightclub fire in Santa Maria, Brazil, one of the deadliest fire incidents in national history. The aim was not to reproduce or explain the real fire in full, but to explore how computational tools can technically support fire investigation by illustrating fire development, smoke transport, human evacuation behavior, and the effects of specific architectural and regulatory conditions. The architectural geometry of the nightclub was reconstructed, and Fire Dynamics Simulator (FDS), in conjunction with PyroSim, was used to model smoke movement, while Pathfinder was employed to simulate evacuation. The model incorporated real architectural data, documented fire load characteristics, laboratory test results for polyurethane foam, available video evidence, and observed fire scene conditions, allowing reasonable qualitative alignment between simulated smoke spread and real visual records.

Table 1: Time of the evacuation simulations of hypothetical scenarios

Scenarios based on maximum capacity		Complete evacuation time (seconds)					
		Comparison of the evacuation time of the hypothetical scenario with the real scenario (%)					
		1) actual conditions	Only one violation was changed, while the others were maintained				6) No guardrails, adequate width and 3 discharges
			2) no guardrails and handrails	3) adequate width	4) two discharges	5) three discharges	
A	741	400.5 sec. 100%	300.0 sec. 74.91%	295.8 sec. 73.85%	325.0 sec. 81.15%	259.5 sec. 64.74%	172.5 sec. 43.07%
B	878	480.3 sec. 100%	417.3 sec. 86.88%	353.8 sec. 73.66%	386.0 sec. 80.37%	315.8 sec. 65.75%	252.3 sec. 52.53%

The simulations allowed visualization of smoke transport pathways within the nightclub, identification of early smoke accumulation zones, and assessment of how smoke rapidly compromised the principal evacuation routes. When integrated with egress modeling, the simulations provided evidence of occupant flow obstruction, critical crowding conditions, reduced movement speed, and prolonged exposure to toxic combustion products. Scenario-based simulations offered further value by allowing “what-if” analyses, including the influence of

overcrowding and exit violations, showing significant increases in evacuation time when compared with legally permitted capacity and meaningful reductions when hypothetical corrective measures were tested. The results are presented in Table 1.

It is essential to emphasize the nature of the computational simulations carried out in this study. The visual representation of fire and evacuation is not the most critical element. The core purpose of the simulations was to test hypothetical scenarios by asking questions such as: What if there were fewer or no guardrails and queue organizers, would evacuation become easier? In this case, the simulation indicates a reduction in evacuation time ranging from 13% to 25% (Scenarios 2A and 2B in Table 1). Ultimately, correcting as many violations as possible is best (Scenario 6A).

However, the simulations also carry intrinsic limitations, which were explicitly acknowledged. Results are dependent on the accuracy and completeness of input data, including material properties, heat release rates, geometry detail, and opening conditions. Numerical outputs represent approximations rather than absolute values, and the visual plausibility of results does not eliminate inherent uncertainties related to combustion behavior, human decision-making, and coupled fire–evacuation dynamics.

Time in computational environments does not necessarily correspond to real evacuation time, and modeling choices such as mesh resolution, simplifications, and boundary conditions influence results. Therefore, the simulations are best interpreted as structured technical examinations to support hypothesis exploration, scenario comparison, and qualitative understanding, rather than definitive reconstructions of the incident.

In this sense, the Kiss Nightclub case reinforces the methodological premise of this article: when rigorously planned, documented, and critically interpreted, computational simulation can serve as a valuable complementary investigation tool, capable of contributing structured insight while remaining clearly bounded by its technical constraints.

2.2.4 Prison Fire – Timeline Reconstruction Through Smoke Modeling

Another example of a clearly bounded forensic application of computational fluid dynamics is presented by Jahn et al.[13.], who analyzed the December 8, 2010 fire at the San Miguel prison in Santiago, Chile, where 81 inmates died. The available evidence, including witness testimony, indicated that the fire was intentionally initiated during a confrontation between inmate groups when a burning mattress was thrown onto a bunk bed inside a cell. Although the ignition circumstances were relatively well understood, the key forensic question concerned the temporal development of the fire and whether prison guards had sufficient time to intervene. The public defender's office therefore requested an independent technical investigation to estimate the probable timeline of the fire and to evaluate the thermal conditions affecting the padlocks of the cell doors during the early fire stage.

To address these questions, CFD simulations were used to analyze smoke propagation within the prison building and to compare predicted smoke movement with CCTV recordings from locations distant from the fire origin. By matching the simulated smoke arrival times with the first appearance of smoke visible in the video recordings, the investigators were able to reconstruct a

plausible sequence of events. Additional simulations evaluated the temperature evolution of the padlocks exposed to hot gases from the developing fire. The results indicated that the fire developed rapidly and that the padlocks would have reached temperatures that prevented manual handling without protection by the time guards arrived at the cells. In this case, CFD was not employed to determine ignition cause but to support a time-sequence reconstruction based on observable smoke movement and thermal exposure under defined assumptions

3. DISCUSSION

Accordingly, conclusions supported by CFD in forensic fire analysis should be limited to consistency-based inferences. Computational models can demonstrate whether a defined scenario reproduces observed patterns of smoke movement, thermal development, or evacuation performance within declared assumptions. They are most defensible when applied to comparative or counterfactual questions, and least appropriate when used to assert ignition origin or causation without independent evidentiary support.

Following the theoretical foundation and the presentation of selected examples of computational simulations applied to fire investigations, it is possible to identify several strategies and advantages associated with the use of fire modeling. This section aims to highlight specific opportunities offered by computational simulation in the context of fire investigation. In addition, it outlines anticipated limitations inherent to this method. The points discussed here are intended to establish a set of best practices for conducting computational simulation as part of fire investigative procedures.

Simulation is Only One Component of a Fire Investigation; computational modeling supports but does not replace a complete investigative process and must be used alongside scene examination, laboratory testing, witness analysis, and other forensic procedures. **Establishing Context for Computational Simulation** is essential, as every model must be grounded in a clearly defined investigative framework, whether focused on thermodynamic behavior, structural response, smoke movement, or evacuation dynamics, since context determines both the relevance and interpretability of numerical results.

Defining the Scope requires explicit objectives and hypotheses, because simulation outputs are meaningful only within the boundaries of the questions posed and cannot be generalized beyond those defined investigative limits. **Availability of Specialized Personnel and Resources** is a prerequisite for reliability, as high-quality modeling depends on qualified operators, multidisciplinary expertise, and adequate computational infrastructure capable of handling complex numerical calculations. **Knowledge of Thermodynamic Principles in Fire Modeling** is fundamental, given that errors in combustion modeling, boundary conditions, unit consistency, or thermal property inputs can invalidate an entire simulation.

Software Selection must align with the investigative objective, recognizing that tools such as CFAST, FDS, PyroSim, and Pathfinder offer distinct capabilities for zone modeling, detailed CFD analysis, smoke transport, structural exposure, and evacuation assessment. **Understanding Software Functionality, Limits, and Simplifications** is equally critical, since all computational tools rely on approximations and assumptions that require careful interpretation, mesh refinement strategies, and awareness of model constraints to avoid distortion of results.

Rigorous Evaluation and Documentation of the Fire Scene forms the empirical foundation of credible modeling, as accurate representation of geometry, ventilation conditions, fuel load, and event chronology directly affects model validity. **Obtaining Reliable Material Data for Fire Load Representation** is often challenging, because properties such as heat release rate, ignition temperature, thermal conductivity, density, and specific heat may require laboratory testing, and the use of non-representative data introduces significant uncertainty.

Establishing and Comparing Scenarios enables investigators to assess multiple plausible configurations and determine which most consistently aligns with observed fire behavior, thereby supporting hypothesis screening and reconstruction of missing information. **Substitution Modeling** permits systematic evaluation of specific variables, such as alternative materials, door states, or egress configurations, to understand their influence on fire development and occupant exposure. **Changing One Variable at a Time** strengthens interpretive clarity by minimizing confounding effects and allowing clearer identification of causal influence before exploring multi-variable or optimized scenarios. Finally, **Rigorous Documentation of Post-Simulation Processes** is indispensable, as full disclosure of assumptions, input data, uncertainties, and outputs ensures reproducibility, peer review scrutiny, and forensic credibility.

The discussion presented in this section is necessarily limited in scope, offering only a concise outline of thirteen methodological elements that can guide the use of computational simulation in fire investigations. Each of these items (ranging from establishing context and defining scope to scenario modeling, material data acquisition, and post-simulation documentation) could be expanded into a distinct methodological chapter or even developed as standalone investigative protocols. In their current form, these steps function as an introductory pathway, illustrating the breadth of considerations involved when integrating CFD and related tools into investigation practice.

Taken together, the thirteen topics point toward the potential development of a structured checklist for practitioners, supporting consistent and transparent use of simulation in fire investigations. However, as summarized here, they represent only a preliminary distillation of broader technical demands. A more detailed treatment would necessarily deepen the thermodynamic, computational, procedural, and forensic principles underlying each step. This synthesized discussion therefore serves primarily to highlight opportunities, limitations, and conceptual foundations for the constructive and scientifically grounded application of computational simulation within fire investigation procedures.

Computational simulations in fire investigation present undeniable analytical value, but they also carry inherent limitations and disadvantages that must be explicitly acknowledged, especially when their outputs are used within a forensic context. Fundamentally, numerical models operate under simplifications and approximations of highly complex thermochemical and fluid-dynamic processes. Their reliability is directly conditioned by the availability and quality of input data (geometric definition, material properties, heat release rate, ventilation conditions, opening chronology) and many of these variables are frequently unknown, partially documented, or permanently lost in real fire scenes.

Even when laboratory data exist, uncertainties persist, and deviations between simulated and real-scale fire behavior are not only possible but expected, as demonstrated in benchmark studies

that have reported relevant differences in temperature fields, heat fluxes, extinction times, and smoke movement when compared with real tests. Thus, although visually persuasive and technically sophisticated, CFD outputs remain approximations, not factual reproductions of reality.

There are also methodological and operational constraints intrinsic to computational modeling. Models are highly sensitive to user choices, including mesh resolution, boundary conditions, combustion models, and scenario definition. Small configuration errors may cascade into significant distortions in predicted results. Many platforms are not universally valid across all fire stages (for example, reduced robustness in fully developed post-flashover regimes or complex multi-compartment configurations).

In practice, simulations demand multidisciplinary expertise, high computational resources, extensive documentation, and disciplined adherence to verification and validation procedures, requirements that are not always feasible in investigative environments, especially when time, data, or resources are constrained. Moreover, the apparent realism of graphical outputs may generate cognitive bias, encouraging overconfidence in results that should, in fact, be interpreted cautiously.

Finally, there are forensic and interpretive disadvantages. Numerical simulations cannot “reverse” a fire to determine origin or causation; they cannot replace physical evidence; and they must never function as standalone proof. Time in simulation environments does not necessarily correspond to real chronological fire time, absolute values derived from models are inherently uncertain, and results are meaningful only within the strict context of the assumptions adopted.

4. CONCLUSIONS

This study demonstrates that computational simulation is a valuable but supplementary tool within fire investigations. Fire modeling can support hypothesis testing, scenario reconstruction, and descriptive analysis of fire dynamics; however, it cannot replace comprehensive investigative procedures. Its reliability depends on well-defined context and scope, qualified personnel, appropriate software selection, accurate material and scene data, and rigorous validation.

The review identifies best practices for applying simulations in investigation contexts, emphasizing: establishing clear objectives and hypotheses; understanding thermodynamic principles and software limitations; documenting the fire scene with precision; acquiring representative fire-load properties; defining and comparing scenarios; adjusting one variable at a time; validating outputs when possible; and interpreting results descriptively rather than relying on absolute numerical values.

Advancing the role of CFD in fire investigation depends on strengthening investigative methodologies, improving validation mechanisms, and expanding collaborative, multidisciplinary modeling teams. Even so, computational simulations may still yield inconclusive results. Therefore, simulation outputs must always be integrated with other examinations and interpreted within a structured investigative framework. When applied responsibly, CFD enhances the reconstruction of fire dynamics and supports scientifically grounded conclusions about fire origin, development, and contributing factors.

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Session 4

Sesión 4

Sessão 4

A simple evacuation model for confined spaces

Arturo Cuesta*

Researcher
UC - Santander
España

Pablo Saez

Researcher
UC - Santander
España

Javier González-Villa

Profesor
UC - Santander
España

Daniel Alvear

Researcher
UC - Santander
España

Keywords: Evacuation modelling; Confined spaces; Stochastic; Validation

ABSTRACT

This study introduces the Confined Spaces Evacuation Tool (CSET), a simplified model designed to estimate evacuation times from confined spaces and vessels in dockyards. The model was validated against Pathfinder simulations and empirical data from an evacuation drill conducted in a void tank, as well as a full-scale evacuation drill on a Ro-Pax ferry. The results show good agreement between simulations and observations, indicating that CSET can deliver fast and realistic estimates suitable for early-stage safety planning onboard.

1. INTRODUCTION

Confined spaces are fully or partially enclosed areas with limited entry or exit, not intended for continuous occupancy, and often associated with significant safety hazards [1,2]. In shipbuilding and ship repair, such spaces—including cargo holds, storage tanks, and engine rooms—are common locations where hot work activities, such as welding and oxygen cutting, are frequently performed, increasing the risk of fire and smoke spread. Evacuation from such spaces is particularly challenging due to the complex and dynamic environment. First, ongoing repair activities create changing layouts, temporary structures, and limited evacuation routes. Second, critical ship systems may be partially out of service, exposing workers to unexpected and unfamiliar conditions. Third, high noise levels, hearing protection, and language barriers can reduce the effectiveness of warnings, while workers may delay evacuation to secure hazardous operations, further increasing risks. Together, these factors strongly influence evacuation feasibility, timing, and overall life safety. To address these challenges, authorities, employers, and shipowners rely on prescriptive regulations, procedural measures, and static plans [3–5]. However, the dynamic nature of dockyard operations highlights the need for flexible approaches and tools that can support safety planning of operation activities in dockyards.

Evacuation modelling and simulation, widely used to assess safety in buildings, industrial facilities, and transportation systems, can also enhance safety in such new, complex working environments [6]. Previous research focused on building construction sites, which share characteristics with vessels in dockyards, using evacuation and fire models to estimate safe escape times [7], adapting an existing evacuation model to represent temporary structures and surface conditions with empirical validation [8], or proposing conceptual agent-based frameworks [9]. One study has addressed vessel evacuations in dockyards, suggesting that agent-based models can reasonably predict worker evacuation performance [10].

Despite the widespread use of evacuation modelling, its application to confined spaces on shipyard vessels remains limited. Current evacuation models are not designed to represent scenario-specific features (e.g. manholes, scaffolds, cat ladders), are computationally intensive and cannot operate near real-time, and require expert users to manage complex and dynamic operational conditions. As a result, there is a lack of practical, validated tools capable of providing rapid, reliable assessments of evacuation performance in these unique environments.

The purpose of this paper is to address this gap by introducing the Confined Spaces Evacuation Tool (CSET), a simplified yet robust simulation model tailored to the specific characteristics of these enclosures. CSET combines stochastic variability, empirical validation, and rapid computation to provide practical, preliminary assessments of evacuation scenarios, supporting safety planning in shipbuilding and repair operations without the high complexity and resource demands of traditional agent-based models.

2. METHOD

2.1. Model overview

The Confined Spaces Evacuation Tool (CSET) addresses the problem of worker evacuation from confined spaces aboard vessels in dockyards. The model is designed to (i) perform multiple stochastic simulations, (ii) explicitly account for variability in human behaviour through randomised behavioural parameters, and (iii) predict total evacuation times under different operational scenarios. In CSET, the evacuation time associated with each available exit (e.g., ladder, stair, hatch, manhole, or door) is computed as the 95th percentile of the simulated evacuation time distribution and is expressed as:

$$t_{evac_{door}} = P_{0.95} \left[\min_i(t_{pre_i})_{door} + \frac{d_{door}}{\max_i(v_i)_{door}} + \frac{n_{door}}{w_{door} * f_{door}} \right]_j \quad (1)$$

Where:

i	=	i -th worker (occupant)
j	=	j -th exit
t_{pre_i}	=	pre-evacuation time of each worker (s)
d_{door}	=	travel distance (usually from the farthest point or midpoint to the exit)
v_i	=	walking speed of each worker (m/s)
n_{door}	=	percentage of workers per exit (%)
w_{door}	=	width of the exit (m)
f_{door}	=	flow rate of people through each exit (person/s·m width)

CSET version 1.0 enabled the simulation of individual, user-defined confined spaces, providing stochastic, near real-time evacuation time predictions based on individual worker characteristics, along with graphical outputs. The general input data for the model include the number of workers, the number of exits and the width of each exit, the evacuation travel distance, the percentage of workers assigned to each exit, the number of simulations conducted for the same scenario, the pre-evacuation time, the walking speed, and the specific flow through the exits. Version 2.0 extended its capability by introducing a full-vessel, graph-based representation of compartments and transit zones (Figure 1), allowing simulation of complete ship evacuations. Optimal evacuation routes are computed using Dijkstra's algorithm, incorporating distance, flow capacity, occupancy, and safety constraints.

Parameterisation of human behaviour is supported by a database of empirical data derived from previous shipboard data collection in normal conditions and evacuation drills, which informs the assignment of pre-evacuation times, horizontal walking speeds, ascending and descending walking speeds through different evacuation means (i.e. stairs, ladders scaffolds), and flow rates for typical onboard evacuation means (i.e. cat ladder, stair, hatch, manhole, or door) reported in [10]. The graphical user interface enables visualization of evacuation times at both global and compartment levels and supports the exploration of hypothetical occupancy scenarios through a colour-coded risk representation (Figure 1).

The software was migrated from C# to a Python/Kivy framework, enabling cross-platform deployment on Windows and Android devices. This migration supports dynamic loading of deck plans, portable project files, and real-time adaptability to changes in occupancy or vessel configuration. Functional validation confirmed accurate project reconstruction and consistent simulation performance across platforms, supporting practical onboard application without reliance on office-based systems.

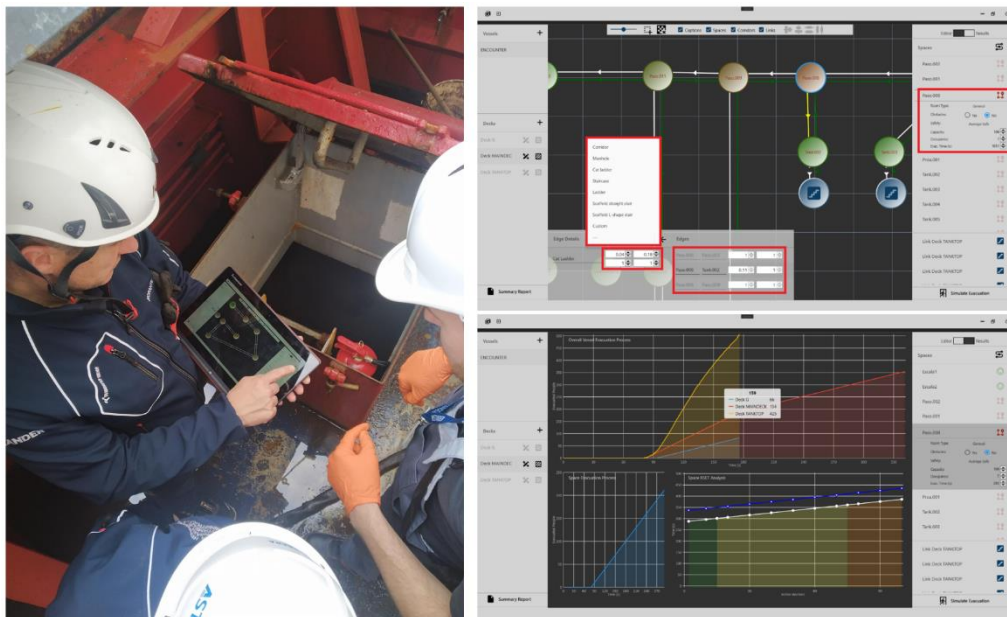


Figure 1: Graphical user interface of CSET version 2.0.

2.2. Validation procedure

Empirical validation is essential to assess the reliability of the CSET model. Three validation exercises were performed: (i) comparison with the Pathfinder model under varying occupancy levels in an engine room, (ii) comparison with observed evacuation data from a confined space (void tank), and (iii) comparison with an evacuation drill on a Ro-Pax ferry in dry dock involving workers in the casing/tank, pump room, and engine rooms.

Comparison with Pathfinder.- The CSET was first validated through a comparative analysis with Pathfinder, an agent-based evacuation model developed by Thunderhead Engineering. For the comparison, the engine room of a passenger ship was selected as a representative confined space. Four evacuation scenarios were defined by varying the number of workers present in the engine room (50, 100, 150, and 200 workers). Identical input parameters were implemented in both models, including the exit flow capacity through the engine room staircase (0.88 p/m/s), based on [1], and horizontal walking speeds ranging from 0.56 m/s to 1.19 m/s, based on [10]. Pre-evacuation times were not considered here in order to check the effects of movement dynamics and exit flow on evacuation performance, and to ensure a direct and consistent comparison between both models without introducing additional behavioural variability. One hundred runs were performed for each scenario using both models. Mean evacuation times were compared and relative errors were calculated.

Evacuation of a confined space.- The second validation exercise used empirical data from a partial evacuation drill conducted in a tank adjacent to a ship's engine room in a dockyard. The evacuation involved workers exiting the tank through a manhole accessed via scaffolding. Data were collected using three mini-cameras installed inside the tank to record worker response (Fig. 4). The cameras were installed during a scheduled break to ensure that workers were unaware of the drill. Once all 18 workers were inside the tank, a firefighter initiated the evacuation using a verbal warning and a whistle. The observed evacuation time required for all workers to exit the tank was 8 min 44 s. One hundred CSET simulations were performed reproducing the observed geometry, occupancy, and exit capacity, and the resulting evacuation time distribution was compared with the observed evacuation time.

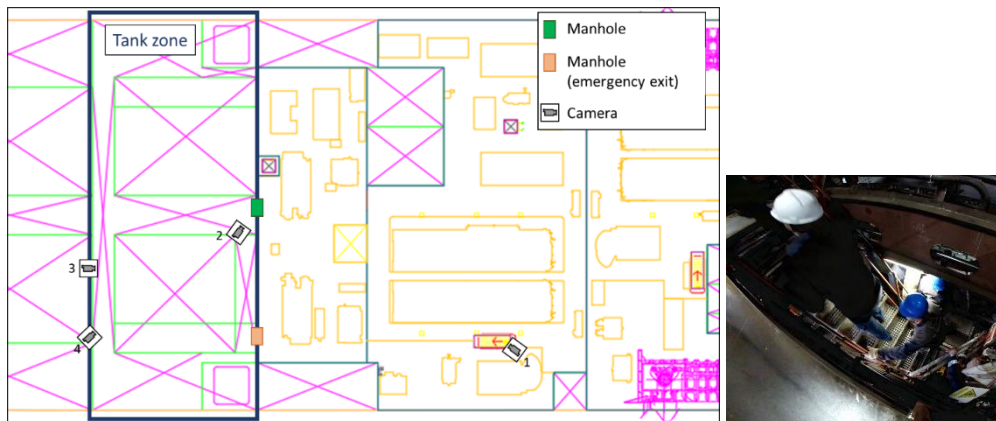


Figure 2: Tank layout, cameras location and evacuation via the engine room staircase.

Evacuation of a vessel in a dockyard.- The third validation exercise was based on empirical data collected during an unannounced evacuation drill conducted on a Ro-Pax ferry in dry dock (Figure 3). A detailed description of the drill and the associated empirical dataset is provided elsewhere [10]. The vessel was equipped with two starboard gangways: D3 (deck 3, forward) and D5 (deck 5, aft).

Evacuation was monitored using eleven cameras, which recorded worker presentation times in confined spaces and arrival times at the gangways. Arrival time was defined as the video frame in which a worker's trailing leg left the gangway, enabling the generation of the evacuation curves. A total of 41 workers evacuated via gangway D5, with initial locations in the casing/tank areas on decks 7 and 8 ($n = 20$) and the adjacent stern areas spanning decks 6 to 10 ($n = 21$). Gangway D3 was used by 109 workers, primarily originating from the engine rooms ($n = 43$) and the pump room ($n = 31$); the remaining workers ($n = 35$) were located on deck 3 and higher decks in the bow section.

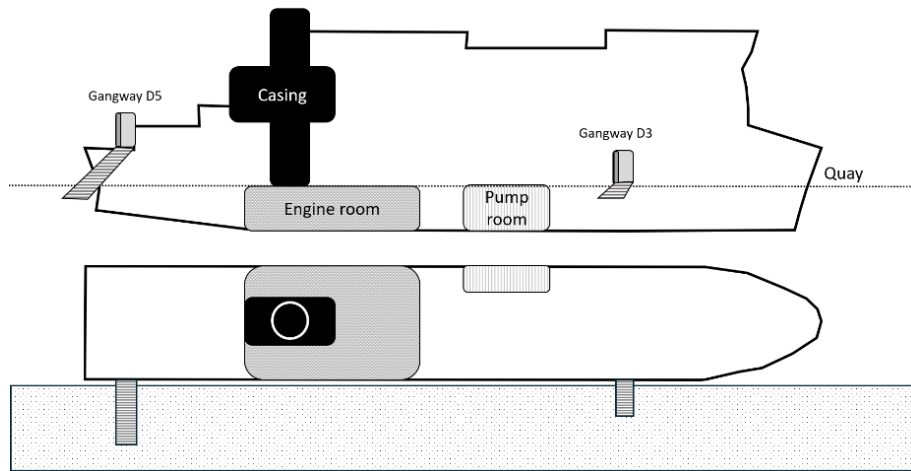


Figure 3: Gangways and confined spaces onboard.

CSET simulations were performed reproducing the observed vessel geometry, worker distribution, and exit capacities. While the complexity of the internal working-site layout was modelled, the exact initial locations of workers—particularly those on decks 3, 5, and 6 (42% of the population)—were unknown and were therefore assigned in accordance with a previous study [10] (Table 1). In summary, the model configuration was subject to uncertainties related to the stochastic nature of human behaviour and to limited information on the initial conditions of the evacuation drill. Each scenario was run 100 times. Although a formal convergence analysis was not conducted [11], this number of repetitions was considered sufficient to produce stable outputs, with an estimated uncertainty of 2–3% [12].

Model–data agreement was evaluated using a functional analysis approach [13–15]. The comparison was based on relative differences in Total Evacuation Time (TET) and three functional metrics: (i) Euclidean Relative Distance (ERD), which quantifies the average pointwise difference between observed and simulated arrival curves; (ii) Euclidean Projection Coefficient (EPC), which measures the best achievable agreement between observed and simulated arrival curves; and (iii) Secant Cosine (SC), which assesses similarity in curve shape by comparing the gradients of the simulated and observed arrival curves. These Euclidean-based metrics were used as quantitative measures of agreement. Perfect agreement between simulations and empirical data is indicated by $TET = 0.0$, $ERD = 0.0$, $EPC = 1.0$, and $SC = 1.0$.

Table 1: Population distribution, pre-evacuation times, and exit usage used in the simulations.

Deck	Origin	N occupants	Exit use	Pre-evacuation time (s) Mean $\pm$ SD [Range]
1	Engine room	10	D3	101 $\pm$ 94 [2-334]*
	Pump room	6		95 $\pm$ 88 [0-240]*
2	Engine room	18		101 $\pm$ 94 [2-334]*
	Engine room	14 (crew)		552 $\pm$ 39 [532-693]*
	Pump room	10		95 $\pm$ 88 [0-240]*
	Next to the pump room	15		95 $\pm$ 88 [0-240]*
3	Near Gangway D3	9		30 [0-60]^
	Stern	8		350 [250-450]*
	All deck	19		60 $\pm$ 30 [0-180]^
5	All deck	7		60 $\pm$ 30 [0-180]^
6	Stern	9		60 $\pm$ 30 [0-180]^
7	Casing/Tank	11	D5	112 $\pm$ 39 [54-191]*
8	Casing/Tank	10		112 $\pm$ 39 [54-191]*
10	Stern	4		112 $\pm$ 39 [54-191]*

* Based on the Drill [10]; ^Estimated by the authors; + based on PD 7974 [16]

3. RESULTS

3.1. Comparison with Pathfinder

Table 2 summarizes the evacuation times predicted by CSET and Pathfinder. Across all scenarios, the relative differences between the mean evacuation times produced by the two models remain below 5%, suggesting that CSET provides evacuation time predictions for confined spaces that are comparable to those obtained with Pathfinder.

Table 2: Statistical characteristics of evacuation times (s) from 100 simulations.

Scenario	CSET	Pathfinder
	Mean $\pm$ SD [Range]	Mean $\pm$ SD [Range]
50 workers	89 $\pm$ 0.7 [87-91]	87 $\pm$ 3.7 [79-97]
100 workers	168 $\pm$ 0.9 [166-171]	167 $\pm$ 3.5 [160-176]
150 workers	250 $\pm$ 1.1 [247-253]	251 $\pm$ 4.4 [241-262]
200 workers	329 $\pm$ 1.2 [325-332]	332 $\pm$ 7.9 [317-367]

3.2. Evacuation of a confined space

Figure 4 presents the results of the simulations performed for the tank evacuation, where each point represents one of the 500 simulation runs. The observed time required for all workers to exit the tank was 8 min 44 s. As the primary output of CSET, the 95th percentile of the simulated evacuation time distribution yielded a predicted evacuation time of 8 min 48 s. Note that the 95th percentile is the main output in CSET model. The small difference between the observed and simulated values indicates consistency between the empirical data and the simulation output, while illustrating the applicability of CSET for estimating evacuation times for confined spaces.

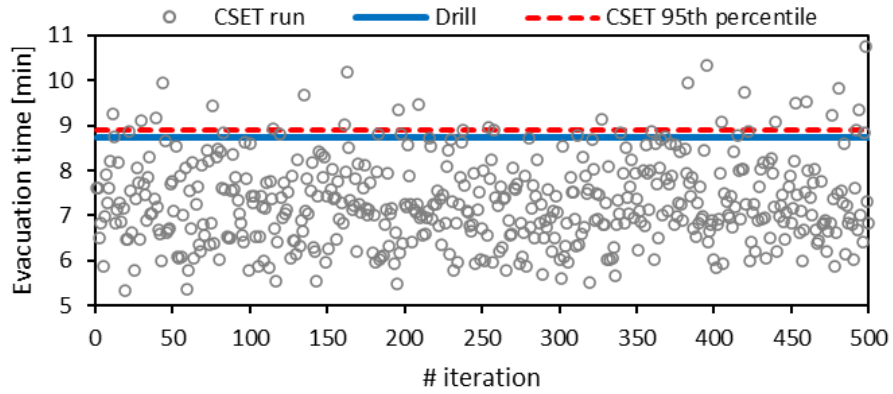


Figure 4: Evacuation time predictions of the CSET for the tank evacuation.

3.3. Evacuation of a vessel in a dockyard

Figure 5 presents the average exit-time curves obtained from 100 repeated simulations, along with the variability range defined by the minimum and maximum values. Comparison with the observed evacuation performance shows that the total average evacuation time predicted for gangway D3 is slightly underestimated by 10 s (767 s versus 777 s), corresponding to a relative error of approximately 1.3%. In contrast, the average evacuation time predicted for gangway D5 is overestimated by 9 s (321 s versus 310 s), with a relative error of approximately 2.9%.

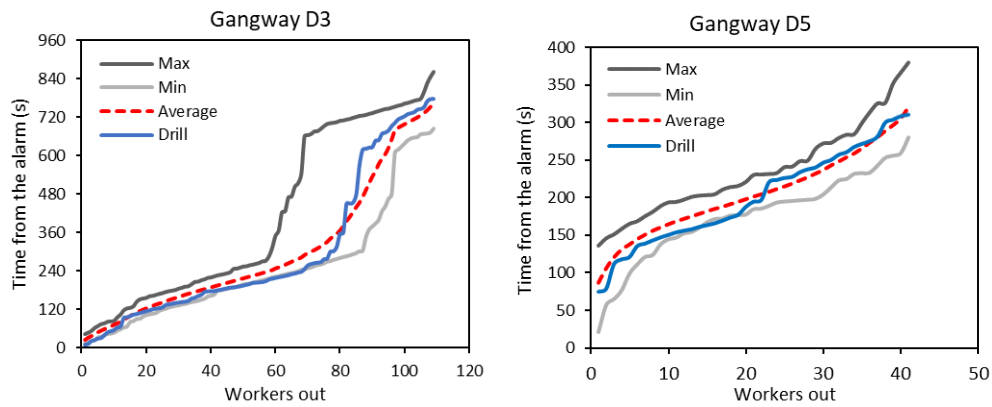


Figure 5: Predicted evacuation curves (max., min. and average of 100 runs) vs observed evacuation curves in gangways.

For gangway D3, the Euclidean Relative Distance (ERD) was 0.16, the Euclidean Projection Coefficient (EPC) was 1.06, and the Secant Cosine (SC) was 0.72. Slightly improved agreement was observed for gangway D5, with ERD = 0.13, EPC = 1.05, and SC = 0.80.

When considering the combined evacuation curves for the vessel (gangways D3 and D5), the agreement with the drill data further improved (Figure 6), yielding ERD = 0.07, EPC = 1.00, and SC = 0.89. All metrics satisfy the threshold values proposed by Galea et al. [17] ($TET < 0.15$; $ERD < 0.25$; $0.8 \leq EPC \leq 1.20$; $SC > 0.80$), indicating good agreement between the simulated and observed data. Consequently, the third validation criterion was satisfied.

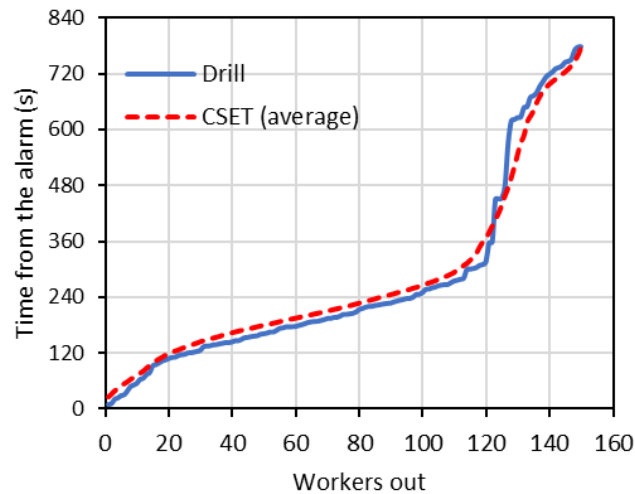


Figure 6: Predicted average evacuation curve vs observed evacuation curve.

4 DISCUSSION

This study presents the Confined Spaces Evacuation Tool (CSET), a simplified simulation model designed to estimate evacuation performance in confined shipboard environments. CSET generates rapid, stochastic predictions of evacuation times while accounting for variability in human behaviour and the unique characteristics of confined spaces. The model was validated against the agent-based Pathfinder software and empirical data from a confined-space tank drill and a full-scale Ro-Pax ferry evacuation. Across all exercises, discrepancies between simulated and observed evacuation times were small, supporting the use of CSET for preliminary evacuation assessments in dockyard settings.

Comparison with Pathfinder indicated relative differences in mean evacuation times below 5% across all occupancy scenarios, suggesting that the stochastic framework—based on key behavioural parameters and exit flow constraints—captures the primary mechanisms governing evacuation. While Pathfinder explicitly resolves individual trajectories and interactions, these details were not required to produce reliable estimates of total evacuation time for early-stage planning or scenario screening.

Validation against empirical drills further confirmed the model's applicability. In the tank evacuation, the predicted 95th percentile evacuation time differed by only a few seconds from observations. In the Ro-Pax ferry drill, relative errors in total evacuation time were approximately 1.3% for gangway D3 and 2.9% for gangway D5. Simulated evacuation curves also reproduced

the temporal progression of observed arrivals, indicating that CSET can approximate both aggregate evacuation times and evacuation dynamics across multiple decks and compartments. Several limitations should be acknowledged. The study focused on a single vessel in dry dock, limiting generalizability to other ship types or operational scenarios. Validation relied on one full-scale drill and one confined-space exercise, which may not capture the full range of worker behaviour. Key input parameters, including unknown initial locations for 42% of workers, estimated pre-evacuation times, assumed horizontal walking speeds, and shortest-path routing, introduced uncertainty that likely affected simulation precision. Despite these constraints, CSET provides practical value as a decision-support tool, enabling rapid estimation of evacuation times, evaluation of worker densities, and assessment of temporary or procedural measures. Its low computational cost and intuitive interface allow efficient scenario exploration during both planning and operational phases, complementing more detailed agent-based models. However, CSET is intended to support—not replace—expert judgement and evacuation modelling studies, with scenario design, parameterization, and interpretation guided by professional oversight. Additional empirical validation across diverse vessels and operational conditions would further enhance confidence in its wider applicability.

5. CONCLUSION

CSET offers a practical decision-support tool for planning and operational safety, enabling the assessment of evacuation times, worker densities, and temporary evacuation measures. Future research should explore different vessel types, shipyard layouts, and operational scenarios, as well as the evaluation of procedural and structural evacuation strategies. Overall, CSET is a promising approach that provides a validated, efficient, and empirically informed solution to improve safety and support evidence-based decision-making in shipyard environments.

6. ACKNOWLEDGMENTS

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ATTITUDES OF COMPANIONS DURING HOSPITAL FIRE EVACUATION

Federico Latosinski* Profesor UNPSJB Argentina	Arturo Cuesta Researcher UC - Santander España	Daniel Alvear Profesor UC - Santander España	Daniel Fernández Profesor UNPSJB Argentina
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Keywords: Hospital evacuation, Human behaviour, Caregivers, Social affiliation behaviour.

1. INTRODUCTION

The evacuation of healthcare facilities during a fire constitutes a complex challenge for fire safety engineering, given the coexistence of patients with varying levels of functional dependence alongside medical and administrative staff, ranging from those capable of self-preservation (1) (i.e., able to protect themselves without staff intervention) to occupants requiring assisted evacuation. Typical examples of the latter include neonates, patients reliant on life-support systems, individuals in the immediate post-operative phase under the effects of anesthesia, and patients presenting severe mobility or neurological impairments. In many cases, patients are accompanied by individuals who provide assistance. The evacuation process in hospital environments is shaped by human and organisational factors (2-4). Fires and evacuations in hospitals have been documented, underscoring the complexity of this phenomenon (5-7). Research on assisted evacuation processes has largely focused on variables such as staff response times, travel speed and the influence of building geometry on available safe egress time (8-14). However, the response of patients' companions has so far received limited attention. Companions are neither part of the hospital staff nor patients, however, they provide assistance to patients and, in the event of an emergency, they have to be evacuated too. Previous studies on human behaviour in fires show that decision-making during emergencies is influenced by risk perception, the credibility of the message received, and interaction with others (15-17). In addition, the role of heuristics and cognitive biases in decision-making has been incorporated, factors such as the perceived authority of the message sender and previous experiences may either reinforce or inhibit protective actions by occupants (18-20). Within this context, mathematical and computational models are widely used to simulate the evacuation process and analyse assisted evacuation scenarios in healthcare facilities (21-25).

The aim of this study is to examine the behavioural responses of companions of hospitalised patients in a general care ward during a potential fire scenario, specifically addressing their compliance with evacuation orders issued by hospital staff. Using empirical data obtained from a structured survey, the decision to evacuate is evaluated considering gender, type of relationship with the patient, most trusted notifier, and previous experience in evacuation drills.

* Autor correspondiente — Facultad de Ingeniería, Universidad Nacional de la Patagonia San Juan Bosco, Argentina.

Telef.: +54 297 4379521, E-mail: federicolatosinski@ing.unp.edu.ar

2. METHODS AND MATERIALS

2.1 Data collection

The study was conducted at Hospital Zonal Alvear, a publicly managed healthcare facility located in Argentina, where face-to-face interviews were carried out with 160 individuals acting as companions of hospitalised patients. To this end, a structured exploratory questionnaire was designed and administered to assess the attitudes and behavioural intentions of companions during a hospital fire evacuation. Additionally, telephone interviews were conducted with 49 caregivers residing in the same city as the hospital, all of whom reported professional experience providing care to patients at Hospital Zonal Alvear.

For each participant, a comprehensive set of variables was collected, including gender, type of relationship with the patient, time spent in the hospital, previous experience in evacuation drills, response to an audible alarm, compliance with hospital staff orders, management of personal and patient belongings during evacuation, identification of the most trusted notifier, and changes in attitude. The questionnaire comprised the following questions related to behaviour during emergency situations:

- A) If you hear a general alarm and do not see or smell smoke, what do you think your response would be?
 - 1. Evacuate.
 - 2. Wait in the room until someone tells me what to do.
 - 3. Go and look for hospital staff to ask what is happening.
- B) If hospital staff ask you to evacuate the room and leave the building by yourself, leaving the patient in the room, what would you do?
 - 1. Follow staff instructions.
 - 2. Stay with the patient and wait to be evacuated together.
- C) When leaving the room, you would:
 - 1. Collect your belongings and/or the patient's belongings to take them with you.
 - 2. Leave the room without taking your belongings or the patient's belongings.
- D) If evacuation is required, who do you consider, in your opinion, to be the most trusted notifier (i.e. whose instructions you trust)? Rank in order of preference.
 - 1. Nurse/physician (medical staff).
 - 2. Security guard.
 - 3. Firefighters.
- E) If your most trusted notifier asks you to leave the room, would you follow the instructions?
 - 1. Yes.
 - 2. No.

2.2 Participants

The study included a total of 209 participants. Of these, 49 were external caregivers interviewed by telephone, all of whom were registered in the National Registry of Home Caregivers, administered by the Ministry of Human Capital of the Argentine Republic (<https://www.argentina.gob.ar/capital-humano/familia/registro-nacional-de-cuidadores-domiciliarios>). Of the total sample, 76.0% of participants (n = 160) were female and 24.0% (n = 49) were male. With respect to the relationship to the hospitalised patient, 65.5% of respondents (n = 137) were identified as family members, while 34.5% (n = 72) were classified as external caregivers. The mean duration of time spent in the hospital was comparable between the two groups, with family members reporting an average of 10.1 ± 5.5 hours and external caregivers 10.2 ± 4.6 hours figure 1. Time spent in the hospital does not follow a regular or predictable pattern for any group. Instead of clustering neatly around an average, companions' hospital stays vary widely, with some spending very little time and others staying for much longer (Shapiro–Wilk test: $W = 0.854\text{--}0.915$, $p \leq 0.002$ for gender groups; $W = 0.787\text{--}0.894$, $p < 0.001$ for relationship groups). Even though the average time is similar across genders and types of companions, the uneven distributions and extreme values indicate that individual experiences differ considerably. Overall, 42.5% of respondents (n = 89) reported prior participation in evacuation drills, whereas 57.5% (n = 120) indicated no previous evacuation experience.

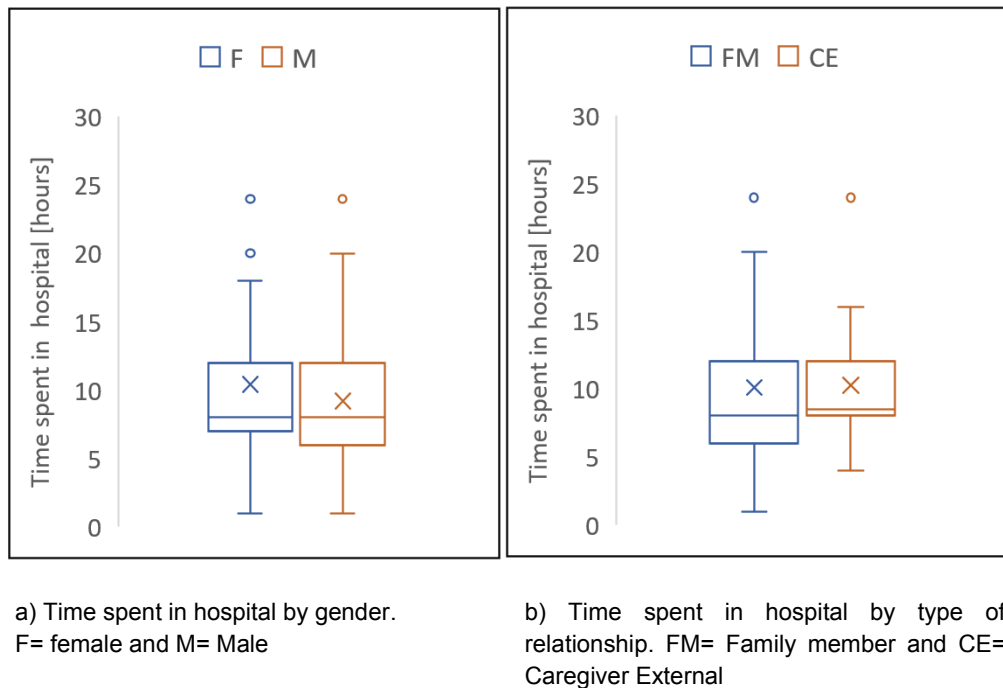


Figure 1: Box-and-whisker plots showing the daily time spent in the hospital by companions.

2.3 Ethics

The study protocol received prior approval from the hospital's governing board. All interviews were conducted during daytime hours, and participants were informed that the study was conducted exclusively for academic purposes. The questionnaire was anonymous, and privacy policy information (e.g. study purpose, survey duration, and data protection procedures) was clearly communicated to participants. Given the low-risk and non-intrusive nature of the study, written informed consent was not required. Participation was voluntary, and completion of the questionnaire was taken to imply consent to participate.

2.4 Data analysis

The normality of continuous variables was assessed using the Shapiro–Wilk test, homogeneity of variances using Levene's test, and differences between group means using Welch's t-test. Associations between categorical variables were analysed using contingency tables and Pearson's χ^2 test, with odds ratios (OR) and Cramer's V reported as measures of effect size. All statistical analyses were conducted using a 5% significance level ($\alpha = 0.05$).

Finally, binary logistic regression models were employed to analyse companions' responses to evacuation orders issued by hospital staff. Model 1 evaluates the initial decision to comply with the order, whereas Model 2 examines changes in decision when the order is issued by the most trusted notifier, focusing on the subgroup of individuals who initially did not comply with staff instructions figure 2. Model fit was assessed using likelihood-based indicators, including the Akaike Information Criterion (AIC) and McFadden's pseudo- R^2 .

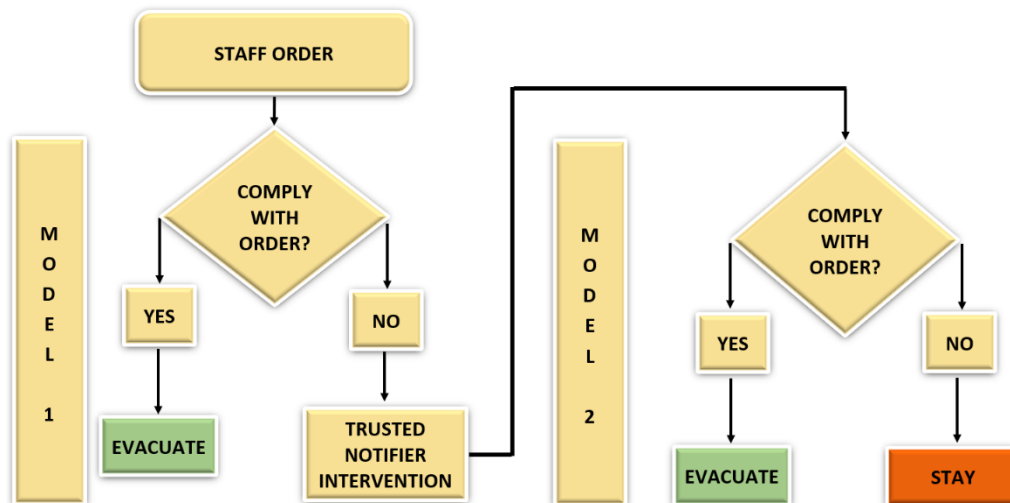


Figure 2: Conceptual representation of the sequential decision-making process used to analyse companions' behavioural responses to evacuation orders issued by hospital staff.

3. RESULTS

Table 1 presents the frequencies of responses to each question, as well as their breakdown by gender, type of relationship, and evacuation drill experience.

3.1 Response to the alarm

In response to an audible alarm without visual or olfactory evidence of smoke, 69% of companions indicated that they would leave the room to seek information, 25% stated that they would wait in the room with the patient, and the remaining 6% reported that they would evacuate the building. No statistically significant association was observed between companions' responses to an audible alarm and gender ($\chi^2 = 1.717$; $df = 2$; $p = 0.423$). No association was found with the relationship to the patient ($\chi^2 = 3.663$; $df = 2$; $p = 0.160$). Likewise, no association was identified between companions' responses and previous experience in evacuation drills ($\chi^2 = 1.263$; $df = 2$; $p = 0.531$).

3.2 Compliance with staff instructions

A total of 75.8% of companions indicated that they would not leave the room if hospital staff requested that they evacuate leaving the patient alone, while the remaining 24.2% stated that they would follow staff instructions. No association was found between companions' responses to staff evacuation requests and gender ($\chi^2 = 0.003$; $df = 1$; $p = 0.950$). A statistically significant association was found between compliance with staff instructions and type of relationship with the patient ($\chi^2 = 10.733$; $df = 1$; $p = 0.001$). External caregivers (EC) showed a 2.9 times higher probability of complying with instructions than family members (FM) (OR = 2.9; 95% CI: 1.5–5.6), with a moderate effect size (Cramer's $V = 0.23$). Finally, no statistically significant association was observed between compliance with staff evacuation requests and previous experience in evacuation drills ($\chi^2 = 0.059$; $df = 1$; $p = 0.806$).

3.3 Management of personal belongings during evacuation

Once companions decide to evacuate, 60.3% reported that they would take their personal belongings and/or the patient's belongings, while 39.7% stated that they would leave without taking anything. No statistically significant association was found between belongings management and gender ($\chi^2 = 3.418$; $df = 1$; $p = 0.064$). However, a statistically significant association was observed between belongings management and the type of relationship with the patient ($\chi^2 = 18.847$; $df = 1$; $p < 0.001$). External caregivers showed higher relative probabilities of taking belongings during evacuation compared to family members (OR = 4.2; 95% CI: 2.1–8.9), with a moderate effect size (Cramer's $V = 0.30$). A statistically significant association was also identified between belongings management and previous experience in evacuation drills ($\chi^2 = 7.620$; $df = 1$; $p = 0.005$). The relative probability of individuals without drill experience taking personal or patient belongings was 2.2 times that of those with experience (OR = 0.45; 95% CI: 0.25–0.83), with a weak effect size (Cramer's $V = 0.19$).

3.4 Most trusted notifier

When asked about the most trusted notifier, firefighters were most frequently selected (51.3%), followed by security staff (27.6%), and lastly medical staff (21.2%). A statistically significant association was observed between gender and the most trusted notifier ($\chi^2 = 7.173$; $df = 2$; $p = 0.027$), with a weak effect size (Cramer's $V = 0.19$). A statistically significant association was also found with type of relationship ($\chi^2 = 12.988$; $df = 2$; $p = 0.001$), with a moderate effect size (Cramer's $V = 0.29$). Analysis of previous drill experience showed a statistically significant association ($\chi^2 = 6.096$; $df = 2$; $p = 0.047$), with a weak effect size (Cramer's $V = 0.20$).

3.5 Effect of the notifier

Among companions who initially refused to follow hospital staff instructions, 48.2% indicated that they would comply if the evacuation order were issued by their most trusted notifier, while the remaining 51.8% stated that they would maintain their refusal.

No statistically significant association was found between gender and the willingness to change the decision ($\chi^2 = 1.207$; $df = 1$; $p = 0.260$). A statistically significant association was found between type of relationship with the patient and willingness to change one's decision when instructed by the most trusted notifier ($\chi^2 = 8.32$; $df = 1$; $p = 0.003$). Family members showed higher relative probabilities of changing their decision compared to external caregivers (OR = 3.26; 95% CI: 1.35–8.29), with a moderate effect size (Cramer's $V = 0.28$). No statistically significant association was found between previous drill experience and change of decision ($\chi^2 = 1.500$; $df = 1$; $p = 0.061$).

3.6 Time spent in the hospital

Analysis of companions' length of stay by gender showed no statistically significant differences between female and male groups (Wilcoxon test: $W = 4297.5$; $p = 0.113$), and no differences in dispersion were observed (Levene's test: $F = 0.004$; $df = 1$; $p = 0.946$). Similarly, no statistically significant differences in length of stay were identified between family members and external caregivers (Wilcoxon test: $W = 5204.5$; $p = 0.344$), nor were differences in dispersion observed (Levene's test: $F = 3.004$; $df = 1$; $p = 0.085$).

3.7 Multivariate analysis and binary logistic regression

Results are presented in Table 2. Considering all companions, model 1 showed that the type of relationship with the patient was significantly associated with compliance with staff instructions, with external caregivers exhibiting a higher probability of compliance. Gender, most trusted notifier, and previous drill experience were not significantly associated with this outcome. The subgroup of companions who initially refused to comply with staff instructions was examined in model 2, in which changes in decision following intervention by the most trusted notifier were again associated with type of relationship, with no significant associations observed for gender, notifier type, or previous drill experience. Equation 1 estimates the probability that companions

comply with evacuation orders issued by hospital staff (model 1), whereas equation 2 represents the binary logistic regression model used to estimate the probability of changing one's decision following intervention by the most trusted notifier, conditional on an initial refusal to evacuate, model 2. EC refers to external caregivers, FF refers to firefighters, and M refers to male, while DRILL denotes prior evacuation drill experience.

$$\log\left(\frac{p}{1-p}\right) = -1.50 + 1.01(\text{EC}) + 0.47(\text{M}) - 0.21(\text{FF}) - 0.03(\text{DRILL}) \quad (1)$$

$$\log\left(\frac{p}{1-p}\right) = 0.16 - 1.12(\text{EC}) + 0.01(\text{M}) - 0.21(\text{FF}) - 0.70(\text{DRILL}) \quad (2)$$

Table 2: Results of binary logistic regression models. Model 1 evaluates factors associated with companions' initial decision to comply with staff instructions during a hospital evacuation. Model 2 examines changes in compliance decisions when the evacuation order is issued by the most trusted notifier (firefighter).

Variable	Model 1			Model 2		
	β	OR [IC 95 %]	p	β	OR [IC 95 %]	p
Intercept	-1.50	-	-	0.16	-	-
Type of relationship (EC=1 vs FM)	1.01	2.75 (1.23 – 6.17)	0.01	-1.12	0.33 (0.13 – 0.79)	0.01
Gender (M=1 vs F)	0.47	1.61 (0.63 – 4.12)	0.31	0.01	1.01 (0.37 – 2.76)	0.98
Notifier (Firefighter=1 vs others)	-0.21	0.81 (0.37 – 1.75)	0.58	-0.21	0.80 (0.35 – 1.86)	0.61
Evacuation drill experience (Yes=1 vs No)	-0.03	0.97 (0.45 – 2.08)	0.93	-0.70	2.02 (0.88 – 4.63)	0.09
AIC	183.20			148.61		
McFadden R ²	0.04			0.07		

4. DISCUSSION

The results of this exploratory study provide insights into patterns of companions' potential behaviour during a hospital evacuation, as well as the factors that may influence these actions. In response to an audible alarm, only 6% of participants indicated that they would evacuate the building. This behaviour showed no statistically significant association with other variables, aligning with previous research on pre-evacuation decision-making in emergency contexts (12, 17).

Table 1: Frequencies [%]

Response to the alarm																	
Gender						Type of relationship						Evacuation drill experience					
Evacuate		Wait		Seek information		Evacuate		Wait		Seek information		Evacuate		Wait		Seek information	
F	M	F	M	F	M	FM	EC	FM	EC	FM	EC	Y	N	Y	N	Y	N
6.9	2.0	25.2	24.5	67.9	73.5	4.4	8.3	22.1	30.5	73.5	61.2	7.8	4.3	24.7	25.2	67.4	70.6
Compliance with staff instructions																	
Gender						Type of relationship						Evacuation drill experience					
Complies		Does not comply		Complies		Complies		Does not comply		Complies		Complies		Does not comply		Complies	
F	M	F	M	F	M	FM	EC	FM	EC	Y	N	Y	N	Y	N	Y	N
24.1	24.5	75.9	75.5	17.1	37.5	82.9	62.5	25.0	23.5	75.0	76.5						
Management of belongings																	
Gender						Type of relationship						Evacuation drill experience					
Take belongings		Do not take belongings		Take belongings		Take belongings		Do not take belongings		Take belongings		Take belongings		Do not take belongings		Take belongings	
F	M	F	M	F	M	FM	EC	FM	EC	Y	N	Y	N	Y	N	Y	N
63.7	49.0	36.3	51.0	49.6	80.5	50.4	19.5	49.4	68.3	50.6	31.7						
Most trusted notifier																	
Gender						Type of relationship						Evacuation drill experience					
Firefighters		Medical staff		Security staff		Firefighters		Medical staff		Security staff		Firefighters		Medical staff		Security staff	
F	M	F	M	F	M	FM	EC	FM	EC	FM	EC	Y	N	Y	N	Y	N
57.0	31.4	19.0	28.5	24.0	40.1	38.6	67.6	27.2	13.2	34.2	19.2	43.9	56.1	18.2	23.1	37.9	19.8
Notifier effect																	
Gender						Type of relationship						Evacuation drill experience					
Change decision		Does not change decision		Change decision		Change decision		Does not change decision		Change decision		Change decision		Does not change decision		Change decision	
F	M	F	M	F	M	FM	EC	FM	EC	Y	N	Y	N	Y	N	Y	N
45.3	58.3	54.7	41.7	58.5	30.0	41.5	70.0	58.7	40.6	41.3	59.4						

F:Female/M:Male/FM:Family member/EC:External caregiver/Y:Yes/N:No.

The type of relationship with the patient revealed differences in compliance with staff instructions. While 75.8% of companions reported that they would not follow staff instructions if this meant leaving the patient alone in the room, external caregivers showed a higher probability of complying with staff instructions than family members. This difference may reflect the stronger emotional attachment of family members to the patient, which can lead them to prioritize the patient's immediate presence over formal evacuation procedures. Such behaviour is consistent with affiliative behaviour described in evacuation research, where individuals tend to remain with or seek close others rather than immediately complying with evacuation instructions (16). From an operational perspective, this finding reinforces the need to explicitly consider family companions in evacuation procedures, as their behaviour may differ from what is expected.

External caregivers showed a higher probability of removing personal or patient belongings during evacuation, while companions without previous drill experience more frequently attempted to take belongings. A possible explanation is that external caregivers may adopt a professional or procedural mindset, with part of their responsibility being to ensure that the patient's essential belongings are safely gathered. In contrast, participants without drill experience may act on instinct, attempting to secure belongings due to uncertainty or perceived necessity, which could potentially delay evacuation. This behaviour may translate into additional delays and obstructions in evacuation routes. Further research is needed to confirm this and to analyse the potential impact of such behaviours.

Firefighters were identified as the most credible figures, followed by security staff and medical staff, with preference for the notifier associated with gender and, more strongly, with the type of relationship; previous drill experience showed only a weak effect. These findings highlight the importance of perceived legitimacy of the information source during an emergency and its potential impact on compliance with evacuation orders. Research indicates that source credibility—shaped by expertise, trustworthiness, and perceived legitimacy—affects how individuals assess risk and decide to act, with warnings from trusted authorities more likely to be followed than ambiguous signals. In hospital evacuations, companions' compliance may thus depend not only on the content of instructions but also on the perceived authority and legitimacy of staff (26, 27). In the context of hospital evacuations, these findings suggest that companions' compliance with staff instructions may depend not only on the content of the warning but also on their perception of the staff's authority and legitimacy.

Furthermore, analysis of the notifier effect among companions who initially refused to evacuate revealed that approximately half would be willing to change their decision if the order came from the most trusted figure. Family members showed a higher probability of changing their behaviour than external caregivers. This finding suggests that, although initial resistance to evacuation may be high, strategic communication through highly trusted actors could improve the effectiveness of evacuation orders. Additionally, previous drill experience could not be associated with change of decision, suggesting that the effect of relationship type may be stronger than drill experience in evacuation decision-making.

Associations between variables do not necessarily imply explanatory capacity regarding evacuation behaviour. This is evident when incorporating these variables into a multivariate modelling. Two models were created. Model 1 evaluated factors associated with companions'

initial decision to comply with staff instructions during a hospital evacuation. Model 2 examined changes in compliance when the evacuation order was issued by the most trusted notifier (firefighter), focusing on participants who initially indicated they would not follow staff instructions. Overall, these models indicate that the type of relationship with the patient and the credibility of the notifier are important determinants of compliance behavior during hospital evacuations. While the models explain only a small fraction of the variance, they provide insight into potential behavioral patterns and emphasize the need to consider both emotional and authority-related factors when designing evacuation procedures and training programs. Low values of McFadden's pseudo- R^2 are common in logistic regression models and should not be interpreted as poor model fit, particularly in social and behavioural research (28). The proposed models are not intended to provide individual-level predictions, but rather to estimate conditional probabilities that characterize the behaviour of companions under different evacuation scenarios. In addition, the Akaike Information Criterion (AIC) values reported in table 2 support the selected model specifications, indicating an adequate balance between goodness of fit and model parsimony for both stages of the analysis. Differences in AIC values between model 1 and model 2 reflect their distinct sample sizes and conditional structure, rather than a direct comparison of model performance. The results should be interpreted considering certain limitations inherent to survey-based data collection. Responses reflect stated behavioural intentions rather than observed actions under real emergency conditions. Furthermore, the questionnaire was administered without visual or video-based scenario representations, which may have introduced additional response biases.

5. CONCLUSIONS

The study conducted on 209 individuals acting as companions of patients hospitalized in general care wards allowed a quantitative characterization of different potential behaviours in a fire evacuation scenario.

Upon activation of an audible alarm without visual or olfactory evidence of smoke, 69% of companions indicated that they would leave the room to seek information, 25% would remain with the patient, and only 6% would evacuate immediately. No statistically significant associations were identified between this initial response and gender, type of relationship with the patient, or previous evacuation drill experience.

When hospital staff requested evacuation of the room leaving the patient alone, only 24.2% of companions stated that they would comply, while 75.8% indicated that they would not. In this case, a statistically significant association was identified with type of relationship, with external caregivers showing a 2.9 times higher probability of complying with staff instructions compared to family members. No associations were observed with gender or previous drill experience. Regarding belongings management during evacuation, 60.3% of companions indicated that they would remove personal and/or patient belongings. This behaviour was not associated with gender but showed statistically significant associations with both type of relationship and previous drill experience. External caregivers showed a 4.2 times higher probability of taking belongings during evacuation, while companions with drill experience reduced the probability of taking belongings by approximately half compared to those without such experience.

With respect to the most trusted notifier, firefighters were selected by 51.3% of companions. The choice of notifier showed statistically significant associations with gender, type of relationship, and previous drill experience, although effect sizes ranged from weak to moderate.

Among companions who initially refused to evacuate leaving the patient alone, 48.2% indicated that they would change their decision if the order came from their most trusted notifier. In this group, a statistically significant association was found with type of relationship, with family members showing a 3.2 times higher probability of changing their decision compared to external caregivers. No significant associations were observed with gender or previous drill experience.

Multivariate analysis confirmed that type of relationship with the patient is associated with compliance with staff instructions.

Analysis of daily time spent in the hospital showed no statistically significant differences by gender or type of relationship with the patient.

These results highlight the need for further research and the importance of incorporating the role of companions into hospital evacuation planning and human behaviour modelling.

As future work, the probabilistic models developed in this study could be embedded into agent-based evacuation simulation platforms, such as Pathfinder, by means of behavioural triggers. The use of triggers would allow modelling sequential evacuation requests and heterogeneous responses among companions, based on the conditional probabilities estimated from the regression models. This integration represents a promising step towards coupling empirical behavioural data with performance-based fire safety analyses in healthcare facilities.

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**USO DE SIMULAÇÃO COMPUTACIONAL PARA ANÁLISE DE CENÁRIOS
DE ABANDONO EM SITUAÇÃO DE INCÊNDIO NO RESTAURANTE
UNIVERSITÁRIO DO CAMPUS CENTRAL DA UFRGS**



Aline Lechner
Engenheira Civil
Brasil



Ângela Gaio Graeff
Professora
UFRGS
Brasil



**Gabriela Dalfollo
Brackmann**
Doutoranda
UFRGS
Brasil

Palavras-chave: simulação; cenários de abandono; Pathfinder; situação de incêndio; segurança contra incêndio.

1. INTRODUÇÃO

O incêndio ocorrido na Boate Kiss em 27 de janeiro de 2013 provocou grande comoção nacional e impulsionou a atualização da legislação de segurança contra incêndio (SCI) no Rio Grande do Sul (RS), no sentido de torná-la mais rígida e oferecer maior segurança à sociedade. Em 2017 também houve a criação de uma lei federal, que ficou conhecida como Lei Kiss [1]. Entretanto, as regulamentações vigentes ainda apresentam um caráter demasiadamente prescritivo, deixando de lado novas soluções que poderiam ser adotadas, que valorizam as particularidades de cada edificação. Nesse sentido, simulações computacionais de abandono de edificações são ferramentas muito úteis que contribuem para que se consiga prever o comportamento dos usuários de forma mais assertiva, pois a partir dela pode-se analisar as interações dos ocupantes com a edificação, verificar pontos críticos da arquitetura e estimar o tempo de abandono da edificação [2]. As simulações computacionais podem ser utilizadas tanto para avaliar o projeto de edificações existentes quanto para a elaboração de novos projetos. No caso de edificações existentes em que não seja possível atender integralmente as exigências

* Autor correspondente — Laboratório de Ensaios e Modelos Estruturais (LEME), Universidade Federal do Rio Grande do Sul. Campus do Vale, s/n, 90.540-000, Porto Alegre, RS, Brasil. E-mail: angela.graeff@ufrgs.br

das legislações vigentes, a simulação computacional de abandono se torna uma importante ferramenta para realizar adequações internas de *layout* e melhorar o fluxo de saída.

Desse modo, o presente trabalho buscou avaliar as condições de abandono do Restaurante Universitário (RU) do Campus Central da Universidade Federal do Rio Grande do Sul (UFRGS) a partir de simulações com o *software* Pathfinder, considerando as exigências da legislação do RS e as regulamentações do Corpo de Bombeiros Militar do Rio Grande do Sul (CBMRS). Para isso foi realizada uma avaliação do *layout* existente e das condições de abandono da edificação com base na população calculada, nas larguras mínimas das saídas e nas distâncias máximas a percorrer permitidas pela RT nº 11 Parte 1 [3] – procedimento normativo adotado no RS para dimensionamento das saídas de emergência. Além da análise normativa, foram desenvolvidas simulações computacionais de abandono para observar o provável comportamento dos ocupantes considerando oito diferentes cenários de emergência. Esse trabalho buscou compreender o fluxo de saída em caso de emergência de uma edificação existente com elevado fluxo de pessoas, e como mudanças simples de *layout* podem contribuir para melhorar as condições de abandono do local.

2. ANÁLISE DA EDIFICAÇÃO

O local escolhido para a realização desse estudo é o RU do Campus Central da UFRGS, localizado na Av. João Pessoa, Porto Alegre/RS. A planta baixa apresentada na Figura 1 identifica as saídas de emergência do local: os acessos e as descargas foram nomeados como AA (acesso A), AB (acesso B), DA (descarga A), DB (descarga B) e E1 (escada de acesso ao nível 2). O *layout* atual do RU, para controle do acesso dos usuários, utiliza DA e AA como entrada, e AB e DB como saída. Porém, em uma situação de emergência, AA e DA também poderiam ser utilizados como rota de fuga. Cabe salientar que não há nenhuma separação física permanente que impeça o deslocamento entre AB e DA, e AA e DB.

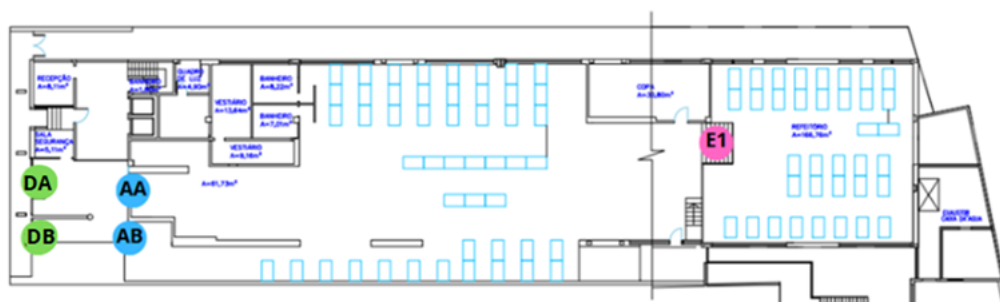


Figura 1: Planta baixa com identificação de saídas, acessos e escada.

A planta baixa da Figura 1 foi fornecida pela CADINFRA, órgão de infraestrutura interno da UFRGS. Para confirmar as medidas apresentadas na planta baixa foram realizadas visitas técnicas autorizadas ao local, em que foram verificadas as dimensões dos acessos, descargas e dos corredores, bem como a disposição, a quantidade e o tamanho de alguns mobiliários, que influenciam o *layout* do espaço e a movimentação dos ocupantes.

Durante as visitas verificou-se que, apesar da descarga A possuir duas portas com folhas duplas equipadas com barras antipânico, apenas duas das quatro folhas permanecem abertas, conforme mostra a Figura 2. Foram realizadas tentativas de abertura das demais folhas, sem sucesso, o que indica que o sistema das barras antipânico pode estar danificado.



Figura 2: Vista das descargas A e B.

Com base nas informações obtidas nas visitas, foram realizados ajustes nas dimensões que constavam na planta para que fosse considerada a situação real do local, assim como a inclusão do mobiliário. O próximo passo consistiu na criação de uma nova planta baixa, com o *software* Revit, pela qual foi possível obter também uma visualização 3D da edificação, para que a simulação computacional de abandono pudesse ser realizada. As figuras 3, 4 e 5 apresentam comparativos entre fotos do interior do RU e a modelagem 3D correspondente realizada no *software* Revit.

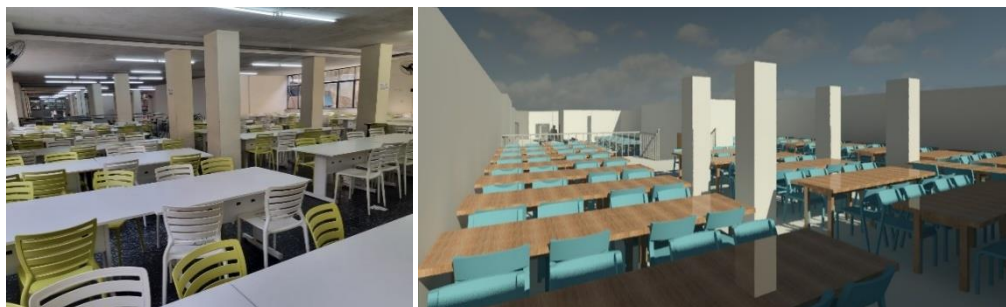


Figura 3: Vista do nível 2: ambiente real e modelo 3D.



Figura 4: Vista dos acessos A e B: ambiente real e modelo 3D.



Figura 5: Vista de AB do corredor: ambiente real e modelo 3D.

O cálculo de população é essencial para o dimensionamento das saídas de emergência. A população calculada define o número de pessoas que podem estar presentes em uma edificação ao mesmo tempo, sendo crucial para assegurar a adequação do número de saídas de emergência e a capacidade dos sistemas de segurança.

Para a classificação da edificação e de suas áreas subsidiárias, foi utilizado o Decreto Estadual nº 51.803 [4] e atualizações. De acordo com a Tabela 1 do Anexo Único desse decreto, a edificação pode ser classificada como F-8 (local para refeição) juntamente com áreas subsidiárias com classificação D-1 (local para prestação de serviço profissional ou condução de negócios).

Para realizar o cálculo da população foi utilizado o Anexo A da RT nº 11 Parte 1 [3]. Para edificações do Grupo F-8 adota-se 1 pessoa por m^2 de área. Para o Grupo D adota-se 1 pessoa a cada 7 m^2 de área. Assim, para o cálculo da população do RU, foi considerada a classificação F-8 na área do restaurante ($680,74 \text{ m}^2$), e a classificação D nas áreas de escritório, copa e sala de segurança ($103,28 \text{ m}^2$). Com base nesses dados, a população da área considerada como F-8 foi de 681 pessoas, e da área considerada como D-1, 15 pessoas, o que soma um total de 696 pessoas.

Em levantamento feito no local verificou-se que o RU possui aproximadamente 390 lugares distribuídos em dois níveis distintos: no nível 2 possui 193 assentos, enquanto que na parte inferior, foram contabilizados 196 assentos. Além disso, cerca de 15 funcionários trabalham no local.

3. SIMULAÇÃO COMPUTACIONAL DE ABANDONO

A simulação computacional de abandono de emergência foi realizada com o *software* Pathfinder, desenvolvido pela Thunderhead Engineering [5]. O Pathfinder é um programa simulador de abandono que se baseia no comportamento dos ocupantes, levando em consideração a arquitetura do local e as características dos usuários, como velocidade, largura dos ombros e capacidade de se encolher entre obstáculos. Ao realizar uma simulação, obtém-se dados de retorno como o tempo necessário para realizar o abandono e a visualização de pontos críticos em cada cenário, podendo-se verificar os locais de possível engarrafamento. A seguir, são apresentados os parâmetros adotados no *software*.

A simulação foi realizada no modo *steering*, utilizado para simular de forma mais realista o movimento dos ocupantes, considerando as interações com o ambiente e com os outros ocupantes. Foi considerado um único perfil para toda a população, levando em consideração que os usuários do restaurante são, em sua maioria, adultos. A Tabela 1 apresenta os valores utilizados para os parâmetros do *software* Pathfinder.

Tabela 1: Parâmetros do *software* Pathfinder.

Parâmetro	Valores
Velocidade dos ocupantes	1,2 a 1,5 m/s
Largura dos ombros	44,7 a 48,8 cm
Altura	1,62 a 1,74 m
Fator de redução	0,7
Tempo de persistência	1,0 s
Distância de conforto	0,08 m
Tempo de resposta a colisões	1,5 s

De forma simplificada considerou-se que toda a população da edificação iniciou o abandono no instante zero. Assim, os resultados apresentados neste trabalho, bem como os tempos de abandono obtidos, devem ser interpretados considerando que o tempo de reação começa a partir do momento em que os ocupantes percebem o risco e iniciam o abandono, o que pode variar conforme seu comportamento e sua localização em relação ao foco de incêndio.

Foram realizadas simulações computacionais de abandono para oito diferentes cenários de emergência. No cenário 1, foi considerada a população total calculada conforme os critérios da RT nº 11 Parte 1 [3], e o abandono acontece de acordo com as plantas baixas ajustadas conforme dados obtidos no levantamento cadastral, utilizando DA e DB como rotas fuga. No cenário 2 considerou-se a mesma população total calculada no cenário 1, mas com apenas duas folhas das portas da DA abertas, e foi simulado pois a edificação possui duas folhas da DA danificadas, portanto, considera a situação atual da edificação.

No cenário 3 considerou-se a população calculada e uma situação hipotética, em que as duas folhas da DA continuam inutilizáveis, e por isso a DA não foi considerada como uma saída de emergência. Com isso, todo o abandono aconteceria apenas por DB. O cenário 4 considerou a população calculada e uma mudança hipotética no *layout* da edificação, como se a área atualmente usada como entrada fosse isolada e não pudesse ser utilizada como saída em situações de emergência. Com isso, AA e DA foram bloqueados por uma barreira, simulando uma possível alteração física no espaço.

O cenário 5 considerou a população calculada e que o incêndio teve início na área dos *buffets*, que ficam próximos ao AA. Dessa forma, esse acesso foi comprometido, e os ocupantes foram obrigados a utilizar apenas o AB. No cenário 6 foi considerada apenas a população contabilizada durante a visita realizada no local, com um acréscimo de 50 pessoas circulando entre a entrada e a saída do RU, já que, além da população que ocupa os lugares disponíveis, há também um fluxo de circulação no espaço, com pessoas entrando e saindo.

No cenário 7 foi considerada a população calculada, e as dimensões dos acessos e descargas ajustados de acordo com o exigido pela legislação vigente. Para isso, removeu-se o mobiliário que dificultava a circulação no AB (refrigeradores e um conjunto de três mesas) e ajustou-se as dimensões das saídas de emergência. O cenário 8 apresentou os mesmos ajustes adotados no cenário 7, ou seja, com os acessos e descargas dimensionados conforme a legislação vigente e remoção do mobiliário, porém com diferença na população. Foi utilizada a mesma população do cenário 6, baseada na quantidade de assentos observados durante a visita ao RU, incluindo 50 pessoas circulando entre entrada e saída.

4. RESULTADOS

4.1 Cenário 1

Descrição do cenário: 696 ocupantes, DA (4 folhas) e DB utilizadas para o abandono.

No primeiro cenário, o tempo total de abandono foi de 188 s, cerca de 3,14 min. A Figura 6 (a) mostra o mapa de densidade no tempo de 56,6 s, onde é possível perceber os principais pontos de engarrafamento. Os maiores acúmulos ocorreram nos acessos às rotas de descarga e não nas descargas em si, o que indica que o problema está mais relacionado à arquitetura interna e aos caminhos percorridos até a descarga (acessos) do que à quantidade ou largura destas. As áreas em vermelho representam uma densidade superior a 3 ocupantes/m², o que pode dificultar a movimentação e aumentar o tempo total de abandono. Isso aconteceu principalmente na região central de AA e no corredor lateral esquerdo que dá acesso ao AB, onde os fluxos se concentram. Além das distâncias percorridas, o próprio *layout* interno contribui para a complexidade do abandono. Elementos como refrigeradores, *buffets* e mesas criam pontos de obstrução e estreitamento nos percursos, o que vai contra as recomendações da RT nº 11 Parte 1 [3] que exige que os caminhos estejam desobstruídos e tenham largura mínima contínua até a saída.

4.2 Cenário 2

Descrição do cenário: 696 ocupantes, DA (2 folhas) e DB utilizadas para o abandono.

Nesse cenário o tempo total de abandono aumentou para 198 s, aproximadamente 3,3 min, ou seja, 10 s a mais em comparação com o cenário anterior. Embora esse acréscimo possa parecer irrelevante isoladamente, ele representa uma diferença importante considerando situações de emergência. A Figura 6 (b) mostra o mapa de densidade aos 57,5 s, e reforça o padrão observado anteriormente, em que a maior concentração de pessoas continua acontecendo nos acessos às descargas, especialmente nas regiões internas, onde os fluxos convergem. A zona em vermelho volta a indicar densidades críticas, superiores a 3 ocupantes/m².

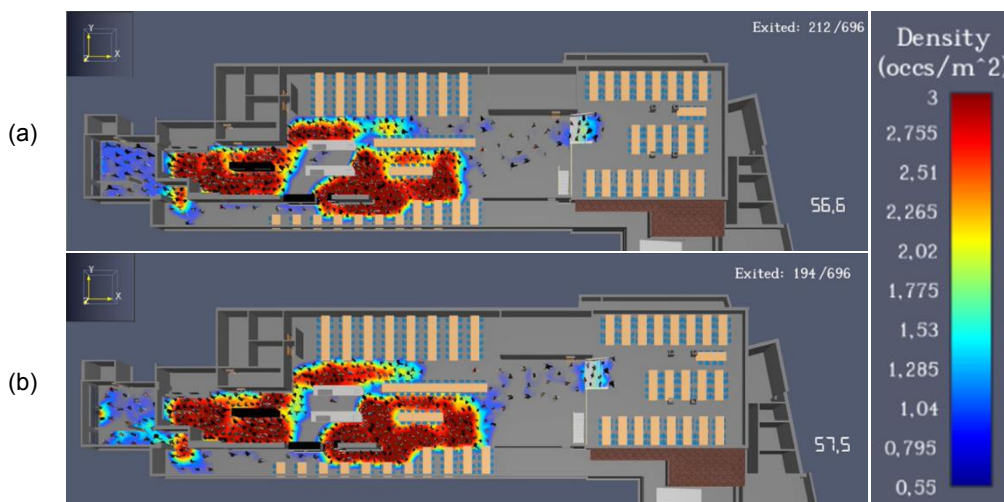


Figura 6: Representação das áreas com maior concentração de ocupantes: (a) cenário 1 aos 56,6 s; (b) cenário 2 aos 57,5 s.

4.3 Cenário 3

Descrição do cenário: 696 ocupantes, abandono acontecendo apenas por DB.

O tempo total de abandono foi de 358 s, aproximadamente 5,96 min. A Figura 7 (a), registrada aos 196,8 s, demonstra como o abandono ficou concentrado do lado esquerdo da edificação. As áreas em vermelho escuro indicam densidades críticas, com muito congestionamento nos corredores e na entrada de AB. Apesar de 375 pessoas já terem abandonado o local, percebe-se que os demais ocupantes ainda enfrentavam dificuldade para sair da edificação, o que pode ser especialmente perigoso quando se leva em consideração que durante um incêndio há liberação de calor e fumaça, que podem comprometer a integridade física dos ocupantes que permanecem no interior da edificação. Isso reforça como a distribuição e a largura das saídas precisam ser respeitadas para garantir que o abandono aconteça de forma rápida e segura em situações reais.

4.4 Cenário 4

Descrição do cenário: 696 ocupantes, alteração no *layout* com AA e DA bloqueadas.

O tempo total de abandono foi de 757,5 s, aproximadamente 12,6 min, o mais alto entre os cenários. A Figura 7 (b), registrada aos 73,3 s, mostra um grande acúmulo de fluxo no salão central, com praticamente toda a área em vermelho intenso, indicando densidades críticas acima de 3 ocupantes/m². Esse resultado reforça que alterações no *layout* precisam levar em consideração o dimensionamento e a distribuição das rotas de fuga, pois até mesmo mudanças aparentemente simples podem causar grande impacto no abandono e comprometer a segurança de todos os usuários em situações de emergência. Hoje, tanto o AA quanto DA podem ser utilizados como rotas de fuga em situação de emergência, mas caso fossem bloqueados, a edificação perderia uma rota de fuga essencial, o que comprometeria diretamente seu o abandono.

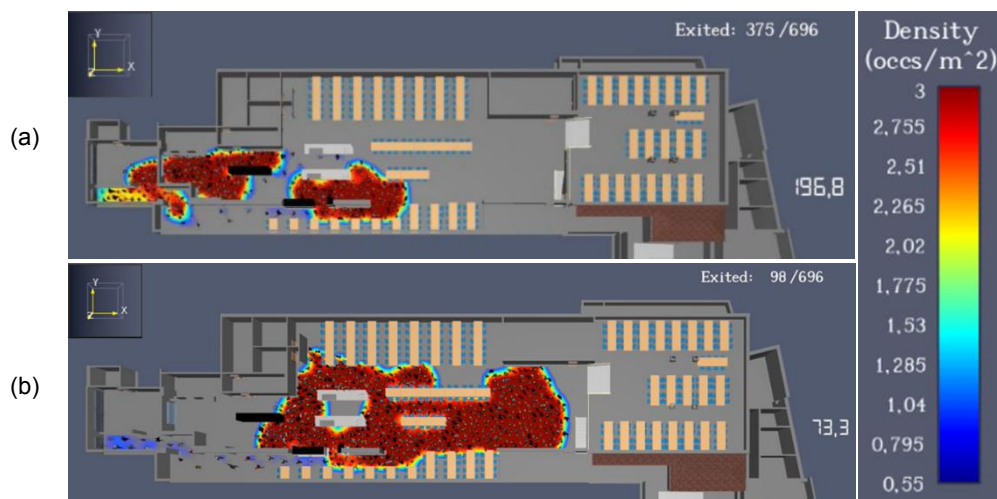


Figura 7: Representação das áreas com maior concentração de ocupantes: (a) cenário 3 aos 196,8 s; (b) cenário 4 aos 73,3 s.

4.5 Cenário 5

Descrição do cenário: 696 ocupantes, foco do incêndio na área dos *buffets*, bloqueando AA.

O tempo total de abandono nesse cenário foi de 744,3 s, aproximadamente 12,4 min. A Figura 8 (a), capturada aos 77,6 s, mostra claramente o acúmulo intenso de pessoas na área central, próxima aos *buffets*, com densidade superior a 3 ocupantes/m². O congestionamento é agravado tanto pela localização dos *buffets* quanto pela impossibilidade de uso do AA, que antes era uma das rotas de fuga mais utilizadas. Equipamentos de *buffet* são fontes de calor e precisam de manutenção constante para não oferecer um risco à população. Esse cenário reforça a necessidade de avaliar os riscos associados à disposição dos equipamentos internos, principalmente os que envolvem calor ou eletricidade, como os *buffets*. Além de comprometer

uma das principais rotas de fuga, o início do incêndio nesse ponto é ainda mais crítico, porque a área fica ocupada por um grande número de pessoas nesse local, como mostra a Figura 8 (a). Isso aumenta o risco de acidentes e dificulta o deslocamento inicial, já que os ocupantes precisariam sair da edificação justamente por um local muito próximo de onde o fogo teve início, tornando o abandono da edificação mais lento e perigoso.

4.6 Cenário 6

Descrição do cenário: 455 ocupantes, DA (2 folhas) e DB utilizadas para o abandono.

Nesse cenário o tempo total de abandono foi de 131,8 s, aproximadamente 2,19 min. A Figura 8 (b), registrada aos 64,0 s, mostra que, apesar de ainda haver concentração de pessoas nas áreas de circulação central, o fluxo foi mais distribuído e sem grandes pontos de bloqueio. Apesar de o tempo de abandono ter sido mais curto comparado aos anteriores, o cenário não deve ser interpretado como uma validação da edificação em relação à segurança contra incêndio, pois os pontos de engarrafamento identificados nos demais cenários continuam acontecendo, especialmente nas áreas centrais de circulação, apenas com menor intensidade. Isso mostra que, mesmo com menos pessoas, o espaço apresenta falhas na distribuição das rotas, o que pode comprometer o abandono em situações com maior fluxo. Esse cenário busca representar de forma mais realista a quantidade média de usuários durante o funcionamento normal do restaurante, conforme observado no local.

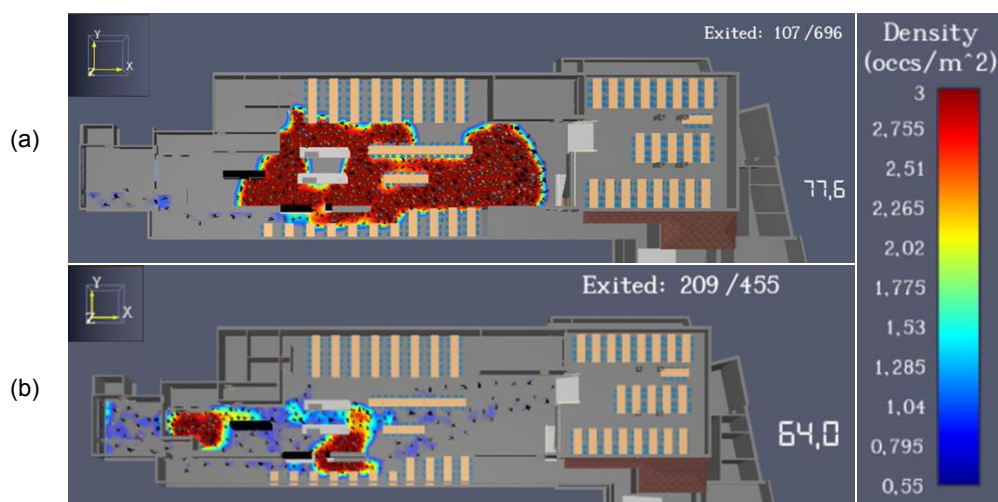


Figura 8: Representação das áreas com maior concentração de ocupantes: (a) cenário 5 aos 77,6 s; (b) cenário 6 aos 64,0 s.

4.7 Cenário 7

Descrição do cenário: 696 ocupantes, saídas de emergência dimensionadas conforme o mínimo exigido e alterações no *layout* arquitetônico.

O tempo total de abandono nesse cenário foi de 148 s, aproximadamente 2,46 min, uma redução de 40 s em relação ao cenário 1, que havia registrado 188 s com os acessos ainda inadequados. A Figura 9 (a), capturada aos 74,4 s, apresenta melhora na fluidez da circulação, especialmente nos pontos antes considerados críticos, como o AB, e também apresenta as áreas que tiveram o mobiliário retirado (refrigeradores e mesas).

4.8 Cenário 8

Descrição do cenário: 455 ocupantes, saídas de emergência dimensionadas conforme o mínimo exigido e alterações no *layout* arquitetônico.

Com os acessos e saídas ajustados, o tempo total de abandono foi de 106,8 s, aproximadamente 1,78 min, representando uma melhora significativa em relação ao cenário 6, que havia registrado 131,8 s com a mesma população, mas com o *layout* real da edificação. A Figura 9 (b) mostra uma evidente redução nos pontos de congestionamento, embora ainda haja algumas áreas críticas.

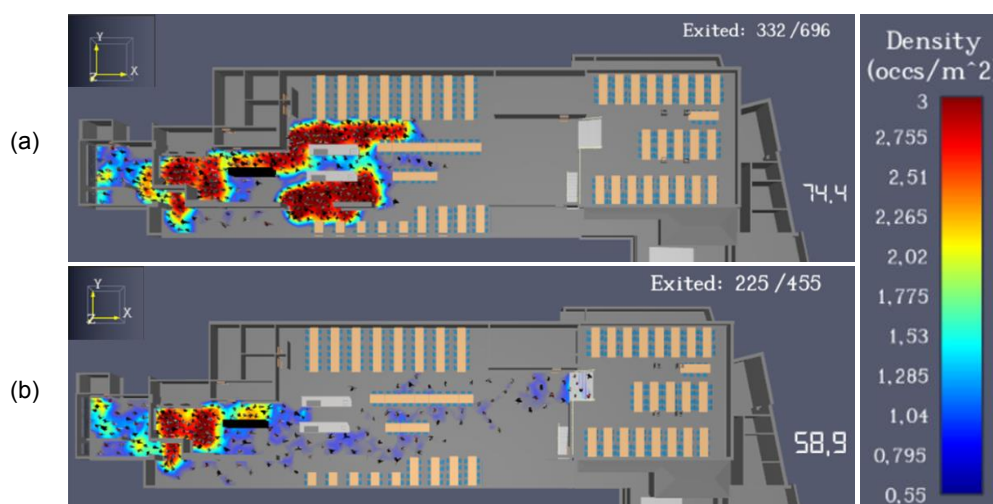


Figura 9: Representação das áreas com maior concentração de ocupantes: (a) cenário 7 aos 74,4 s; (b) cenário 8 aos 58,9 s.

4.9 Análise dos cenários

Nas visitas ao local acreditava-se que os principais pontos críticos da edificação em relação ao abandono seriam as descargas; no entanto, as simulações demonstraram que os pontos mais críticos são os acessos que levam até as descargas. Nas condições atuais a edificação possivelmente apresentaria engarrafamentos significativos nas saídas de emergência, dificultando o abandono. Além disso, é importante salientar que as dimensões dos acessos não respeitam o mínimo exigido pela legislação vigente, as descargas são comprometidas pela falha

na abertura de duas folhas das portas e as distâncias máximas a percorrer ultrapassam o máximo permitido.

O Quadro 1 faz uma comparação entre os cenários simulados. A adequação das saídas de emergência conforme o dimensionamento da RT nº 11 Parte 1 [3] resultou em reduções expressivas nos tempos de abandono. Mesmo com uma população menor (Cenário 6), o *layout* inadequado da edificação ainda gerou congestionamentos, reforçando que não apenas a densidade populacional compromete o abandono. A piora em cenários com bloqueio de rotas (Cenário 4) e início de incêndio na área dos *buffets* (Cenário 5) demonstram a importância de integrar a análise de risco ao *layout* arquitetônico, incluindo a localização de equipamentos e a manutenção das rotas desobstruídas. O melhor resultado geral foi alcançado no Cenário 8, considerando uma população menor junto com um projeto arquitetônico alinhado às exigências normativas de SCI.

Quadro 1: Comparativo entre os cenários simulados.

Cenário	População	Saídas de emergência	Tempo de abandono (s)	Principais observações
1	696	DA (4 folhas), DB, AA, AB	188,0	Congestionamento nos acessos; áreas críticas com densidade superior a 3/m ² .
2	696	DA (2 folhas), DB, AA, AB	198,0	Leve aumento no tempo; padrão de fluxo e engarrafamento se mantém.
3	696	DB, AA, AB	358,0	Acúmulo extremo; fluxo forçado para um único ponto de saída.
4	696	DB, AB	757,5	Cenário mais crítico; grande parte da planta com densidade crítica; deslocamento crítico.
5	696	DB, AB	744,3	Congestionamento na origem do fogo; risco elevado.
6	455	DA (2 folhas), DB, AA, AB	131,8	Menor tempo; engarrafamentos persistentes nas mesmas áreas.
7	696	DA (4 folhas), DB, AA, AB	148,0	Redução significativa no tempo de abandono; deslocamento mais fluido; AB desobstruído.
8	455	DA (4 folhas), DB, AA, AB	106,8	Congestionamentos leves e bem distribuídos; Melhor cenário geral.

OBS: nos cenários 7 e 8 as dimensões das saídas de emergência foram ajustadas conforme o mínimo exigido pela legislação vigente.

Os resultados das simulações evidenciaram a importância do conserto das folhas das portas de saída danificadas para se reduzir os engarrafamentos nas saídas de emergência, e da manutenção preventiva em equipamentos como os *buffets* para a redução do risco de incêndio em área crítica. Quanto ao *layout* do RU, pequenos ajustes como a realocação das mesas, cadeiras e refrigeradores que comprometem a fluidez dos acessos pode ser uma medida de

baixo custo, mas com impacto significativo na segurança e na eficiência do abandono da edificação.

5. CONCLUSÕES

As simulações computacionais indicaram que, nas condições atuais, a edificação apresenta risco de congestionamentos significativos nas saídas de emergência, dificultando o abandono, e um dos principais pontos críticos são os acessos que conduzem até as descargas. O *layout* inadequado gerou congestionamentos mesmo quando considerada uma população menor, evidenciando que o problema não se limita à densidade de ocupação. Cenários com bloqueio de rotas e início de incêndio na área dos *buffets* agravaram o desempenho do abandono da edificação, reforçando a necessidade de integrar a simulação computacional ao projeto arquitetônico.

A adequação das dimensões das saídas conforme a legislação vigente resultou em reduções relevantes no tempo de abandono. O melhor desempenho foi obtido no Cenário 8, que combinou menor população e adequação do projeto às normas de SCI. Medidas como o conserto das folhas de portas danificadas, manutenção preventiva de equipamentos e ajustes simples no *layout* poderiam reduzir congestionamentos e melhorar a eficiência do abandono da edificação. De modo geral, a simulação computacional mostrou-se uma ferramenta relevante para avaliar e otimizar o fluxo de saída em edificações, auxiliando na identificação de pontos críticos e contribuindo para a redução do tempo total de abandono.

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FORMACIÓN EN SEGURIDAD CONTRA INCENDIOS EN ESPAÑA: PANORAMA Y NECESIDADES

Pascale Vacca^{1*}, Alba Àgueda¹, Elsa Pastor¹, Daniel Alvear², Eulàlia Planas¹

¹ Centro de Estudios del Riesgo Tecnológico (CERTEC), Universitat Politècnica de Catalunya

² GIDAI, Universidad de Cantabria

Palabras clave: ingeniería de seguridad contra incendios, formación, diseño basado en prestaciones

1. INTRODUCCIÓN

Los profesionales de la ingeniería de seguridad contra incendios (*Fire Safety* o *Fire Protection Engineers*) desempeñan un papel esencial en el diseño y construcción de edificaciones, integrando soluciones de protección dentro de un sistema global de seguridad [1]. Aunque otros campos de la ingeniería y la arquitectura han abordado tradicionalmente ciertos aspectos de la seguridad contra incendios, el ingeniero especializado en seguridad contra incendios aporta conocimientos específicos que aseguran la eficacia de las medidas adoptadas. La relevancia del ingeniero de seguridad contra incendios ha aumentado significativamente en las últimas décadas debido a la creciente complejidad de las construcciones modernas y la transición hacia el diseño basado en prestaciones [2].

En España, el diseño prestacional de proyectos de edificación está contemplado en el Artículo 5 del Código Técnico de la Edificación (CTE) [3], así como en el Reglamento de seguridad contra incendios en los establecimientos industriales (RSCIEI) [4]. En el marco del CTE, el proyectista puede adoptar soluciones alternativas a las establecidas en los Documentos Básicos, siempre que se justifique técnicamente que las prestaciones alcanzadas cumplen o superan las exigencias básicas de seguridad. Estas soluciones se incorporan al proyecto bajo la responsabilidad del proyectista y se someten al procedimiento ordinario de control administrativo mediante la concesión de la licencia urbanística por parte de la autoridad municipal competente. En el ámbito del RSCIEI, los diseños desarrollados mediante metodología prestacional deben ser aceptados por la autoridad competente en materia de industria de la comunidad autónoma correspondiente y, habitualmente, someterse a una revisión técnica independiente o revisión por pares. Este procedimiento garantiza que el estudio se ha realizado conforme a los escenarios de incendio más relevantes y que las soluciones propuestas ofrecen un nivel de seguridad equivalente o superior al exigido por los códigos prescriptivos. Todo ello exige que los diseños se apoyen en un conocimiento científico-técnico amplio y específico en el ámbito de la dinámica y la protección contra incendios.

La importancia de contar con profesionales adecuadamente formados en seguridad contra incendios se hace aún más evidente si se tiene en cuenta el gran impacto social y económico de los incendios en España. En 2024 se registraron 234 fallecidos por incendios y explosiones, de los cuales 172 se produjeron en viviendas [5]. Esta cifra sitúa el año 2024 –con 4,8 víctimas por

millón de habitantes– como el tercer año con mayor número de víctimas mortales desde 2010, poniendo de manifiesto la persistencia del riesgo y la necesidad de mejorar las estrategias de prevención, diseño y gestión de la seguridad contra incendios [5].

Paralelamente, la seguridad contra incendios constituye un sector económico consolidado y en crecimiento. Según datos correspondientes a 2023, el sector de la protección contra incendios en España está formado por aproximadamente 900 empresas con más de 20 trabajadores, que emplean a cerca de 18.000 personas y generan una facturación próxima a los 3.000 millones de euros anuales [6]. Este contexto evidencia no solo la relevancia técnica y social de la seguridad contra incendios, sino también la necesidad de disponer de profesionales con una formación sólida y especializada, capaces de responder a las crecientes exigencias normativas, tecnológicas y sociales del sector.

En este marco, este trabajo analiza los estándares mínimos de formación en seguridad contra incendios, revisa la oferta formativa disponible en España en esta disciplina y examina de forma crítica sus principales carencias y necesidades aportando criterios que contribuyan a mejorar la capacitación profesional con la finalidad de avanzar hacia un mayor nivel de seguridad frente al riesgo de incendio.

2. ESTÁNDARES MÍNIMOS DE FORMACIÓN EN SEGURIDAD CONTRA INCENDIOS

El ejercicio profesional como ingeniero de seguridad contra incendios, tanto en proyectos como en funciones de autoridad competente o evaluador externo, requiere una base sólida de conocimientos técnicos. En 2018 la SFPE (*Society of Fire Protection Engineers*) publicó un documento en el que se nombraban las competencias técnicas mínimas que los profesionales del sector deberían alcanzar [7]. En la Tabla 1 se presentan las áreas de conocimiento consideradas, junto con el detalle de sus subáreas.

Tabla 1. Áreas de conocimiento asociadas a las competencias técnicas mínimas establecidas por la SFPE [7]

Áreas de conocimiento	Subáreas de conocimiento
Ciencia del fuego	Transferencia de calor Química del fuego Dinámica del fuego
Comportamiento humano y evacuación	Comportamiento humano y respuesta fisiológica frente al fuego Conceptos de evacuación y protección de las personas
Sistemas de protección contra incendios	Sistemas pasivos Sistemas activos Detección y alarma del fuego Extinción del fuego
Análisis de los sistemas de protección	Diseño basado en prestaciones Gestión del humo Análisis de la evacuación Protección estructural frente al fuego

Gestión del riesgo
Modelización del fuego mediante métodos numéricos y por computador
Regulación y estándares en la edificación y frente a los incendios

Además, la SFPE también ha desarrollado 3 planes de estudio modelo [8-10] para garantizar que los programas de Ingeniería de Protección contra Incendios cumplan con los estándares que se esperan en este campo de la ingeniería. Estos planes incluyen dos titulaciones de Grado (Grado en Ingeniería de Protección contra Incendios (GIPCI) y Grado en Tecnología de Ingeniería de Protección contra Incendios (GTIPCI)), y un programa de Máster (Máster en Ingeniería de Protección contra Incendios (MIPCI)). En la Tabla 2 se presentan los títulos de las asignaturas definidas. En relación a los Grados, en esta tabla se puede ver que algunas asignaturas planteadas como optativas en el GTIPCI no lo son para el GIPCI (p.ej., Transferencia de Calor es obligatoria para este último), que los créditos asignados son distintos para varias asignaturas comunes, y que sólo existe una asignatura planteada exclusivamente para uno de los Grados (el GTIPCI): Protección contra incendios en la industria (optativa). En relación al MIPCI, la SFPE indica cinco tópicos que deberían cubrirse en el marco de 2 a 4 asignaturas básicas, i.e., Dinámica y química del fuego, Análisis de peligros y riesgos asociados a los incendios, Metodologías de diseño, Seguridad contra incendios en edificios, y Sistemas de protección contra incendios. Además, se indican las asignaturas/temas adicionales y más aplicados que también se deberían cubrir (véase la 3ª columna de la Tabla 2). Cabe destacar que, si bien la mayoría de las asignaturas planteadas aparecen también en ambos Grados, existen 3 asignaturas exclusivas del Máster: Gestión de incendios en la interfaz urbano-forestal, Análisis de consecuencias, y Planificación del uso del suelo basada en el análisis del riesgo.

Tabla 2. Asignaturas y ámbitos (CB: Ciencias básicas; FG: Formación general; IN: Ingeniería; OP: Optativas) en los planes de estudio modelo de la SFPE para las titulaciones Grado en Ingeniería de Protección contra Incendios (GIPCI); Grado en Tecnología de Ingeniería de Protección contra Incendios (GTIPCI); Máster en Ingeniería de Protección contra Incendios (MIPCI), con los créditos correspondientes (entre paréntesis, si se han definido) según el sistema estadounidense (1 crédito = 1 hora de clase a la semana). *Sólo se indican los cursos/temas adicionales y aplicados [8-10]

Asignaturas	GIPCI	GTIPCI	MIPCI*
Física (y laboratorio)	CB (12)	CB (4)	
Química, Química orgánica (y laboratorio)	CB (6)	CB (8)	
Cálculo, Ecuaciones diferenciales para ingenieros	CB (12)	CB (9)	
Inglés	FG (6)	FG (6)	
Optativas	FG (6)	FG (6)	
Economía aplicada a la ingeniería	FG (3)	FG (3)	
Escritura técnica	FG (3)	FG (3)	
Otras asignaturas generales	FG (18)	FG (14)	
Dibujo asistido por ordenador	IN (3)	IN (3)	
Estadística	IN (3)	IN (3)	
Mecánica	IN (3)	IN (3)	
Mecánica de los materiales	IN (3)	IN (3)	
Dinámica	IN (3)	OP (1)	

Mecánica de fluidos	IN (3)	IN (3)	
Termodinámica	IN (3)	IN (3)	
Transferencia de calor	IN (3)	OP (1)	
Códigos y estándares asociados a la protección contra incendios	IN (-)	IN (-)	x
Química del fuego	IN (-)	IN (-)	
Análisis de peligros y riesgos asociados a los incendios	IN (3)	IN (3)	
Extinción del fuego con base de agua	IN (3)	IN (3)	x
Extinción del fuego sin base de agua y peligros especiales	IN (3)	IN (3)	x
Dinámica del fuego	IN (3)	IN (3)	
Modelización del fuego	IN (3)	OP (1)	x
Protección estructural frente al fuego	IN (3)	IN (3)	x
Almacenamiento y transporte de materias peligrosas	IN (3)	IN (3)	x
Análisis de la evacuación y la protección de las personas	IN (3)	IN (3)	x
Ensayos de fuego	IN (3)	OP (1)	x
Detección, alarma y control de humos	IN (3)	IN (3)	x
Prevención y protección contra explosiones	IN (3)	OP (1)	x
Gestión del riesgo de incendio	IN (3)	IN (3)	x
Proyecto final	IN (3)	IN (3)	x
Optativas técnicas	IN (6)	IN (6)	
Investigación de incendios	OP (1)	IN (3)	x
Operaciones de los servicios de extinción de incendios	OP (1)	OP (1)	
Dinámica de fluidos computacional avanzada	OP (1)	OP (1)	
Diseño y análisis de sistemas de extinción avanzados	OP (1)	OP (1)	
Diseño basado en prestaciones	OP (1)	OP (1)	
Análisis avanzado de la protección de las personas	OP (1)	OP (1)	
Incendios forestales	OP (1)	OP (1)	
Clase de laboratorio complementarias	OP (1)	OP (1)	
Protección contra incendios en la industria		OP (1)	x
Gestión de incendios en la interfaz urbano-forestal			x
Análisis de consecuencias			x
Planificación del uso del suelo basada en el análisis del riesgo			x

3. FORMACIÓN EN SEGURIDAD CONTRA INCENDIOS EN ESPAÑA

Actualmente, en España la formación en ingeniería de seguridad contra incendios se articula a través de másteres y posgrados ofrecidos por entidades privadas y avalados por universidades españolas, así como de cursos de especialización dirigidos a profesionales de diferentes ámbitos con interés en esta disciplina. Asimismo, existen programas organizados por universidades públicas.

3.1 Másteres y posgrados

En España existen actualmente cinco programas de Máster y un programa de posgrado activos, que se recogen en la Tabla 3. Todos ellos se imparten en modalidad a distancia, con la excepción del *International Master of Science in Fire Safety Engineering* (IMFSE), que además es el único programa impartido en inglés, al tratarse de un máster internacional desarrollado en el marco de Erasmus Mundus. El IMFSE tiene una duración de dos años y una carga lectiva de 120 créditos ECTS, mientras que la mayoría de los demás programas de Máster tienen una duración de un año (60 créditos ECTS). Cabe destacar que el Máster ofrecido por EuroInnova cuenta con una carga lectiva notablemente inferior, de tan solo 8 créditos ECTS, mientras que el Posgrado Internacional en Ingeniería y Tecnología de Protección Contra Incendios impartido por la Escuela Superior de Seguridad Integral e Ingeniería del Fuego (ESSIIF), certificado por Universidad Isabel I, también cuenta con una carga lectiva reducida (30 ECTS).

El *Máster en Ingeniería de Seguridad contra Incendios* de la Universidad de Alcalá, el IMFSE y el *Máster en Ingeniería de Protección contra Incendios* de la UNED establecen requisitos académicos previos para el acceso a la formación, exigiendo una titulación equivalente a Ingeniería Superior o Ingeniería Técnica, así como grados en ciencias, arquitectura o disciplinas afines. En contraste, en el resto de programas no se especifica de manera explícita este tipo de requisitos académicos.

Tabla 3. Programas de Máster y Posgrado en España

Formación	Entidad	Modalidad	Créditos ECTS	Requisitos previos
Máster en Ingeniería de Seguridad contra Incendios [11]	Universidad de Alcalá	Semipresencial y a distancia	60	Sí
International Master of Science in Fire Safety Engineering [12]	Ghent University, The University of Edinburgh, Lund University, Universitat Politècnica de Catalunya	Presencial	120	Sí
Máster en Ingeniería de Protección contra Incendios [13]	UNED	A distancia	60	Sí
Máster en Ingeniería y Tecnología de Protección contra Incendios [14]	ESSIIF, certificado por Universidad Isabel I	A distancia	60	No
Máster en Ingeniería de Protección contra Incendios Online [15]	EuroInnova	A distancia	8	No
Posgrado Internacional en Ingeniería y Tecnología de	ESSIIF, certificado por Universidad Isabel I	A distancia	30	No

La Tabla 4 muestra en qué medida los programas de Máster y Posgrado impartidos en España cubren las asignaturas incluidas en los planes de estudio modelo de la SFPE. En este análisis se excluyen las asignaturas básicas de los estudios de grado, dado que estos contenidos se encuentran ya integrados en los títulos de ingeniería del sistema universitario español.

El IMFSE es el programa que presenta una mayor correspondencia con los planes de estudio de la SFPE. No obstante, existen materias específicas, tituladas *Comportamiento y simulación de incendios forestales*, *Riesgo y vulnerabilidad en la interfaz urbano-forestal*, y *Riesgo y seguridad en la industria química* (esta última cubriendo las temáticas de almacenamiento, transporte de materias peligrosas, análisis de consecuencias y planificación del uso del suelo basada en análisis del riesgo), que se imparten exclusivamente en la Universitat Politècnica de Catalunya y son cursadas únicamente por la mitad del estudiantado, dado que la otra mitad realiza sus estudios en la Universidad de Gante (Bélgica).

El *Máster en Ingeniería de Seguridad contra Incendios* de la Universidad de Alcalá también presenta una cobertura amplia de las asignaturas contempladas en los planes de estudio de la SFPE, aunque no cubre las asignaturas altamente especializadas o avanzadas, como Dinámica de fluidos computacional avanzada o Diseño basado en prestaciones.

El resto de másteres y el posgrado recogidos en la Tabla 4 presentan una cobertura parcial de las asignaturas definidas en los planes de estudio de la SFPE, centrándose en determinados ámbitos de la ingeniería de protección contra incendios con distintos niveles de profundidad y especialización.

Asimismo, varios de los programas analizados, concretamente los másteres de la Universidad de Alcalá, la UNED, la ESSIIF y Euroinnova, incorporan módulos específicos dedicados a la elaboración de planes de autoprotección, exigidos en España por el Real Decreto 393/2007, lo que refuerza su alineación con el marco normativo nacional.

Tabla 4. Cobertura de asignaturas contempladas en los planes modelo de la SFPE por los programas de Máster y Posgrado de España

Asignaturas	Máster Uni. de Alcalá	IMFSE	Máster UNED	Máster ESSIIF	Máster EuroInn.	Posgrado ESSIIF
Termodinámica	X	X				
Transferencia de calor	X	X				
Códigos y estándares protección contra incendios	X	X			X	X
Análisis de peligros y riesgos asociados a los incendios	X	X	X	X		X
Extinción del fuego con base de agua	X	X	X	X	X	X
Extinción del fuego sin base de agua y peligros especiales	X	X	X	X	X	X
Dinámica del fuego	X	X	X	X		
Modelización del fuego	X	X	X			
Protección estructural frente al fuego	X	X				
Almacenamiento y transporte de materias peligrosas	X	X				X
Análisis de la evacuación y la protección de las personas	X	X				X
Ensayos de fuego		X				
Detección, alarma y control del humo	X	X	X	X		X
Prevención y protección contra explosiones		X				
Gestión del riesgo de incendio	X	X				
Proyecto final	X	X	X	X		X
Investigación de incendios	X			X	X	
Operaciones de los servicios de extinción de incendios		X				
Dinámica de fluidos computacional avanzada		X				
Diseño y análisis de sistemas de extinción avanzados		X				X
Diseño basado en prestaciones	X	X		X		X
Análisis avanzado de la protección de las personas		X				X
Incendios forestales	X	X			X	
Clase de laboratorio		X				
Protección contra incendios en la industria	X	X			X	
Gestión de incendios en la interfaz urbano-forestal	X	X				
Análisis de consecuencias		X				
Planificación uso del suelo basada en análisis del riesgo		X				

3.2 Cursos de especialización

Los cursos de especialización ofrecidos en España abarcan distintos ámbitos de la ingeniería de protección contra incendios. Entre ellos, destacan dos programas centrados en el diseño basado en prestaciones o desempeño. El primero es el *Curso de especialización en diseño basado en prestaciones/desempeño (PBD) y fundamentos de la simulación computacional de evacuación e incendio*, impartido por la ESSIF [17], con una duración de 100 horas. Este curso ofrece una formación avanzada que abarca los fundamentos de la dinámica de incendios y del comportamiento humano, los aspectos normativos del diseño prestacional, la selección y definición de escenarios de diseño, así como la simulación computacional de incendios mediante el software FDS (Fire Dynamics Simulator) y la simulación de evacuaciones mediante el software Pathfinder. El segundo es el *Curso de diseño basado en prestaciones en seguridad contra incendios*, ofrecido por Cepreven [18], con una duración de 16 horas, que se centra en la presentación de la metodología del diseño basado en prestaciones, sus principios generales dentro de la ingeniería de seguridad contra incendios y su encaje en la legislación española, incorporando asimismo una introducción a las herramientas de modelización de humos y evacuación.

Asimismo, la ESSIF ofrece un amplio catálogo de formación, con más de veinte cursos especializados en protección contra incendios. Entre ellos, destaca el *Curso Experto en Ingeniería y Tecnología de Protección Contra Incendios* [19], con una duración de 750 horas, orientado a una formación en los fundamentos de la protección contra incendios y la teoría del fuego, el análisis normativo, así como el diseño y la aplicación de sistemas de protección activa y pasiva.

Por su parte, la Universidad de Cantabria ofrece el *Diploma Universitario de Experto en Modelado y Simulación Computacional de Seguridad contra Incendios* [20], en modalidad online y con una carga lectiva de 20 ECTS, centrado específicamente en la simulación computacional de incendios y evacuaciones.

Finalmente, el Clúster de Seguretat Contra Incendis de Catalunya (CLUSIC) organiza diversas acciones formativas en el ámbito de los sistemas de protección contra incendios, dirigidas principalmente a instaladores y mantenedores. Además, en los años 2016, 2017, 2019 y 2022, el CLUSIC ha organizado, junto con el Centro de Estudios del Riesgo Tecnológico (CERTEC) de la Universitat Politècnica de Catalunya, el *Curso Monográfico de Simulación de Incendios aplicado al Diseño Prestacional* (53 horas) [21], que aborda la metodología del diseño basado en prestaciones, la simulación de incendios con FDS aplicada al diseño prestacional y la simulación de evacuación y el análisis del comportamiento humano en caso de incendio.

4. DISCUSIÓN

El análisis de la formación en ingeniería de seguridad contra incendios en España muestra un panorama marcado por una elevada heterogeneidad y por una alineación parcial con los estándares internacionales de referencia. Si bien existe una oferta diversa de másteres, posgrados y cursos de especialización, la comparación con los planes de estudio modelo de la

SFPE pone de manifiesto diferencias significativas en cuanto a la profundidad, coherencia e integración de las competencias técnicas consideradas esenciales para el ejercicio profesional avanzado.

Entre los programas analizados, el IMFSE destaca por ser el único que cubre de forma sistemática la mayoría de las competencias nucleares definidas por la SFPE, integrando contenidos científicos, analíticos, experimentales y aplicados dentro de una estructura formativa coherente y de suficiente duración. No obstante, incluso en este caso, algunas materias específicas —como los incendios forestales o el análisis del riesgo en la interfaz urbano-forestal— se imparten de forma parcial, ya que dependen del itinerario seguido por el estudiantado, lo que pone de relieve la complejidad de abarcar de manera completa todos los ámbitos de la disciplina en un único programa.

La oferta nacional presenta, en general, una cobertura adecuada de los fundamentos de la ingeniería de protección contra incendios, especialmente en aquellos programas vinculados a universidades públicas. Sin embargo, se identifican carencias recurrentes en materias avanzadas como la dinámica de fluidos computacional, el diseño basado en prestaciones o el análisis avanzado de la protección de las personas, que resultan cada vez más relevantes en proyectos singulares y en contextos normativos complejos. Estas carencias se pueden compensar mediante cursos de especialización externos, lo que fragmenta la formación y dificulta la consolidación de un perfil profesional integral.

Otro aspecto relevante es la elevada variabilidad en la carga lectiva y en los requisitos de acceso de los programas analizados. La coexistencia de titulaciones con cargas que oscilan entre 8 y 120 créditos ECTS refleja enfoques formativos muy dispares y niveles de profundización difícilmente comparables. Esta heterogeneidad se ve reforzada por la ausencia de criterios homogéneos de acceso en algunos programas, lo que puede derivar en una preparación desigual de los egresados.

Asimismo, la modalidad mayoritariamente a distancia de la oferta formativa limita la incorporación sistemática de formación experimental y de laboratorio, un componente considerado esencial por la SFPE para la adquisición de competencias en ciencia y dinámica del fuego. Si bien la formación online resulta adecuada para determinados contenidos teóricos o normativos, su predominio dificulta el desarrollo de habilidades prácticas, analíticas y experimentales.

Finalmente, debe señalarse de forma positiva que muchos de los programas españoles han incorporado contenidos específicamente orientados al marco normativo nacional, como la elaboración de planes de autoprotección. No obstante, este énfasis normativo, aunque necesario, debería complementarse con una mayor integración de contenidos científicos y técnicos avanzados, especialmente en un contexto marcado por el impacto persistente de los incendios y por la creciente complejidad de los escenarios de riesgo.

5. CONCLUSIONES

El análisis realizado muestra que la formación en ingeniería de seguridad contra incendios en España ha experimentado un desarrollo significativo, con una oferta diversa de másteres, posgrados y cursos de especialización que responden a la creciente relevancia técnica y social de esta disciplina. No obstante, la comparación con los estándares internacionales de referencia pone de manifiesto una cobertura desigual de las competencias técnicas consideradas esenciales para el ejercicio avanzado de la profesión.

En particular, se identifican diferencias relevantes en la profundidad de los contenidos, en la integración de materias avanzadas y en la incorporación de formación experimental y aplicada, aspectos clave en el contexto actual del diseño basado en prestaciones y del uso creciente de herramientas de análisis y simulación. Asimismo, la elevada heterogeneidad en la carga lectiva, los requisitos de acceso y las modalidades de impartición dificulta la consolidación de una formación de posgrado homogénea.

A la luz de estos resultados, parece oportuno reflexionar sobre posibles vías de fortalecimiento de la oferta formativa de posgrado en ingeniería de seguridad contra incendios. En particular, la articulación de programas que integren de manera coherente la base científica, la formación avanzada, la experimentación y el contexto normativo podría contribuir a mejorar la calidad y la coherencia de la capacitación ofrecida. En este sentido, iniciativas de carácter colaborativo entre universidades, que permitan sumar capacidades docentes, infraestructuras experimentales y enfoques complementarios, podrían representar una oportunidad para avanzar hacia una oferta formativa más sólida y alineada con los estándares internacionales.

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Session 5

Sesión 5

Sessão 5

THERMAL INTERACTION ANALYSIS OF INTERNAL CELL COMPONENTS FOR LI-ION BATTERY SAFETY

Juan M. H. Egea, Javier Monsalve-Serrano, Javier Marco Gimeno, Antonio García Martínez

CMT - Clean Mobility & Thermofluids, Universitat Politècnica de València, Camino de Vera s/n, 46022, Valencia, Spain

Abstract

The thermal stability of lithium-ion battery materials critically governs thermal runaway risk, which is the very first step for an EV fire, yet prior studies have predominantly characterized individual components in isolation rather than their realistic inter-material interactions within commercial cell architectures. This work presents a systematic investigation of thermal interaction between the main components extracted from a commercial NMC 21700 cell (cathode/Al collector, anode/Cu collector, inner/outer polymeric separators, and electrolyte) using Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) on adjacent pairs mimicking jelly roll interfaces.

A targeted experimental matrix reveals that inner separator integration delays exothermic peaks by 25-50 °C (cathode: 230 °C; anode: 300 °C) and reduces peak exothermic heat flow via endothermic transitions, while electrolyte amplifies exothermic generation across active materials. TGA shows sequential oxidative decomposition (cathode around 200 °C, anode 600 °C), with the internal separator yielding 25% residual mass, whereas the external separator of the jellyroll undergoes complete decomposition.

A Thermal Severity Index (TSI) map demonstrates that the highest TSI values (lowest stability) arise predominantly from synergistic material interactions rather than isolated components. Separator-electrode interfaces exhibit higher TSI values than individual materials (despite the intrinsic low TSI of the separator), while electrolyte incorporation significantly increases TSI across configurations. This multi-material laboratory framework establishes a relative thermal-hazard ranking for jelly-roll components under controlled heating conditions, providing a foundation for battery safety assessment.

Keywords: Lithium-ion batteries, Separator, Thermal Stability, Internal Components, Battery safety

1. Introduction

Lithium-ion batteries (LIBs) have become indispensable energy storage systems, powering the global transition toward greener mobility and the integration of renewable energy. The widespread adoption of LIBs in electric vehicles (EVs), consumer electronics, and stationary energy storage systems is driven by their high energy density, extended cycle life, and declining manufacturing costs. However, the widespread use of this technology has exposed a critical safety vulnerability: thermal runaway (TR), a self-accelerating exothermic chain reaction that can trigger catastrophic fires [1]. Recent incident data underscore this concern. A comprehensive review of EV battery fires documents numerous incidents worldwide, primarily involving spontaneous ignition, charging failures, post-crash fires, and reignition events. These documented cases highlight LIB thermal runaways' propensity to cause jet flames, explosions, and toxic gas releases, with full-scale tests

showing peak heat release rates comparable to those of internal combustion engine vehicles (4–10 MW) yet marked by persistent reignition risks due to inaccessible battery packs [2]. These incidents demonstrate that despite the remarkable performance advantages of LIB technology in mobility applications, the thermal stability of battery cells remains a paramount safety challenge that demands exhaustive research.

Extensive literature has documented the thermal behavior of lithium-ion cells and the contributions of individual materials to exothermic reactions during failure scenarios [1,3,4]. A comprehensive structural characterization, exemplified by recent teardown analysis of commercial battery cells, reveals that lithium-ion cells are assembled as tightly-wound jelly rolls encased within a protective casing, with alternating layers of anode, separator, and cathode spirally wound with external separators and current collectors (copper for anode, aluminum for cathode) arranged in contact sequence [5]. The thermal safety of a cell is not determined by the behavior of individual materials in isolation, but rather by the cumulative exothermic potential of all constituent components and, critically, by the thermal interactions that occur between adjacent layers during an overheating event. When TR propagates through a cell, the spatial proximity and thermal contact between the anode, separator, and cathode govern the rate and intensity of heat generation, as well as the kinetics of the chain reactions. Understanding these multi-component thermal interactions is a key factor in evaluating battery safety; inadequate characterization of these inner materials introduces unquantified risk into the delivered battery design and safety assessment. Although advanced in-situ instrumentation can be implemented to monitor internal cell responses under abuse conditions, such approaches are complex, cell-specific, and often do not clearly resolve the role of each constituent material, so dedicated methodological studies that isolate and systematically characterize individual components and their interfaces remain necessary for robust battery safety assessment [6].

A significant gap exists in the current literature: the thermal behavior of individual internal battery materials has been extensively characterized in single-material studies [7–9]; however, such investigations do not accurately represent the real operational environment within a cell, where materials are surrounded by other components. To address it, this research employs a systematic experimental approach centered on seven principal materials extracted from a commercial lithium-ion cell, analyzing their thermal behavior by itself and their cross-interactions when positioned adjacent to one another in the same sequence as they exist within the jelly roll structure (external separator, copper current collector, anode, separator, cathode, aluminum current collector and electrolyte). The thermal characterization employs differential scanning calorimetry (DSC) to quantify total heat generation per unit mass of material, complemented by thermogravimetric analysis (TGA) to establish temperature-dependent mass-loss profiles at a laboratory scale. With this, an experimental tool has been designed to classify and rank thermal interaction stability and relative hazard potential across the internal battery materials.

2. Materials and Methods

To conduct this study, a high-performance commercial NMC 21700 cylindrical lithium-ion cell (5 Ah nominal capacity) was fully charged to 100% state of charge (SOC) and systematically disassembled to access its internal components. In Figure 1, a representative scheme of the process is shown. This procedure was executed under strictly controlled ambient conditions within a pure N₂ glovebox environment, keeping H₂O < 1 ppm and O₂ < 100 ppm to ensure operator safety, prevent oxidative degradation, and eliminate contamination risks. A precision incision was made at the superior region of the cell using mechanical cutting tools, targeting the dead space devoid of jelly roll material. The cell casing was methodically removed, enabling complete

extraction of the jelly roll assembly. Subsequently, representative samples were isolated from the principal internal constituents via mechanical cutting for thermal characterization, with all materials preserved under continuous glovebox storage conditions to maintain chemical integrity.

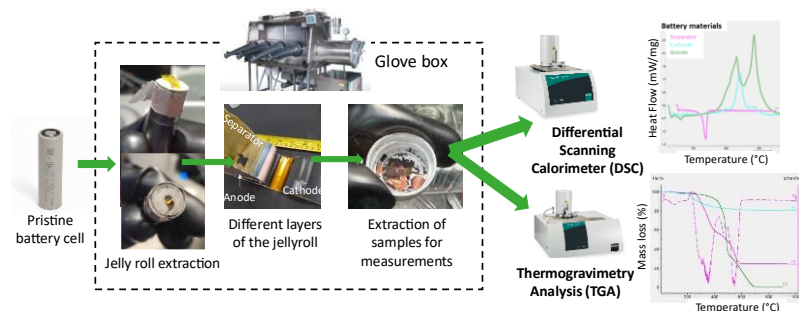


Figure 1. Teardown process of a LIB to extract the internal components.

Following the teardown or disassembly process, seven principal material types were identified from the extracted jelly roll: cathode with an aluminum current collector, anode with a copper current collector, inner polymeric separator, outer polymeric separator, and electrolyte. To comprehensively evaluate both individual thermal responses and interactions under overheating conditions. The theoretical combination encompasses hundreds of multi-component interactions; however, exhaustive testing of all combinations would be experimentally prohibitive. Therefore, a systematic reduction strategy was implemented, schematically illustrated in Figure 2, prioritizing the analysis of pairs of adjacent material interfaces within the jelly roll architecture to better reflect the practical relevance of thermal runaway propagation.

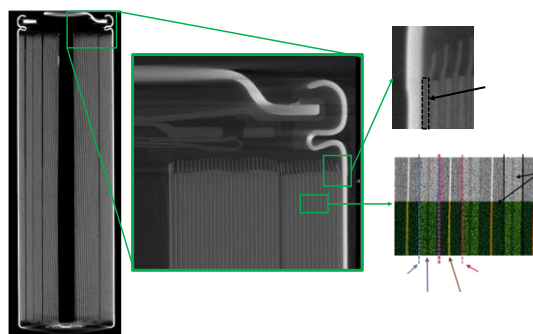


Figure 2. Battery Cell scheme of the internal architecture of the battery cell through Computed Tomography scan (CT-scan).

Based on this compositional analysis, Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) experiments were conducted to investigate thermal interactions among the cell's internal components and their influence on overall thermal behavior. All experiments were performed in triplicate to ensure reproducibility, and final data were reported as the arithmetical mean of these measurements. DSC testing was performed on a DSC 214 Libra instrument under nitrogen purge, using aluminum crucibles with pierced lids. TGA measurements were conducted using Al_2O_3 crucibles up to 1000°C in a reactive synthetic air atmosphere (80% N_2 /20% O_2).

3. Results

Once the individual components were isolated from the teardown, their mass percentages in the complete cell were quantified and summarized in Table 1. The electrochemically active materials, the anode and cathode, where lithiation and delithiation reactions occur during charge-discharge cycling, collectively constitute 43% of the total cell mass. In contrast, the electrochemically inert constituents, comprising current collectors, polymeric separators, electrolyte, and casing, account for the remaining mass.

Table 1. Composition of the internal components from a commercial battery cell by weight.

Component	Mass (g)	Total weight (%)
Casing	8.55	12.9
Venting Cap	2.44	4.1
External Separator	0.70	1.1
Internal Separator	4.65	7.0
Cathode Coating	18.52	28.0
Aluminum Current Collector	6.17	9.0
Anode Coating	9.13	15.8
Copper Current Collector	8.25	11.8
Electrolyte*	6.83	10.3
Total	66.12	100

Sample preparation followed a standardized protocol involving precise weighing of extracted components and meticulous isolation of representative specimens for subsequent thermal analysis. Tables 2 and 3 show the combinations discussed in the previous section for DSC and TGA experiments, respectively.

Table 2. DSC test matrix for the internal components of a battery cell

Test	ES	IS	An	Cu	Cat	Al	E	Mass (mg)
1	x							10.5
2	x						x	10.0 + 1.0
3		x						9.5
4		x					x	10.7 + 1.2
5			x					6.2
6			x	x				6.1 + 3.0
7		x	x	x				10.8 + 6.1 + 3.1
8			x				x	5.9 + 1.1
9					x			12.3
10					x	x		12.6 + 2.2
11		x			x	x		10.5 + 12.9 + 2.7
12					x		x	11.6 + 1.0

ES: external separator; SI: internal separator; AN: anode, Cu: copper, CAT: cathode, Al: aluminum, Ele.: electrolyte

Table 3. TGA test matrix for the internal components of a battery cell

Test	ES	IS	AN	Cu	CAT	Al	Mass (mg)
1	x						15.7
2		x					19.5
3			x				8.4
4			x	x			8.4 + 4.2
5					x		11.7
6					x	x	11.7 + 3.8

DSC and TGA provide complementary insights into the thermal stability and exothermic behavior of battery materials under overheating conditions relevant to TR initiation. DSC quantifies heat flow associated with endothermic and exothermic phase transitions, decomposition reactions, and inter-material thermal interactions, revealing onset temperatures and heat generation rates. TGA simultaneously measures mass loss as a function of temperature, elucidating oxidative decomposition pathways, volatile release profiles, and residue formation under air exposure conditions mimicking fire scenarios. Critically, these techniques enable systematic evaluation of how internal material contacts, such as anode-separator-cathode interfaces, vary total exothermic heat generation through synergistic reaction kinetics, directly contributing to fire propagation hazard assessment beyond isolated material studies.

Figures 3 and 4 present two DSC heat flow traces illustrating critical inter-material interactions: Figure 3 focuses on cathode combinations, and Figure 4 highlights anode interactions. For the cathode, the aluminum current collector induces a modest delay in the peak exothermic heat flow temperature to 230 °C compared to the bare cathode, attributable to its thermal mass. Notably, the inner separator further reduces both the peak temperature and the total exothermic heat flow by acting as a thermal buffer through its dual endothermic phase transitions.

Regarding the anode (Figure 4), the internal separator similarly attenuates peak exothermic heat flow while shifting the maximum temperature onset to approximately 300 °C, demonstrating enhanced thermal decoupling at anode-separator interfaces.

The internal separator significantly attenuates heat flow while delaying the peak temperature by 50 °C. This thermal decoupling arises from the separator's dual endothermic transitions (140-160 °C melting), which broaden the exothermic envelope and prevent a sudden exothermic peak in the anode and copper sample. Then, the separator system exhibits controlled heat release up to 450 °C, whereas the anode test shows only abrupt decay, indicating less heat release at the anode-separator interface.

The DSC traces in both figures reveal that both the aluminum current collector (25 °C delay for cathode) and the inner separator provide thermal buffering, with separator-induced endothermic transitions most pronounced around 150-200 °C. These interactions systematically increase the onset temperature of the exothermic reactions, thereby delaying further TR propagation.

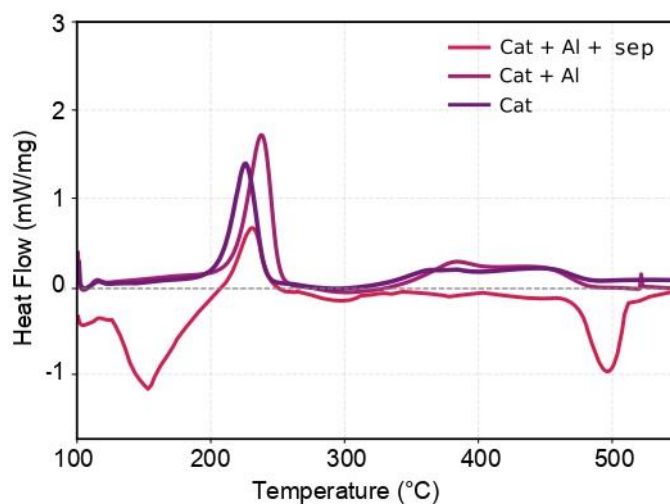


Figure 3. DSC curves of cathode materials show exothermic decomposition onset [°C] and peak heat flow [W/mg] under controlled heating rate of 20°C/min.

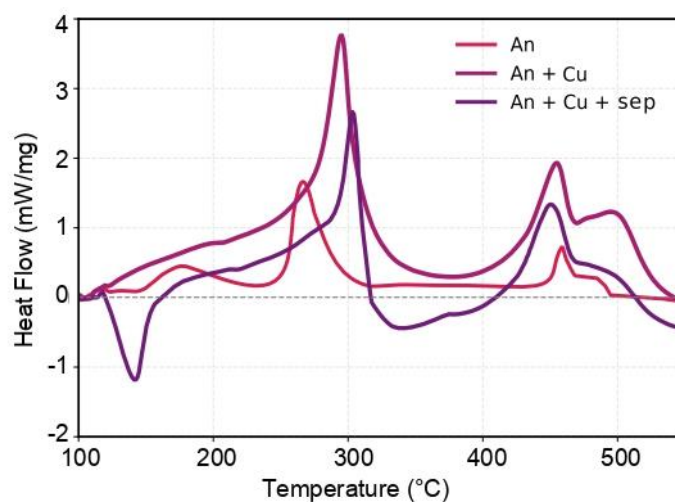


Figure 4. DSC curves of cathode materials show exothermic decomposition onset [°C] and peak heat flow [W/mg] under controlled heating rate of 20 °C/min.

Figure 5 illustrates the pronounced influence of electrolyte on the thermal profiles of cell components, revealing synergistic effects critical to thermal decomposition pathways. Electrolyte substantially amplifies exothermic heat flow in both cathode and anode systems, with the cathode exhibiting an earlier peak exothermic temperature (about 225 °C) while the anode demonstrates greater overall heat generation. The internal separator exhibits an endothermic transition at 150 °C, while the external separator shows a less pronounced endothermic event at higher

temperature. Both separators remain stable up to 500°C in DSC analysis, with the outer separator displaying combustion onset above 500°C, earlier than the inner separator. Crucible limitations prevented evaluation beyond 550°C; higher-temperature decomposition behavior was characterized separately using TGA.

The black dashed trace represents the cumulative heat flow from individual components. Above 125 °C, minor exothermic generation from anode SEI decomposition exceeds electrolyte evaporation endotherm. At 150 °C, net heat flow becomes negative due to separator melting. Cathode exothermic reactions initiate around 225 °C, followed by initial anode contributions. From 450 °C onward, renewed anode exothermic reactions overlap with endothermic separator decomposition processes, highlighting complex multi-stage thermal interplay beyond isolated material behavior. The cumulative trace (dashed) from all components predicts a net endothermic heat flow at 150 °C, confirming that, while the separator is melting, it temporarily delays the heat release but also contributes to short-circuiting.

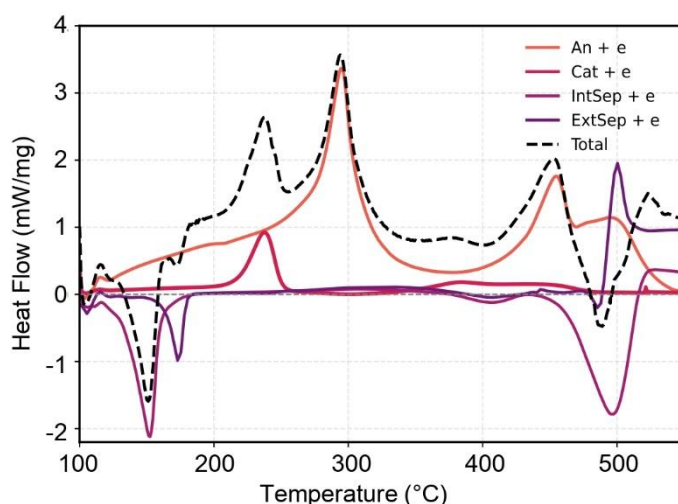


Figure 5. DSC curves show exothermic onset and peak temperatures for individual jelly-roll components (anode, cathode, separator, electrolyte) and their theoretical cumulative profile representing the total heat-release potential under controlled heating conditions. Note: summation assumes additive thermal decomposition without inter-material heat transfer effects.

The oxidative decomposition profiles of the main mass-losing constituents under abuse conditions are presented in Figure 6. The inner separator demonstrates earlier mass loss initiation compared to the outer separator, reflecting differences in polymeric matrix thermal stability; however, at test termination (900 °C), the inner separator retains substantially higher solid residue mass (25% ash content versus no residual mass from external separator), indicating that this type of polymer is thermoset with a highly reticulated structure that reduce heat propagation during overheating conditions in certain temperature range. This differential behavior between external and internal separators highlights the critical role of the internal component at high temperatures and the significance of residue persistence within the jelly-roll architecture for modulating heat release.

The cathode exhibits the earliest decomposition onset among electrode materials, commencing above 200 °C, and shows lower total mass loss (<20%) due to its metal-dominated composition. The primary volatile contributor is oxidation of carbon black, the conductive binder facilitating adhesion between active cathode particles and aluminum current collector foil. No significant interaction effects modify the decomposition kinetics of the active cathode material with or without an aluminum collector.

In contrast, anode decomposition initiates at significantly higher temperatures (600 °C), is dominated by graphite oxidation, and is followed by two distinct mass-loss phases extending through test completion. Copper current collector-containing anode samples significantly contribute to higher final residues (40-50% versus 20% for active material alone) due to the inert metallic fraction. Moreover, the presence of copper induces a low but detectable delay in oxidation onset (about 15 °C), requiring higher temperatures to initiate graphite combustion.

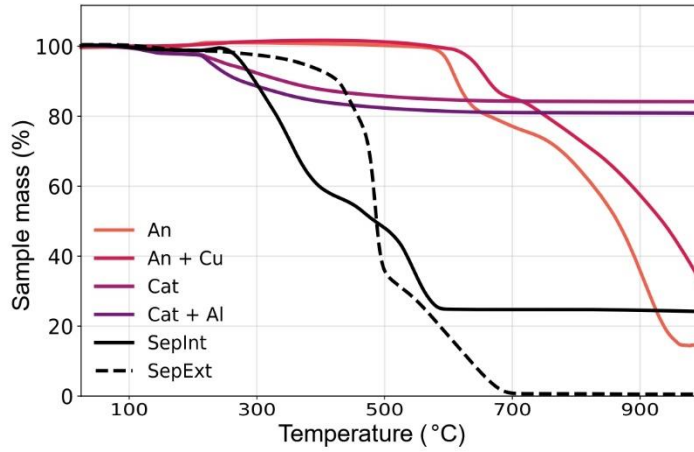


Figure 6. Comparative TGA mass loss curves for internal components (anode, cathode, separator, electrolyte) show decomposition temperature ranges and total mass loss percentages.

Based on the thermal decomposition profiles and mass-loss characteristics identified by DSC and TGA, Figure 7 presents a parameter map that classifies materials according to their relative thermal Severity potential, driven by realistic internal material interactions in LIBs under overheating conditions.

The horizontal axis quantifies the onset temperature of the first exothermic event detected via DSC, serving as a direct indicator of ignition susceptibility (lower values correspond to reactions that are triggered earlier under thermal abuse). The vertical axis employs a normalized Thermal Severity Index (TSI) (Equation 1):

$$\text{Thermal Severity Index (TSI)} = \frac{T_{\text{peak onset}}}{T_{\text{max}}} \cdot \frac{q_{\text{peak}}}{q_{\text{total}}} \cdot m_{\text{loss}} \quad (1)$$

where $T_{\text{peak onset}}/T_{\text{max}}$ captures the relative activation temperature of the first thermal event from the maximum temperature of the DSC test (400 °C), $q_{\text{peak}}/q_{\text{total}}$ quantifies the fractional contribution (with negative values for endothermic and positive values for exothermic reactions) of the first peak to the overall heat flow, and m_{loss} is the TGA mass-loss fraction. Each term in the TSI is normalized with respect to the experimental data set, so that $T_{\text{k}} / T_{\text{max}}, q_{\text{k}} /$

q and m_{ss} all take values between 0 and 1 for the tested configurations. This normalization emphasizes, respectively, the ease of ignition (low onset temperatures), the fraction of heat released in the first triggering event, and the amount of volatile material available to feed further reactions, which are key drivers of thermal runaway propagation. Positive TSI values therefore identify energy-releasing interactions that can sustain or amplify heat generation, whereas negative values correspond to self-limiting or predominantly endothermic behavior.

TSI is a comparative, dimensionless metric tailored to this experimental matrix, enabling consistent ranking of internal material interactions rather than providing an absolute measure of hazard. Within the tested dataset, variations in HF_{peak}/HF_{total} and $F_{Mass\ loss}$ dominate the spread in TSI, while $T_{peak\ onset}/T_{max}$ primarily separates early- and late-ignition configurations.

The TSI map is divided into four regions of increasing thermal Severity: Zone I (red, $TSI > 0$, $T_{peak\ onset} < 200\text{ }^{\circ}\text{C}$) groups materials with earliest onset and highest peak heat flow, exhibiting greatest thermal decomposition severity. Zone II (orange, $TSI > 0$, $T_{peak\ onset} > 200\text{ }^{\circ}\text{C}$) includes configurations with exothermic heat release but with late onset temperature. Zone III (yellow, $TSI < 0$, $T_{peak\ onset} < 200\text{ }^{\circ}\text{C}$) captures materials with early onset but with negative heat release (predominant of endothermic reactions). Zone IV (green, $TSI < 0$, $T_{peak\ onset} > 200\text{ }^{\circ}\text{C}$) represents highest thermal stability combinations with latest onset temperatures and minimal heat flow.

The $200\text{ }^{\circ}\text{C}$ threshold was chosen because it approximately coincides with the onset of cathode-related decomposition observed in our DSC/TGA measurements and the associated oxygen release, which is consistent with temperature ranges reported in the literature for the activation of cathode-electrolyte and SEI degradation reactions under abuse conditions.

Experimental data indicate that higher TSI values (>0.5) arise predominantly from synergistic material interactions rather than isolated components, with separator-electrode interfaces exhibiting greater thermal severity than individual electrodes, highlighting their role in modulating the overall jelly-roll thermal decomposition potential under laboratory heating conditions.

The results presented in Figure 7 clearly indicate that the contribution of internal battery materials to heat release depends on their interactions rather than on their isolated thermal behavior. The anode test is in Zone I, evidences its dominant role in both early heat release and sustained thermal runaway initiation. However, when the anode is combined with electrolyte, the interaction shifts toward Zone II, indicating that although ignition occurs at higher temperatures, the thermal severity increases significantly, indicating that although ignition occurs at higher temperatures, the thermal severity increases significantly for heat release once initiated. In contrast, cathode-related interactions are predominantly located near the boundary between Zones II and IV, suggesting that, while cathode decomposition contributes to heat release, it is less effective at sustaining it than anode-driven reactions. Separator-related interactions are mainly distributed within Zone III, characterized by relatively low onset temperatures but a negative or marginal propagation severity index. This behavior confirms that separator melting or decomposition can occur early during thermal abuse but remains thermally self-limiting unless coupled with more energetic reactions involving active materials.

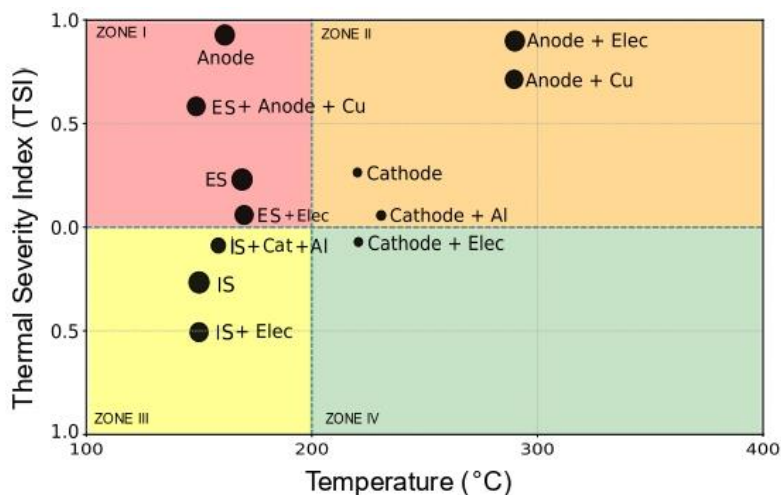


Figure 7. Thermal Severity Index (TSI) map ranks materials by thermal stability. ES: external separator, IS: internal separator, Cat: cathode, Al: aluminum current collector, Cu: copper current collector, Elec: electrolyte.

Summarizing all TSI results, combinations involving separator, electrolyte, and active materials exhibit the highest thermal instability ($TSI \approx 1.0$), indicating that separator-electrode interfaces produce significantly greater exothermic response than individual components under laboratory testing conditions. Although the separator exhibits low intrinsic TSI (-0.25), separator-electrode combinations show more elevated TSI (> 0), indicating synergistic thermal interactions between components under controlled heating conditions.

This emphasizes that the separator contributes to overall jelly roll thermal stability beyond its standalone properties, highlighting the importance of evaluating multi-component configurations in laboratory-scale thermal analysis. The TSI map clearly separates materials that dominate thermal decomposition initiation (early temperature onset, high heat flow on first exothermic peak) from those with moderate stability (separator-electrode combinations), emphasizing that laboratory-scale thermal hazard assessment must account for multi-material interactions within realistic jelly-roll configurations rather than relying solely on individual material properties.

A brief sensitivity analysis indicates that variability in TSI across the data set is mainly driven by the fractional heat contribution of the first exothermic peak and by the associated mass-loss fraction, whereas the onset temperature primarily separates early and late ignition configurations on the horizontal axis. Perturbations of the normalization factors do not modify which combinations are identified as the most thermally severe, which remain dominated by anode-electrolyte mixtures and separator-electrode interfaces. This confirms that the proposed index is robust enough to rank internal material interactions within the investigated battery cell, even though it is not intended as a universal hazard metric for all chemistries or operating conditions.

The TSI map shows that higher index values correspond to lower thermal stability and arise at specific interfaces, particularly anode-electrolyte and separator-anode stacks, whereas separator-dominated interactions generally fall in low or negative TSI regions unless coupled with highly exothermic electrodes. Consequently, minimizing highly reactive anode-electrolyte and cathode-electrolyte contacts at elevated temperature (through reduced free electrolyte, optimized

porosity/wetting, or thermally stable coatings and binders) and engineering separator-electrode interfaces with low TSI are promising routes to enhance safety. Furthermore, the TSI map can be used to focus cell level abuse tests on the most critical regions of the jelly roll (e.g. around anode-electrolyte interfaces and in the 150-250 °C window where separator shutdown and cathode/electrolyte decomposition become active).

The present results provide a component-resolved view of how internal jelly-roll materials behave under abuse-like thermal conditions in high-energy density cylindrical cells. The combined DSC/TGA analysis and the TSI map show that thermal stability is governed by synergistic interactions at specific interfaces (such as anode-electrolyte, separator-anode and separator-cathode) rather than by the isolated behavior of individual materials. For instance, the inner separator exhibits a pronounced endothermic transition around 150 °C that buffers heat flow from both cathode and anode and delays their exothermic peaks, while internal separator leaves about 25% solid residue at 900 °C in contrast to the complete decomposition of the external separator. Within the proposed framework, such differences in heat-absorption capability, residue formation and interface TSI values enable a comparative ranking of internal components and their combinations in terms of their contribution to thermal stability of the inner structure of the battery cell.

Beyond this laboratory-scale thermal-stability mapping of internal components, it is important to recognize the limitations of the present TSI framework. The DSC/TGA measurements are performed on small samples under controlled heating ramps and gas atmospheres, without internal temperature or pressure gradients and without mechanical constraints, so the TSI quantifies the intrinsic decomposition of materials and interfaces under these simplified conditions. As such, it does not explicitly account for heat dissipation paths inside the complete cell, the detailed jelly-roll geometry and gas venting, or the interaction with safety devices such as vents and CIDs.

4. Conclusions

The systematic thermal characterization of commercial NMC 21700 cell components reveals that heat release emerges predominantly from synergistic material interactions rather than isolated material behavior. DSC analysis demonstrates that inner separator integration delays exothermic peaks by 25-50 °C (cathode: 230 °C; anode: 300 °C) and reduces peak heat flow by endothermic transitions (140-220 °C), providing critical thermal buffering at electrode-separator interfaces.

The Thermal Severity Index (TSI) indicates that the highest thermal stability arises predominantly from synergistic material interactions of internal separator rather than from isolated components. However, external separator integration with electrodes yields elevated TSI values compared to individual materials, with measurable shifts in decomposition onset temperatures and peak heat flows. Electrolyte incorporation significantly increases TSI across active materials, positioning anode-electrolyte mixtures in high-TSI regions.

This framework establishes a first step to the mechanistic linkage between microscale thermal stability and macroscale fire safety assessment, validating the multi-component experimental approach while providing insights for battery design optimization and TR mitigation strategies. Next steps include correlating these DSC/TGA results with full-cell performance via adiabatic reaction calorimetry (ARC-HWS) to quantify total heat generation at the cell scale. This micro-to-macro validation will enable predictive modeling of heat generation for TR propagation in realistic

jelly-roll architectures, separator chemistry optimization, interface engineering, and safety certification protocols for next-generation high-energy LIBs.

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FIRE SAFETY IMPLICATIONS OF THERMAL RUNAWAY PROPAGATION AND GAS EMISSIONS IN PRISMATIC LITHIUM-ION BATTERY MODULES

PhD Student **Alejandro Gómez-Soriano**¹,
Assistant Professor **César Carvallo**^{1*},
Associate Professor **Carlos Micó**¹,
Full Professor **Antonio García**¹

¹ IUI CMT–Clean Mobility & Thermofluids, Universitat Politècnica de Valencia, Valencia, Spain.

*Corresponding author: cecargar @ mot.upv.es

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Thermal-Runaway, Lithium-Ion Batteries, Fire Safety, Gas Emissions, Propagation.

Abstract

The increasing use of lithium-ion batteries in electric mobility and stationary energy storage systems introduces critical challenges for fire safety, such as Thermal Runaway (TR) events, that may result in significant heat release, toxic gas emissions, and propagation to neighboring cells in battery modules. This study presents an experimental investigation of TR in Nickel Manganese Cobalt (NMC) cathode battery modules under controlled and realistic conditions. Testing was conducted using the MUBAT (Modular Unit for Battery Abuse Tests), a dedicated and reconfigurable platform capable of accommodating different module configurations while reproducing typical mounting and operating constraints. TR was initiated by thermal abuse through an external resistive heater positioned at one end of the module, promoting unidirectional propagation. Thermal evolution was monitored using a thermocouples network, while gas composition at the exhaust duct was continuously analyzed by Fourier Transform Infrared (FTIR) spectroscopy. Maximum temperatures in the module reached approximately 800 °C, and significant concentrations of CO₂ were observed, as well as CO or hydrocarbons. The experimental campaign provided high-resolution data on thermal propagation and gas emission, offering insight into enclosure fire behavior for battery systems. These findings serve as a reference dataset for model validation, fire risk assessment, and the design of future mitigation strategies. The MUBAT platform establishes a reproducible and scalable methodology for future investigations of different chemistries, states of charge, and cooling configurations, providing critical input for performance-based fire safety analysis, risk modeling, and the development of effective protection strategies for lithium-ion battery systems.

1. Introduction

The rapid deployment of lithium-ion batteries (LiBs) in stationary energy storage applications has intensified the need for robust safety assessment frameworks capable of addressing the complex phenomena associated with thermal runaway (TR) and thermal runaway propagation (TRP). As Battery Energy Storage Systems (BESS) grow in scale and power density, ensuring that their design, installation, and operation comply with international safety standards has become a critical prerequisite for widespread adoption. Regulatory bodies and technical organizations have

therefore developed testing guidelines. As an example, UL 9540A [1], NFPA 855 [2], IEC 62619 [3], and UN 38.3 [4], are some of the updated regulations and standards to characterize the behavior of LiBs under abuse conditions and to quantify the associated fire and explosion hazards. These standards place strong emphasis on parameters such as temperature evolution, gas venting dynamics, combustion behavior, and the spatial–temporal characteristics of TRP in cell and module assemblies.

In this regulatory context, the preliminary April 2025 revision of UL 9540A proposes significant advancements in installation-level testing methodologies for BESS. The updated protocol strengthens the separation between fire and explosion hazard assessment, introduces refined criteria for evaluating enclosure robustness and separation distances, and places increasing importance on vented-gas behavior during fully developed fires. The relevance of effluent gas temperatures, compositions, and flow patterns is thus reinforced, aligning UL 9540A more closely with the physical mechanisms captured in NFPA 855 and enabling more representative validation of active fire-suppression systems. Additionally, there is some previous literature that analyzes the main associated risks and some proposals to address it as exposed by Lopez et al. [5].

Complementing these system-level standards, cell-level regulations such as IEC 62619 define fundamental safety thresholds under thermal, mechanical, and electrical abuse, directly influencing how individual cells respond prior to module-scale TRP. Large-format prismatic cells which now are more common in utility-scale BESS due to their high energy density, pose distinct challenges due to their thermal inertia and their potential to sustain multi-cell propagation once TR is triggered.

Within this framework, the present work introduces an experimental methodology for controlled unidirectional TRP testing in a 5s1p module of large-format NMC prismatic cells. The method employs external overheating to induce TR in a single cell and generate TRP across the module while capturing high-resolution thermal and combustion data. A dense thermocouple network enables interfacial cell-temperature estimation, and FTIR spectroscopy provides continuous, species-resolved characterization of the thermal runaway effluent gases. Three replicate tests were conducted under controlled and repeatable boundary conditions to assess the reproducibility of TRP dynamics and to quantify both the thermal behavior of the module and the evolution of combustion products.

The analysis presented in these experiments provides insights into the spatial–temporal structure of TR propagation, the consistency of cell-level failure sequences, the influence of module architecture on heat accumulation, and the trends in effluent gas composition throughout propagation. The results contribute to ongoing efforts to harmonize scientific understanding with regulatory requirements and to improve the design, validation, and safety assessment of next-generation battery modules used in BESS applications.

1.1. Standards and Regulatory Context

The increasing integration of lithium-ion batteries into critical applications has prompted the development of several international regulations and standards to address safety, performance and testing protocols for lithium-ion batteries. Among these, UL9540A [1], NFPA855 [2], IEC62619 [3] and UN38.3 [4] are some of the usual guidance on valuating the hazards associated with lithium-ion batteries. Those risks are mainly related to gas venting, TR and fire propagation due to those events, both in single cell configurations and complex battery modules systems. These frameworks establish parameters that must be characterized experimentally, to support

risk assessment and regulatory compliance: such as temperature evolution, gas compositions or even propagation dynamics.

Regarding the April 2025 preliminary proposal UL9540A, there are some substantial updates proposed for the installation level test methodology used for evaluating TR fire propagation in Battery Energy Storage Systems (BESS). The main goal of the UL9540A is to adapt some of the testing protocols collected in NFPA855 to the recent large BESS. The proposal explicitly separates the fire-hazard from the explosion hazards evaluation allowing to characterize each phenomenon with tailored methods according to its physical behavior. The aim of these modifications is to improve the validation of the spatial distribution (distances, separations...), enclosures robustness and the effectiveness of active fire suppression systems.

The developed-fire condition concerns a self-sustaining fire including the ignition of the flammable gases released (vented) by the cell, to stress neighboring cells. Two main ventilations configurations are proposed according to UL9540A, what places the gas emissions during the fire testing to play a major role. Additionally, cell temperature and vented gases temperatures, also take significant importance during the test proposed by the proposal, using terms such as the previously mentioned *fire-developed condition*, or *thermal-runaway effluent gases*, *thermal-runaway-propagation protection* and *active fire-protection system*.

Other regulations such as the IEC62619, are more related to the cell level testing defining some essential parameters to determine the safeness of the lithium-ion battery cells. The in-cell regulations have the same importance as the module-level regulations, understanding the in-cell regulations as those applied directly to the elemental unit of a module-level system. If the module-level regulations define some limits for Thermal Runaway Propagation (TRP), the in-cell regulations set the limits for the individual behavior of the cell. Regarding the most common abuse (thermal, mechanical or electrical), the standard establishes the main guidelines for its safety, which most of them are related to the cell temperature.

Within this framework, this work presents a methodology for battery module testing under unidirectional TRP, induced by overheating abuse and allowing the measure of the cell temperature through interfacial thermocouples and the combustion results regarding the thermal runaway effluent gases through Fourier Transform InfraRed spectroscopy (FTIR) measuring.

2. Experimental Setup

Regarding the experimental setup, a series of three identical experiments were conducted to address the main variables previously described temperature and thermal runaway-effluent gases. The experimental campaign consisted of three replicate tests conducted under controlled and identical boundary conditions with the aim of evaluating the reproducibility of the TRP phenomena in Nickel Manganese Cobalt (NMC) large-format prismatic cell-modules. To address the key aspects of TRP a network of interfacial thermocouples and online FTIR gas measuring was used to address the main thermal behavior and the subsequent combustion consequences.

2.1. Battery module Configuration

Regarding the battery module configuration used for the three developed tests, the architecture is based in a 5s1p cell configuration (five cells in parallel connection). The module is based in large-format prismatic cells, as there are one of the dominant trends in novel BESS designs. The large-format prismatic cells, are 1.95 kg each, providing high thermal inertia to the system. These

cells provide the module with a wider energy density than other modules developed with different formats/chemistries, however, the use of large-format cells brings some serious safety concerns in terms of TR and TRP. Regarding the cell dimensions, a 303x100x31 mm (LxHxW) parallelepiped shaped is used for these cells. This leaves 30 cm³ intercell contact and 31mm of cell perpendicular to this face, which will take a significant role for TRP.

Regarding the cell electrical properties, there is a nominal voltage of 3.7V, and an internal resistance (measured at 1kHz) of 0.7 mΩ. Each of the cells was previously charged at the maximum capacity which means a State of Charge of 100% (SOC=100%). SOC=100% represents the worst-case scenario for TRP, as similar studies determined, with highest SOC the TR response gets more violent, as disclosed by Song et al. [6].

2.2. Experimental Procedure

Regarding the experimental procedure, as was mentioned previously, the test matrix is based in three identical tests with the same boundary conditions to address the repeatability of the TRP event. This experimental procedure was specifically designed to induce TRP unidirectionally in the battery module, through the perpendicular direction to the greatest face of the cells. The battery module, as previously mentioned, is composed of five cells each, what will provide for some of the monitored cell-level variables, up to fifteen repetitions that will allow addressing (considering the data set limitations) some insights of the cell-level behavior.

Regarding the initial conditions, all the tests were developed in the same chamber, under exact conditions of temperatures, pressures and air velocities, as well as the previously mentioned SOC of the cells and the module configuration. Regarding the overheating element, pristine heaters were used for each of the experiments without assuming a minimum manufacturer variability. The temperature conditions at the beginning of the test were stabilized at 23°C and the pressure inside the chamber was driven by the extraction system. The extraction system, with 8000 m³/h nominal flow, is located at the chamber outlet. This outlet flow, bridged with the inlet filters, derives in the same pressure conditions inside the chamber for the three abuse tests.

Regarding the main test data acquiring systems, they were configured with an acquisition frequency of 1Hz, the maximum allowed considering the dense thermocouple network and the FTIR measures. It is important to consider that there may be some delay between signals due to the position of the FTIR probe, located in the outlet duct of the chamber, that will be revised in further sections. Once the measuring instruments are online, the heater is turned on, and the first cell is induced into the thermal failure. The heater is turned off once full TR is reached, driven by a certain threshold of temperature rate. Once the first cell is triggered, the test will end once all the cells reach the initial temperature conditions. This procedure ensures that the entire TRP phenomenon is fully captured, or if there is no TRP, the module behavior will be also captured.

2.3. Test Platform Description

Regarding platform where the tests were developed, it is important to highlight that the architecture of it must ensure the repeatability between tests. Withstanding the adverse conditions of the TR events and ensuring identical boundary conditions between tests. To achieve that, a modular abuse unit for these battery module testing was designed. Besides the repetitiveness between tests, one of the main ideas behind the design of this test platform is to emulate realistic enclosure conditions of battery modules packaging, where there are mechanical restrictions all around the battery cells. It is important to mention that for these experiments, the mechanical

arrangement of the battery module is 5s1p, but the modularity of the test platform, will allow several module architectures tests.

The test platform will be housing the five cells of the module in the main steel base plate. It is important to mention that between the cells and the bottom plate, an insulation layer of 4 mm is placed as interface for trying to avoid unmeasured heat transfer due to conduction. Between each cell, there will be also an insulation layer of the same thickness and material, whose thermal conductivity is 0.08 W/mK and a maximum temperature of 1260°C. To compress the cells, two aluminum plates are placed at the extremes of the modules combined with four threaded rods that allow appropriate tightening for maintaining the cell compression forces between tests. Finally, at the top part of the test platform there is a top steel plate that will simulate the typical constraints of a BESS. This top plate will have direct influence on the flame deflection derived from the TR of each cell, exposing the cells to higher temperatures due to convective and radiative heat transfer mechanisms. In Figure 1, a) the platform used for the test can be observed. The combination of all the elements of the test platform will allow to prepare controlled boundary conditions for obtain representative results closer to real operation conditions in real battery modules.

2.4. Thermal Abuse Protocol

The TRP event was initiated using overheating abuse techniques through an external resistive heater placed at one of the extremes of the battery module. This abuse technique aims to emulate real failures in the normal operating conditions of real battery modules. The unidirectional TRP event was initiated by triggering the adjacent cell to the heater. Once the triggered cell reaches the thermal runaway, the heater is turned off, and the TRP phenomenon initiates. To determine when the cell reaches full TR, the temperature rate will be the monitored variable. The main threshold is determined to be at 6°C/s. Above that threshold, the full TR event is considered to be developed.

Some of the most common tests for single cells relieve homogeneous heating techniques such as Accelerating Rate Calorimetry (ARC) test, that withstands for determining important parameters in cell level safety as disclosed by García et al. [7]. However, the side heating method used for these tests represents closely real failure conditions. The resistive heater used for the side heating in these tests provides a heating power of 350 W, deriving in a heating curve from the type $T(t) = a \cdot t^b + c$. For each of the tests, pristine resistive heaters were used for maximizing repeatability between tests, avoiding possible damage derived from the TR of the cells.

2.5. Instrumentation and Measurements

The instrumentation of the battery module relies on temperature measures, gas emissions measures and online natural luminosity imaging. The temperature measures were conducted using a thermocouple network distributed along the module, comprehending the top part of the cells at 20 mm of the venting port and the interfaces of each cell. The top thermocouples will record the temperature of the hot gases at the top of the cell during the TR of each cell while the thermocouples placed in the mid of the cell faces will record the temperature evolution of the TRP and will serve for estimating each cell temperature. In Figure 1, a) the entire thermocouple network can be observed. In addition to the temperature sensing, as was previously mentioned, natural luminosity imaging will be also included for safety purposes during the tests. Despite being

an essential source of results, it will provide some insights into the developments of the test during the execution of them allowing to increase safety considerations.

The test volume consists of a closed and thermally insulated volume that allows different instrumentation of several tests due to the different optical access and wall bushings. As was previously mentioned, it is equipped with continuous air extraction system, installed in the outlet pipe of the volume. The outlet pipe will be also where the FTIR probe is installed, which combined with the continuous air extraction will ensure the measurement of the gas release by the battery module along the entire test. It is important to consider that it may be some slight delays between the thermal response of the battery module and the combustion resulting gases observed with the **FTIR** due to the separation between the probe and the main unit under test. In Figure 1, b) the entire test volume is displayed.

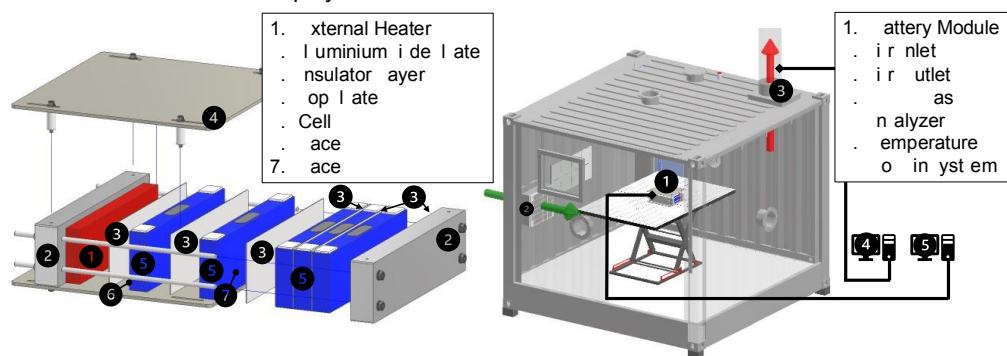


Figure 1: Battery module assembly and test chamber description.

3. Results

This section presents the main analysis of the results obtained from the three unidirectional TRP tests. This phenomenon is mainly governed by heat transfer, which involves temporal and spatial implications. Thus, this section is structured to progressively link temperature evolutions in the sequence of the TR events and the corresponding behaviors, as well as some derived indicators of the severity and celerity of the propagation dynamics across the module. The objective is to identify reproducible patterns across the modules and quantitatively characterize the main conduct of TRP in terms of intensity or celerity, as well as the main consequences in terms of TR effluent gases.

The first set of results shows the temporal evolution of the cell temperatures measured during the three experiments. This cell temperature is estimated by the averaging of the cell face temperatures, assuming uniform gradient between faces. This temporal evolution allows visualizing the chronological order of cell failures and some degree of repeatability between the experiments. It is important to remark that the instant of the TR of each cell is marked with red dashed lines. The criteria to determine this instant is based on the cell temperature rate, metric

that determines the selfheating rate of the cell and clearly discloses the fully developed thermal runaway when exceeding 6°C/s.

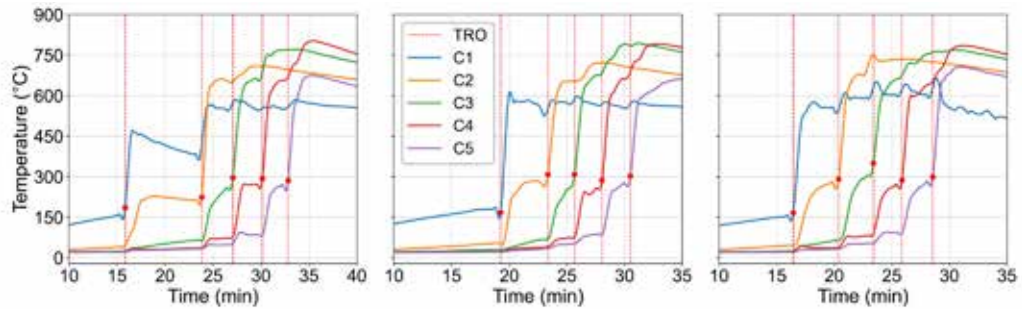


Figure 2. Temperature evolution, test 1 to 3.

The Figure 2, a), b) and c) for test 1 to 3, clearly display the sequential pattern of failure of the TRP in the battery modules. The initial TR observed in cell 1 induces the TRP in all the cells downstream the triggered cell, sequence which is highlighted with the Thermal Runaway Onset (TRO) red dashed line.

Figure 2, a), exhibits a noticeably longer propagation time between the triggered cell and the following cell, deriving in a more pronounced cooling phase, and longer exposition of the second cell to higher temperatures. However, it is visible how the TR of the trigger cell consistently occurs in a time window slightly below the five minutes delay between the start of the experiment, represented in the xaxis. Additionally, after the TRO of the second cell, the propagation times between cells, remains consistently similar between cells and experiments. It is also visible how the maximum temperatures are around 800°C, and how this maximum increases when the propagation advances up to the last cell in the module, when this peak temperature decreases. While the timeseries illustrates the overall dynamics, heatmaps are better tools to understand the spatial distribution of the temperatures at each instant, named from “t1” up to “t ”, one for each TRO. The resulting matrix contains three rows, one for each test and five columns with five subcolumns, one for each onset time and one for each cell. The color range selected has two main ranges: firstly, 20-100°C which approximately represent the working range above the initial test temperature. The second range corresponds to 100-850°C, which represents the characteristic temperatures reached during the TR event in each cell. This heatmap is displayed in Figure 3, and complements the mentioned behavior of the temperatures, which are clearly higher in the inner cells even after the TRO of various downstream cells. It is also visible how the cells away from the TR events remain in a controlled temperature window, however, as the TRP advances towards the module, the temperature of the downstream cells starts rising above the defined region of safe temperatures. This heatmap provides a clear visual of the temperature distributions with a defined temporal resolution, allowing each of the cells states in each of the TRO instants.

It is important to highlight the repeatability between all the tests, which shows that the spatial temperature distributions are highly similar. This TRP starts with the onset of the triggered cell identified as “nset C.1”, which at the instant of the TRO induce slightly higher temperature in the following cell, while the rest of the module is almost still. he “nset C.” instant, discloses a complete developed TR event in the upstream cell reaching above 400°C in all the test performed.

This fully developed TR event in the first cell, that has induced the TRO in the second cell, also induces higher temperatures to the rest of the module. While during the TRO of the first cell, the second cell was below 0°C, in the case of “ onset C. ”, the next cell is significantly at a higher temperature. It is clearly visible how the temperature of the cells starts rising as the TRP progresses towards the module deriving in higher temperatures in downstream cells and increasing the temperature of the non-failed cells. Fo example, regarding the instant “ onset C. ” is visible how the last non-failed cell is almost around the 100°C at the instant of the TR of the cell four, while the second cell in “ onset C.1”, as mentioned, was below 60°C. This heatmap clearly illustrates temporal and spatial resolution about the temperature behavior, however, does not provide clear perspective in terms of the overall module and critical aspects as module maximum temperatures.

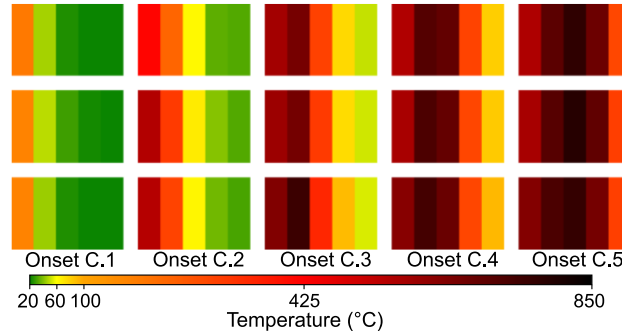


Figure 3. Thermal runaway propagation map

Based on the temperatures fields previously observed, two severity indices are introduced and computed, using the following analytical expressions. These indices incorporate the main characteristics of the TRP event allowing direct comparison between cells and tests. Firstly, the Fire Severity Index (FSI) is defined to condense the thermal distribution, based on the maximum temperatures observed during each of the tests (j) and in each cell (i), and their definition can be found in (1). Directly related with the severity of the event in terms of maximum temperatures, is also the celerity of the event. To address the celerity of each of the TR events of the cells, the Fire Celerity Index (FCI) is computed. This metric provides crucial insights about the rate of change of the temperature for each of the TR events, basing the definition of the index in this parameter as is defined in (2).

$$FSI_i^j = \frac{T_{max_i}^j - T_{min}}{T_{max} - T_{min}} \quad (1) \quad FCI_i^j = \frac{dT/dt_{max_i}^j}{dT/dt_{max}} \quad (2)$$

In Figure 4, a) the FSI reveals that the highest severity regarding temperatures consistently occurs in the interior cells of the module (cell 3 and 4). This concentration can be attributed to their more restrictive thermal environment within the battery module, which limits the heat dissipation path in comparison with the outer cells. Additionally, as was previously revised, there is a progressive temperature rise observed along the propagation path that contributes to obtaining warmer boundary conditions in the overall module, that may derive in that observed higher temperatures. Furthermore, it is important to remark the similarities between the indices described, which discloses that the maximum temperatures obtained in the interior cells are highly similar between them. This is clearly illustrated for example in the third and fourth cell of the module in all the test, which presents an index in the range between 0.95 and 1.00.

In contrast, Figure 4, b) displays a different behavior of the FCI, exposing more uniform pattern despite the initial cells. The trigger cell and the subsequent shows higher celerity values, indicating faster temperature-rise dynamics during their individual TR events. This behavior is specifically evident regarding the first cell of the second test, where the maximum value is observed. That behavior of the first cells, can be linked with the previously displayed graphs, as at was displayed in Figure 3 the triggered cell presents the lower TRO temperatures, while as exhibited in Figure 4 a) the maximum temperatures indices reached in these cells are similar to the absolute maximums observed in the interior cells. Additionally, these larger differences observed in the first cells may be also linked to the initially colder boundary conditions of the battery module during the triggering of the first cell and the TRP to the subsequent cell, that was previously mentioned, deriving in higher temperature rises.

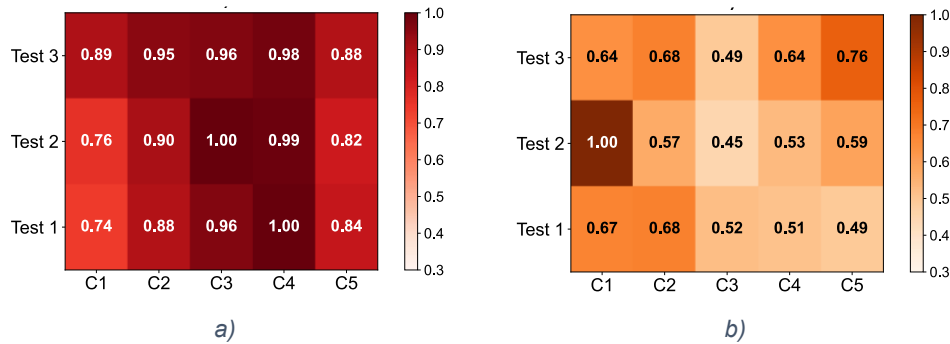


Figure 4. a) Fire severity index, b) fire celerity index

Based on the previously defined TR instants, the Figure 5 a), presents the evolution of the propagation times as a function of the cell positioning inside the battery module. It is important to mention that the time scale is modified to match the first instant TRO of the triggered cell. Additionally, the cell position was taken using the center of each of the cells, considering the corresponding gaps derived from the previously mentioned configuration. With this approach, all the representations start from the same instant, providing a clear understanding of the propagation phenomena. Furthermore, the cell center also concurs with the uniform temperature gradient hypothesis assumed for estimating the cell temperature. This analysis allows deriving an effective TRP velocity, which is displayed in Figure 5 b), where each column represents the propagation velocities between adjacent cells.

In Figure 5 a) a clear trend emerges across the three tests, related to the timing between the consecutive TR events. Despite the TRP between the first two cells, the progression observed with the cell position is almost linear. Although the first test presents some slight deviation from the rest, the overall behavior remains remarkably consistent among the three experiments. This temporal behavior is directly translated into propagation velocities shown in Figure 5 b). It is visible how the lowest propagation velocities are observed between the first and the second cell, while the highest velocities, are observed between the interior cells. This discloses that the first TRP is apparently the slowest propagation event, which also agrees with the reduced slope of the first step of the Figure 5 a). Beyond this initial step the overall behavior is consistently similar between then, finding slight differences between the inner cells and the las cell modules. In the inner cells, slight maximum of velocity is found which can be attributed to the enhanced heat accumulation

within the interior region of the module, which enhances the cell heating and consequently accelerates the TR event in those cells.

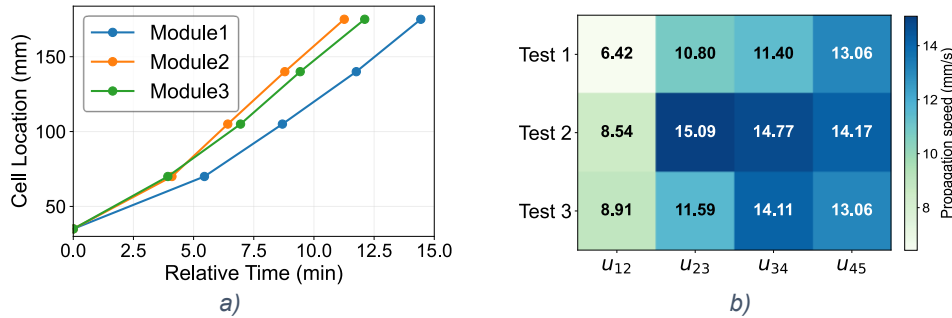


Figure 5. a) TR propagation times, b) propagation velocities (mm/s)

Finally, the results sections conclude with the main summary of the combustion results obtained from the TR experiments, the effluent gases measured using FTIR. These effluent gases are considered as the gases and vapors emitted during the TR event of a lithium-ion battery cell, according to the standard UL9540A. The Figure 6 displays the temporal evolution of the effluent gases observed from each of the TR events of each of the cells. This measured effluent gases comprehend carbon dioxide (CO₂), carbon monoxide (CO), methane (CH₄), ethylene (C₂H₄) and butyne (C₄H₆), which are considered the main components. Regarding the maximum concentrations observed, it is visible how the dominant components of the effluent gases is carbon dioxide, which appears in substantially higher concentrations than any other species. Small but consistent quantities of carbon monoxide and unburned hydrocarbons are also identified, highlighting the incomplete combustion of the gaseous products released during TR. Nevertheless, the amounts of these unburned species remain significantly lower than the CO₂ levels observed. It is also noteworthy that, despite the generally stable and repeatable behavior across individual cells, a gradual increase in CO concentrations is observed as the TR propagates through the module. Similar, though less marked, tendency can be inferred for the unburned hydrocarbons in some of the tests. This suggests progressively more violent consumption of the available oxygen as the TRP phenomenon advances along the module. However, it is important to remark that the air extraction system is continuously renovating the available air inside the test chamber, allowing it to refill with fresh air inside the test chamber. Additionally, due to the temporal evolution, is visible how for some of the cells, the TR event appears before the main combustion of the effluent gases released during the fully developed TR, as for example in the first cell of the second test, Figure 6, b).

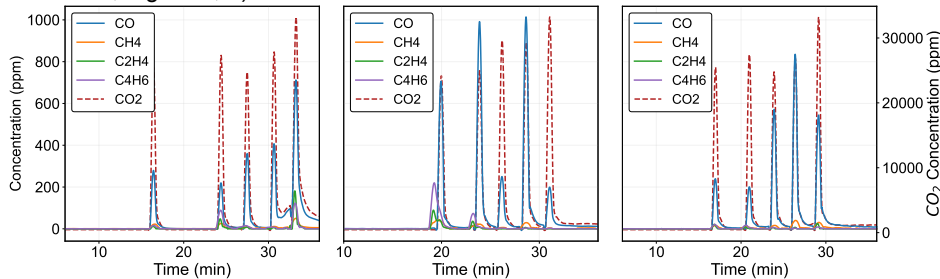


Figure 6. Temporal evolution of the effluent gases of the battery module, test 1 to 3.

4. Conclusions

This study presents a detailed experimental investigation of the TRP event in large-format NMC battery modules under controlled and reproducible conditions. Across the three identical experiments with similar boundary conditions, the results demonstrate a highly consistent TRP sequence, characterized by sequential order of failure of the cells, the similarities between the propagation times and the stable thermal signatures. After the analysis of all the results across the temporal and spatial thermal evolution, characteristic indices, propagation velocities and effluent gases, the main key findings are summarized as follows:

1. High repeatability of TRP dynamics:

The temperature evolution and the TRO instants exhibited string consistency across the three tests. The triggered cell reached TR within a narrow window, and the subsequent propagation of the TR maintained similar temporal spacing between cells, confirming the robustness of the methodology.

2. Progressive heat accumulation and spatial dependence:

The interior cells of the battery module reached systematically higher temperature than the outer cells, as quantified through the FSI. This behavior is attributed to the limited heat-dissipation pathways and accumulating thermal loads as a consequence of the advance of the **TRP** through the module. Additionally, the FCI also revealed higher temperature-rise rates in the initial cells what can be influenced by the colder initial boundary conditions of the battery module.

3. Consistency of the TRP dynamics:

The propagation step observed between the first and second cell, consistently exhibited to be the longest delay among all propagation steps. This behavior can be attributed to the initial colder thermal state of the battery module, between the TR of the first and the second cell. As the propagation progress towards the battery module, the downstream cells are exposed to warmer initial conditions due to the heat accumulation and the propagation steps between cells in the three tests, remaining in a similar range, with slightly higher values in the interior cells, exposing the strong repeatability of the TRP event.

4. Combustion pathways extracted from effluent gases composition.

The FTIR measurements showed that CO₂ is the predominant product observed in the effluent gases, while CO and light hydrocarbons also appearing in small but consistent quantities. A gradual increase in the CO concentration is observed as the TRP events advance towards the module despite the continuous air renewal, exposing incomplete combustion events of effluent gases as the TRP is developed.

Summarizing, this work presents a repeatable and representative methodology for analyzing module-level TRP in large format NMC cells. The results not only showed high repeatability in the thermal and combustion signatures, but also stable and consistent propagation velocities with nearly uniform timings between cells. This quantitative consistency strengthens the reliability of the dataset and the physical interpretation of the main phenomena that governs TRP. Moreover, the combined thermal and effluent gases measurements offer a regulatory relevance by supplying synchronized, module-level data that directly support ongoing updates on safety standards. Altogether, these insights contribute to the assessments of TRP severity, possible fire mitigation strategies and the development of next generation BESS architectures capable of more effectively managing thermal-runway hazards.

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Analysing European fire incidents in Electric Vehicles



Martina Manes
Lecturer in Civil
Engineering,
School of
Engineering,
University of
Liverpool,
United Kingdom



Ulises Rojas-Alva¹
Research Associate,
Fire-Safe
Sustainable Built
Environment
(FRISSBE)
Department,
Slovenian National
Building and Civil
Engineering Institute
(ZAG),
Slovenia

Keywords: Lithium-ion battery LIB, mobility devices, thermal runaway, fire incident, frequency rates

ABSTRACT

This study aimed to investigate existing European datasets on fire incidents involving LIB-based electric vehicle devices to effectively identify fire scenarios and quantify incident rates. It is in this light that several readily available fire incident datasets from the Netherlands, London, Denmark, Sweden, Norway, and Finland have been critically examined with respect to terminology, data collection, statistical variables, quality assurance processes, and data availability. The results show that the datasets exhibit variability in the available fire statistical variables, collection methodologies and quality assurance processes. The incidents reported across the datasets show increases of 1.4 to 6.75 for EVs, 1.9 to 4.9 for BEB and BET, and 2.2 to 32.1 incidents per year for LEVs, respectively. The calculated frequency rates for EVs vary from 0.5 to 1.32 incidents per year per 10,000 vehicles for the European datasets for the last year of reported data, for LEV from 0.21 to 0.43 incidents per year per 10,000 LEV, while for large electric vehicles (BEB and BET) varies widely, indicating that the dataset is not yet statistically reliable. The findings will increase awareness of fire risk, implement data-driven applications of LIBs, and enhance international collaboration in data collection and reporting.

¹Corresponding Author – ZAG Požarni Laboratorij, Obrtna cona 35, 1370, Logatec - Slovenia.

Telef.: +386 70 639 260, e-mail: ulises.rojas-alva@zag.si

1. INTRODUCTION

The lithium-ion battery (LIB) technology has been developing extensively since the 1990s, and the objective of the electrochemistry field is towards high-energy density [1], where electrochemists are working to develop LIB chemistries and design to improve the energy densities, more energy in less mass. Thus, in the future, society will experience LIBs with an ever-increasing energy density, leading to more affordable and efficient electromobility devices. However, such condensed energy in small volumes can also pose threats to society. In the latest Global EV Outlook published in 2024 [2], several key trends in the global EV market can be highlighted. Electric vehicle sales have shown a remarkable upward trend from 2012 to 2023, with figures in millions. In China, due to a competitive market, projected sales growth is approximately 25% in 2024, reaching around 10 million EVs and capturing 45% of the total global market. In the USA, growth is projected at 20% in 2024, whereas in Europe, it is projected at 10%. Despite this modest rise in Europe, EVs will represent one in four cars. Outside the major EV markets, overall growth is projected at 40% over 2023, reaching over 1 million units worldwide. Beyond passenger electric vehicles, LIB technology is also permeating large vehicles and light electric vehicles (LEV) [3]. Battery electric buses (BEBs) have increased from 100,000 to 800,000 since 2014. In the case of battery-electric trucks (BETs), the trend is on the rise, reaching fewer than 100,000 in 2021, with the Chinese market as the most significant contributor.

LIB technology has been reported as a cause of fire ignition, leading to catastrophic consequences due to various reasons (overcharging, overheating, crashing, etc) [4]. The starting point or phenomenon is the thermal runaway of the LIB cell. Once the onset is achieved, the process becomes very rapid, leading to cell rupture. Thereafter, through the rupture opening, venting of gases and ejecta or particulates occurs, releasing energy as the gases react with one another and with the oxidiser in the air. In early ignition events, an overexpanded jet (jet flame) is formed. If the ignition of the jet is delayed, then a deflagration can take place (9-10% of the reported incidents with EVs lead to explosion) [4–6]. EVs and other mobility applications (trucks, buses, bikes, scooters, etc.) can then pose a further threat to the built environment, its occupants, and users, as, if thermal runaway occurs, the safety design of the building can be compromised, especially in open or closed car parks, garages and proximity of charging points. For fire engineers and authorities, as part of the safety design of the built environment and infrastructure, it is relevant to perform fire risk analysis, such as fault tree and event analysis. Such analyses require the incident rate of fire occurrence, the fire consequences, influencing factors and their effects on fire consequences. Therefore, data are essential for a comprehensive understanding of the phenomenon and for identifying and mitigating risk.

Nonetheless, incident datasets for fire incidents are scarce and readily available across various mobility applications, and data quality may introduce reliability and accuracy challenges. A study conducted by Tohir & Martín-Gómez to investigate the EVs fire risk assessment framework using Fault Tree Analysis [7] estimated the frequency of EV fires. Although this methodology systematically evaluated potential causes of EV fires and their probabilities, it did not provide a qualitative analysis of the datasets and focused only on EVs, without analysing other applications such as BEB, BET, and LEVs. As LIB is considered an emerging technology, introduced mainly after 2020, the data may refer to only a few years, as local and national authorities have only recently begun collecting such data. This highlights the need to evaluate the available datasets on fire incidents involving mobility devices.

Therefore, the aim of the research is to conduct a comprehensive analysis of the existing European fire statistical dataset to understand the actual performance of LIB mobility applications under fire conditions. The objectives are to map the available European fire statistical datasets related to EVs in terms of responsible authorities, collection methodology, examined years, fire statistical variables, and data quality; develop a gap analysis highlighting differences and similarities across countries; and provide guidance to move towards a harmonised fire statistical collection. Once the description of the existing datasets is introduced, the analysis focuses on evaluating frequency rates, defined as the number of reported EV fire incidents divided by the cumulative number of EVs in the country or globally. For the current study, the focus is only on EVs, defined as passenger vehicles and light commercial vehicles (vans), light electric vehicles (e.g., bikes, scooters), and large vehicles such as battery electric trucks (BET) and battery electric buses (BEB).

2. METHODOLOGY

The research methodology focuses on identifying existing fire statistical datasets related to LIB fires in Europe, by application, including EVs, BEB, BET, LEVs, and others. The available data were analysed with respect to responsible authorities, collection methodology, examined years, fire statistical variables, and data quality. Usually, the dataset refers to a country, region, or specific area. Fire statistical trends are presented by fire incidents, LIB types, potential fire causes and influencing factors, and, where possible, fatalities and injuries. The analysed published data were accessed online in the form of annual reports, publicly available datasets, conference or journal publications and from interactive online dashboards. The investigated fire statistical datasets are highlighted below:

- London Fire Brigade (LFB): Lithium and Electric Vehicle fires [8].
- Netherlands Institute for Public Safety (NIPV): Alternative powered vehicles [9–11].
- Danish Emergency Management Agency (DEMA): Statistical Bank [12–14].
- The Norwegian Directorate for Civil Protection (DSB): Fire statistics [15].
- Swedish Civil Contingencies Agency MSB: Statistical database on accidents, injuries and rescue operations [16,17].
- Finland: Rescue Service Resource and Accidents Statistics (PRONTO) [18–20].

The majority of the examined European fire incident datasets comprise national data, except for LFB, which is related to the London Metropolitan Region. For European countries, the cumulative number of registered passenger cars and light commercial vehicles was obtained from the European Commission's European Alternative Fuels Observatory [21], other websites [22,23] or specific publications [16]. Lastly, mobility devices studied are divided, whenever possible, into the following sub-categories:

- Electric vehicles or EVs (including all hybrids), such as passenger cars and light commercial vehicles (vans).
- Battery electric buses and minibuses or BEB (including all hybrids).
- Battery electric Trucks or Lorries (including all hybrids).
- Light electric vehicles (LEV) such as e-bikes, e-scooters, e-hovers and e-motorbikes (<32 km/h).

3. RESULTS AND DISCUSSIONS

3.1 Fire incident datasets

A detailed summary of the datasets for selected European countries is provided in Table 1. Based on the analysis in Table 1, the London Fire Brigade (LFB) has been publishing data on fires involving lithium batteries since 2017 [8], as EV fires appear to be an emerging risk in London. The publicly available dataset presents information recorded by the Fire and Rescue Services in the aftermath of an event that is updated monthly. As illustrated in Table 1, the LIB types are subdivided into 4-wheels, such as car, van, bus/coach, lorry/HGV, Minibus, Agricultural vehicle, Trailer, Towing caravan and multiple vehicles; 2 wheels, including e-scooter, e-bike, motor home, motorcycle and bicycle; portable devices related to e-cigarette and other LIB devices referred to other road vehicles and Other LIB. In addition to the LIB types, the vehicle power type and vehicle manufacturer are also collected (Table 1). Moreover, the other fire statistical variables refer to the fire incident description by year, month, and geographical location of the fires, as well as the pre-fire incident description of the ignition source and power, the item first ignited, and whether the LIB is mentioned in the reports. No data are available on variables related to the fire stage or post-fire conditions. Fire and Rescue Service collects the information in the aftermath of an event, and LFB applies a quality assurance process.

NIPV and the Fire Brigades across the country created a national dataset [9] on incidents involving alternatively powered vehicles from 2021 to 2025, regularly updated, with a dashboard that collects incident information via a questionnaire. The NIPV dataset's variables are listed in Table 1; however, not all variables are readily available in its interactive online dashboard [10,11], and some are published in the yearly incident report. Fire statistical variables include type of incident (firefighter, assistance, firefighter and assistance), vehicle type, battery pack specifications (battery not involved, battery involved, battery damaged by incident but not involved in the fire, unknown), involvement of charging structure, used resources, and casualties (fatalities or casualties). The data are collected through a questionnaire shared with the Fire Brigades, and quality checks are applied to ensure data accuracy and completeness.

In Denmark, DEMA [12–14] collects information on EV type (EV, HEV), incident type (driving and non-driving), registered influences in the event, and registered impact when using the extinguishing container. The Fire Brigades collect the information, and DEMA ensures all reports undergo quality checks. In Norway [15], the information is related to EV type (EV, HEV). Fire departments collect all relevant data and upload it to a database. In Sweden [16,17], incident information is assessed by Fire Officers and added to a central database. The fire statistical variables include vehicle type (EV, bus, truck), LEV (e-bike), and fire occurrence specification (during journey, while charging, and others). In Finland [18–20], statistics are sourced from the PRONTO information system and refer to EV type (EV, Hybrid Electric Vehicle - HEV, Plug-in Hybrid Electric Vehicle - PHEV).

Table 1 – Fire incident dataset in European countries.

Region or country	Variables	
LFB (London Fire Brigade)	Application	EV, Multiple vehicles, Van, Lorry, Bus, Minibus, Agricultural vehicle, Trailer, towing caravan, motor home, e-bike, e-scooter, motorcycle, other (other road vehicles, other LIB)
	Publication frequency	Monthly
	Variable collected	Calendar year, Month, type, ignition source power, ignition source, item first ignited, vehicle power type, vehicle manufacturer, Borough name, Ward name, Ward code, LIB mentioned in the report?, fatalities and casualties
	Collection method	Fire and Rescue Service collect the information in the aftermath of an event
	Quality assurance	LFB applies a quality assurance process
NL (Netherlands)	Application	EV, BEB, BET, LEV
	Publication frequency	Yearly
	Variable collected	Type of incident (driving and not driving), vehicle type, battery pack specifications (battery not involved, battery involved, battery damaged by incident but not involved in the fire, unknown), involvement of charging structure, used resources, casualties (fatalities and injured)
	Collection method	Survey responses to questionnaires sent to the Fire Brigades. This includes detailed incident reports related to battery fires
	Quality assurance	Repeated checks by researchers to ensure data accuracy and completeness
DK (Denmark)	Application	EV
	Publication frequency	Monthly
	Variable collected	EV type (EV, HEV), registered influences in the event, registered impact when using the extinguishing container
	Collection method	Data input by the Fire Brigades into a database
	Quality assurance	DEMA ensures all data is reported correctly
NO (Norway)	Application	EV
	Publication frequency	Live
	Variable collected	EV type (EV, HEV)
	Collection method	Fire departments collect all relevant data and upload it to a database. Mixed methodology with 70% registered automatically and 30% manually
	Quality assurance	NA

Region or country	Variables	
SE (Sweden)	Application	EV, BEB, BET, LEV
	Publication frequency	NA
	Variable collected	Vehicle type (EV, BEB, BET), LEV (e-bike), fire occurrence specification (during journey, while charging, and others)
	Collection method	Information is assessed by Fire Officers and added to a central database
	Quality assurance	NA
FI (Finland)	Application	EV, BEB
	Publication frequency	Bi-annually
	Variable collected	EV type (EV, HEV, PHEV)
	Collection method	Statistics are sourced from the PRONTO information system
	Quality assurance	NA

3.2 Fire incidents and incident rates for EVs

The fire incidents from all the datasets for electric vehicles (passenger cars and vans), including EV and HEV, studied herein, are depicted in Figure 1. For the majority of the investigated dataset, reported incidents have increased each year since data collection began, indicating potential challenges for users, the built environment, and authorities. The problem becomes more apparent as the number of registered electric vehicles increases in the countries where the datasets were collected. The only exception is the LFB dataset, where the number of reported incidents ranges from 56 in 2017 to 33 in 2020, peaking in 2022. The reason for this evolution could be related to several factors. It is important to consider that the London Metropolitan Area experiences an influx of registered vehicles from neighbouring councils and districts. Therefore, in future studies, data from all the UK councils will be evaluated. In the Netherlands dataset, the number of EV fire incidents increased from 37 in 2021 to 57 in 2024. It is worth noting that all incidents reported in the Dutch data (crashes, accidents, etc.) are included, and only incidents in which the battery was known to cause a fire are considered for this study. The incident dataset from Denmark increased from 3 incidents in 2018 to 46 in 2023, representing an increase of 7 incidents per year. Similar increases as found in Denmark could be seen in reported incidents from Norway, from 15 in 2016 to 80 in 2024 (increment of 6.75 incidents per year), Sweden from 8 in 2018 to 40 in 2024 (a rise of 5.75 incidents per year), Finland from 1 in 2015 to 17 in 2023 (an increase of 1.4 incidents per year).

For all the datasets, the estimated frequency rates are illustrated in Figure 2. The rates represent global incidents and include EVs and HEVs. The frequency rates have not been subdivided by variable subset, and this will be carried out in future studies. As seen in Figure 2, the frequency rates tend to decrease and stabilise over time. For the latest year of reported data, the incident rates for Denmark, Norway, Finland, and Sweden are 0.5, 1.32, 0.77, 0.76, and 0.57 incidents per 10,000 vehicles, respectively.

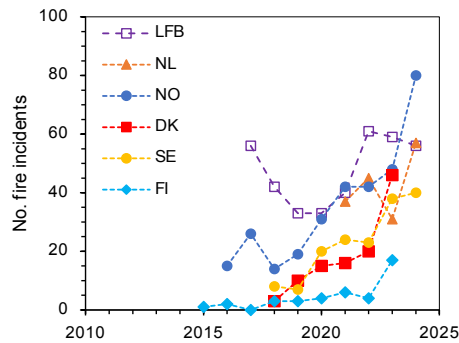


Figure 1 – Number of fire incidents for EV and HEV from various regions (London Fire Brigade – LFB), countries (Netherlands NL, Norway NO, Denmark DK, Sweden SE, Finland FI).

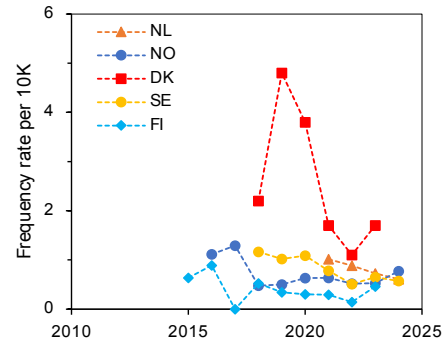


Figure 2 – Estimated frequency rates for EV and HEV from various regions (London Fire Brigade – LFB), countries (Netherlands NL, Norway NO, Denmark DK, Sweden SE, Finland FI).

3.3 Fire incidents and incident rates for BEBs and BETs

Figure 3 illustrates fire incidents from the BEB and BET datasets. As with passenger cars and light commercial vehicles, some data show that reported incidents involving electric buses and trucks have increased each year since the first year of collection. The incident data for BEB and BET from LFB witnessed increments of 4.9 and 11.9 incidents per year from 2020 to 2024, respectively. Such trends could potentially continue or increase in future years as Transport for London aims to electrify London's bus fleet to target a net-zero carbon city by 2030. The Finnish data for BEB also experienced an increase of 2 incidents per year. Contrary to the general upward trend, the Swedish data showed a decrease in reported incidents.

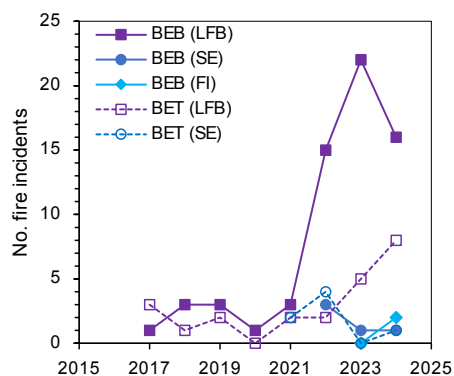


Figure 3 – Number of fire incidents for BEB and BET from the London Fire Brigade (LFB), Sweden (SE) and Finland (FI).

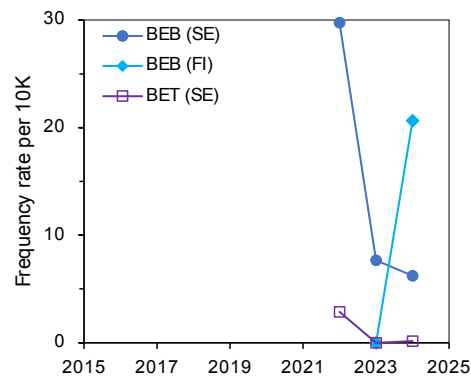


Figure 4 – Estimated frequency rates for BEB and BET from Sweden (SE) and Finland (FI).

The estimated frequency rates for Sweden and Finland are depicted in Figure 4. Unfortunately, datasets from other European countries did not report incidents involving large electric vehicles,

or they lacked data on the number of registered vehicles; e.g., it is unclear how to quantify the number of registered BEB or BET in the London Metropolitan Area. As seen in Figure 4, it is clear that there are major disparities in frequency rates, with the latest rates for Swedish BEB, Finnish BEB, and Swedish BET at 20.6, 6.2, and 0.15 incidents per year per 10,000 vehicles, respectively. Continuous data collection could increase the population size, thereby enhancing statistical power to estimate the incident rate in datasets with limited information. In the future, datasets from other countries will also be included in the analysis.

3.4 Fire incidents and incident rates for LEVs

Figure 5 illustrates fire incidents from the datasets for LEVs, where notable increases in reported incidents over time are also observed. The datasets from LFB show a high surge in reported incidents, with 32.1 incidents per year. This increase in LEV fires is also attributable to the rise in the number of LEVs implemented by Transport for London to promote sustainable alternatives for city travel. For example, in July 2024, 900 additional e-bikes were introduced for rental in the city. The Netherlands and Sweden witnessed increments of 32.1, 15.5 and 3.3 incidents per year, respectively. The estimated frequency rates for selected Dutch and Swedish LEVs are depicted in Figure 6. The frequency rates are slightly lower than those in Section 3.2. The average frequency rates are 0.43 incidents per year per 10,000 e-bikes in Sweden and 0.21 incidents per year per 10,000 LEV in the Netherlands. Even if incident rates appear low, they should be monitored over time, as the stock of LEV devices is increasing in many cities and countries worldwide.

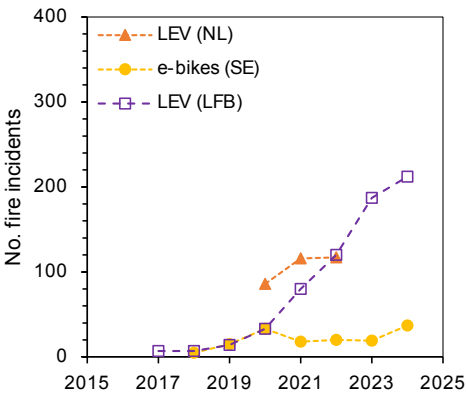


Figure 5 - Number of fire incidents for light electric vehicles from the London Fire Brigade (LFB), Sweden (SE), and the Netherlands (NL).

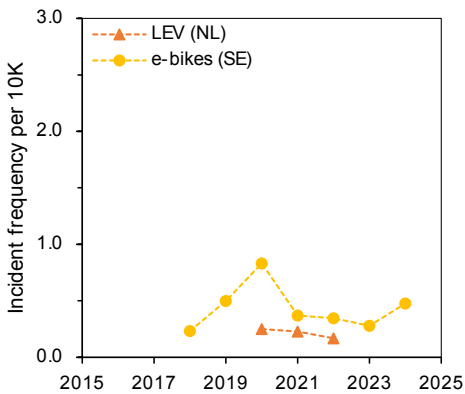


Figure 6 - Estimated frequency rates for light electric vehicles from Sweden (SE) and the Netherlands (NL).

4. CONCLUSIONS

The analysis presented in this paper highlighted significant variation in the European collection of data on LIB fires (LF, B, the Netherlands, Denmark, Sweden, Norway, and Finland). The variables collected across the datasets vary and are mainly related to the number of fire incidents and the types of vehicles. Furthermore, the LFB dataset has the most variables among the datasets

examined. Despite such variability, it is still possible to perform a global comparative analysis of incidents across various types of electric mobility devices (passenger cars, light commercial vehicles, battery electric buses, battery electric trucks, and light electric devices). It is also important to note that potential uncertainties and missing values can be mitigated through quality checks, thereby enhancing the robustness of the findings.

In most cases, reported fire incidents involving electric mobility devices have increased substantially over the years, with the highest increments of 74, 4.9, and 564 incidents per year for EVs, large electric buses, and LEVs, respectively. The calculated frequency rates for EVs range from 0.5 to 1.38 incidents per year per 10,000 vehicles across the European datasets, based on the last reported year. The frequency rates for large electric vehicles (BEB and BET) vary widely, suggesting the data may not yet be statistically relevant. Finally, the frequency rate for LEV is estimated at 0.21-0.43 incidents per year per 10,000 LEV.

Future work will continue the analysis in greater detail to evaluate the roles of the multiple reported variables and will include other datasets, including other international datasets. Furthermore, the analysis will focus on providing guidelines for a harmonised fire statistical collection to increase the accuracy and reliability of the EV fire data, evaluate the real performance of LIB during fires, identify the risk for communities, and determine preventive measures to ensure fire safety approaches in terms of reduction of likelihood and consequences.

ACKNOWLEDGMENTS

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ESTIMATION OF AXIAL THERMAL CONDUCTIVITY IN LITHIUM-ION CELLS VIA POWER STEPS

Diego Penagos-Vasquez, Javier Marco Gimeno, Javier Monsalve-Serrano¹, Antonio García

CMT - Clean Mobility & Thermofluids, Universitat Politècnica de València, Camino de Vera s/n, 46022, Valencia, Spain

Keywords: Thermal conductivity; Lithium-ion batteries; Power steps; Thermal insulation

ABSTRACT

Accurate characterization of thermal properties in lithium-ion cells is essential for reliable simulation models. However, their anisotropic and composite structure complicates heat transfer prediction, and experimental thermal conductivity data remain limited. To address this gap, this study proposes a method to estimate the axial thermal conductivity of cylindrical lithium-ion cells using a quasi-adiabatic setup with axial heat flow and stepped thermal power. Six cells were tested at 100% state of charge, using thermal insulation to reduce radial losses and a cooling plate to extract heat axially. Five controlled power steps were applied up to a maximum temperature of 80 °C. As result, the maximum recorded temperature was 74.73 °C for the cylindrical NCA 5.0Ah cell, with a maximum axial thermal conductivity of 19.65 W/mK ($\sigma = 0.31$ W/mK). For the NMC 5.3Ah cells, the maximum temperature reached 70.88 °C and the maximum conductivity was 19.13 W/mK ($\sigma = 0.27$ W/mK). Overall, the results demonstrate a reproducible estimation of axial thermal conductivity in cylindrical lithium-ion cells, with average values below 20 W/mK under controlled thermal conditions.

1. INTRODUCTION

The growing demand for sustainable energy has accelerated the development of electric vehicles and energy storage systems [1-2]. Lithium-ion batteries have become a dominant technology due to their high energy density, fast charging capability, long service life, and favorable cost-to-performance ratio [3-4]. As battery performance improves, thermal safety becomes increasingly critical, requiring accurate thermal modeling to predict behavior under different operating conditions [5-8]. The reliability of such models strongly depends on accurate thermal properties, particularly thermal conductivity, which governs internal heat distribution within the cell [9-10]. Lithium-ion batteries exhibit anisotropic thermal behavior due to their heterogeneous structure, typically composed of graphite or silicon anodes, cathodes such as LFP, NMC, or NCA, and polymer separators (PE or PP).

¹ Corresponding author-Clean Mobility & Thermofluids, Universitat Politècnica de València, Camino de Vera s/n, 46022, Valencia, Spain.
Telef.: +34 963 877659, E-mail: jamonse1@mot.upv.es

In the literature, some methods have been reported for measuring the thermal conductivity of lithium-ion batteries depending on cell geometry. The heat flow method is widely used and consists of placing a prismatic or pouch cell between two plates acting as heat source and sink. Kovachev et al. [11] applied this method to a 41 Ah LMO-G cell at 30% SOC, obtaining a conductivity of 0.77 W/mK. Later studies reported a decrease in conductivity with cell aging due to SEI growth [12]. Similarly, Bazinski et al. [13] measured 0.35 W/mK for a 14 Ah LFP-G cell at 50% SOC using lateral heating foils, while Vertiz et al. [14] obtained 0.238 W/mK using a heater between two cells. For cells with a state of health below 80%, Vertiz et al. [14] reported a reduced value of 0.201 W/mK.

Another widely used technique is the guarded hot plate method, where a prismatic cell is placed vertically to promote one-dimensional heat flow. Bazinsky et al. [15] applied this method to 10 Ah and 14 Ah LFP-G cells at 50% SOC, obtaining thermal conductivities of 35.9 and 28.9 W/mK. Aiello et al. [11] reported 25.74 W/mK using aluminum blocks as heat sinks. Other approaches, such as Thermal Impedance Spectroscopy, show limitations in repeatability and accuracy [16], while the 3 ω method involves high experimental complexity that limits routine application [17-18].

These methodologies are not directly applicable to cylindrical cells due to geometric constraints that hinder uniform heat flow [19]. Alternative approaches have therefore been proposed. Maleki et al. [20] estimated thermal conductivity indirectly for a US-18650 cell from thermal diffusivity of stacked electrode layers, obtaining 3.4 W/mK. Fleckenstein et al. [21] applied Thermal Impedance Spectroscopy to a 4.4 Ah LFP-G cell, reporting 0.35 W/mK. Drake et al. [22] used adiabatic heating in a vacuum chamber for 26650 and 18650 LFP-G cells, obtaining 32 and 30 W/mK, although external heating does not reproduce the distributed heat generation during electrochemical operation. Huang et al. [23] measured axial heat flow using copper bars and a numerical correction for thermal losses (ASTM D5470), reporting 11.5 W/mK for an 18650-NCA-G cell. Jiang et al. [24] later adapted this method using brass cylinders, obtaining values between 12.90 and 13.50 W/mK for an 18650 NCA cell.

Based on literature review, no standardized experimental procedure comparable to those used for prismatic cells has been identified for cylindrical cells. Moreover, many reported setups require specialized equipment not commonly available in conventional laboratories. Therefore, this study proposes a simplified method to estimate the axial thermal conductivity of cylindrical lithium-ion batteries under quasi-steady-state conditions using conventional instrumentation. The approach employs an adiabatic configuration with axial heat flow and stepped thermal power, based on heat flow methods used for prismatic cells. Three temperature measurement points were defined according to the manufacturing characteristics of the tested batteries, providing a reproducible methodology with clear operational and stabilization criteria. The motivation of this work lies in the use of materials and equipment that can be readily implemented in a conventional laboratory environment. In this way, the present work aims to contribute to the development of a reproducible experimental methodology for measuring the axial thermal conductivity of cylindrical lithium-ion cells, incorporating clear operational and stopping criteria under quasi-steady-state conditions.

2. METHODOLOGY AND EXPERIMENTAL SETUP

Thermal conductivity, k , quantifies a material's ability to transfer heat by conduction. This property is governed by Fourier's law, which is expressed in Equation (1):

$$q = -k \frac{dT}{dx} \quad (1)$$

Where q represents the heat flux, k is the thermal conductivity of the material, and dT/dx is the temperature gradient in the direction of heat transfer. In the case of a cylindrical lithium-ion cell, if heat transfer occurs predominantly in the axial direction under quasi-steady-state conditions, Fourier's law can be expressed as shown in Equation (2):

$$k = \frac{\dot{Q} L_{\Delta T}}{A \Delta T} \quad (2)$$

where $L_{\Delta T}$ is the axial distance between the temperature measurement points ΔT , A is the cross-sectional area of the cell through which heat is conducted in the axial one-dimensional direction, and ΔT is the temperature difference between the heater and the reference measurement point. For heat generation, $\dot{Q}$, a heater controlled by a power supply was used, in which the amount of current flowing through the resistive element was regulated. The heat generation rate was determined using Equation (3):

$$\dot{Q} = I_H U_H \quad (3)$$

Where I_H is the current supplied to the heater and U_H is the applied voltage. The cells analyzed in this study are summarized in Table 1. For each cell reference, three cells were tested.

Table 1: Cells employed in the experimental procedure

Parameter	NCA 5.0Ah	NMC 5.3Ah
Height (mm)	21	21
Diameter (mm)	70	70
Weight (g)	70.5	70.5
Maximum voltaje (V)	4.2	4.2
Maximum discharge current (C)	8	3
Capacity (Ah)	5	5.3
Chemistry	NCA-G+Si	NMC-G
Maximum temperature (°C)	80	60

Figure 1 shows the thermal monitoring scheme implemented on the cell. The locations of eight thermocouples distributed along the axial direction of the cell are indicated. The heater and the heat exchanger are coupled through aluminum blocks in order to ensure a homogeneous distribution of the heat flow at both interfaces. The temperature of the heat exchanger and the climatic chamber was maintained at 25°C. A maximum experimental temperature of 80°C at T_1 was selected, which is below the venting temperature of both cells. On the right-hand side, image

A shows the location of thermocouples T_5 , T_7 , and T_8 at the top surface of the cell. In this region, the geometric discontinuity between the venting cap and the cathode connection can also be observed, corresponding to a surface that is not in continuous contact with the active material of the cell. Image B shows the insulating material layer used to reduce the presence of air at the cell surface, which was fixed using Kapton tape. Image C illustrates the insulated cell and the axial lengths considered for the thermal conductivity calculation: $L_{\Delta T_1}$ and $L_{\Delta T_2}$, both equal to 70 mm, and $L_{\Delta T_3}$, equal to 64 mm. The selection of these lengths is related to the characteristic manufacturing features of 21700 cylindrical cells. Specifically, $L_{\Delta T_1}$ compares thermocouples T_1 and T_8 , $L_{\Delta T_2}$ compares T_1 and T_7 , and $L_{\Delta T_3}$ is defined using T_1 and the average temperature recorded between T_5 and T_6 . Finally, thermocouples T_2 , T_3 , and T_4 , located between 3 mm and 35 mm from T_1 , were used solely for test control purposes.

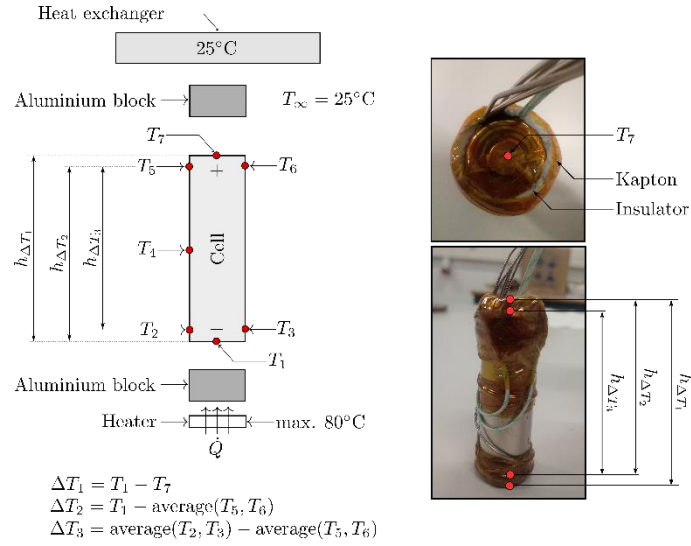


Figure 1: Thermal instrumentation of the cylindrical cell

Figure 2 presents the exploded view of the cell shown in Figure 1 assembled inside the test setup. The experimental system consists of two caps made of Sopra XPS SL insulating material, characterized by a low thermal conductivity ($k = 0.033 \text{ W/mK}$ at 25°C). The cylindrical cell was centered within the insulation block, resulting in a minimum radial insulation thickness of approximately 32 mm between the cell surface and the external boundary of the insulating material. This configuration significantly reduces radial heat losses and promotes a quasi-adiabatic environment around the lateral surface of the cell. The lower end of the cell was connected to an aluminum heater block, while the upper end was coupled to an aluminum block connected to a heat exchanger maintained at 25°C . Thermal paste was applied at both interfaces to minimize contact resistance and ensure efficient heat transfer along the axial direction. In addition, the lateral faces of the heater block were thermally insulated, further limiting radial heat dissipation from the base of the cell. Under these conditions, heat transfer is expected to occur predominantly along the axial direction between the heater and the cooling interface, resulting in a quasi-one-dimensional heat conduction path through the cell.

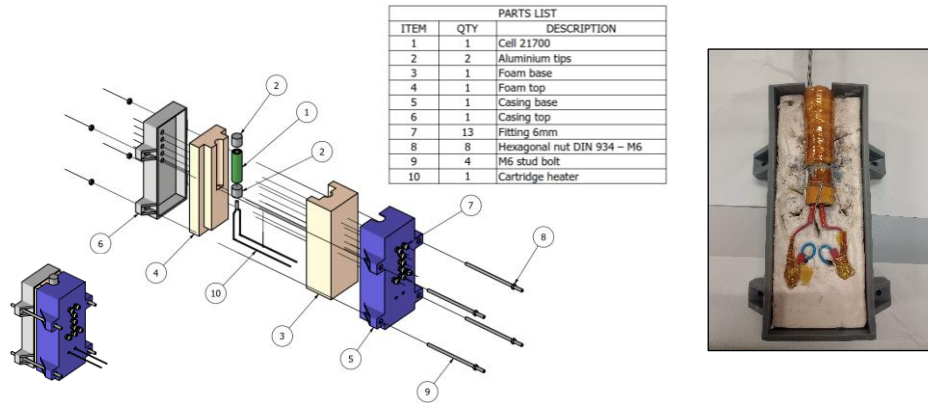


Figure 2: Experimental setup of the cell assembly

Figure 3 shows the laboratory equipment used in the experimental tests for thermal conductivity measurements. The setup includes a cooling system and a climatic chamber, both operating at 25 °C, a power supply that controls the current supplied to the heater, and the data acquisition system. Two independent data loggers were used with a sampling frequency of 1 Hz: one for recording the cell temperature and another for monitoring the temperature of the heat exchanger. Inside the climatic chamber, the test setup shown in Figure 2 can be observed. The heat exchanger was installed at the top and connected through the aluminum tip.

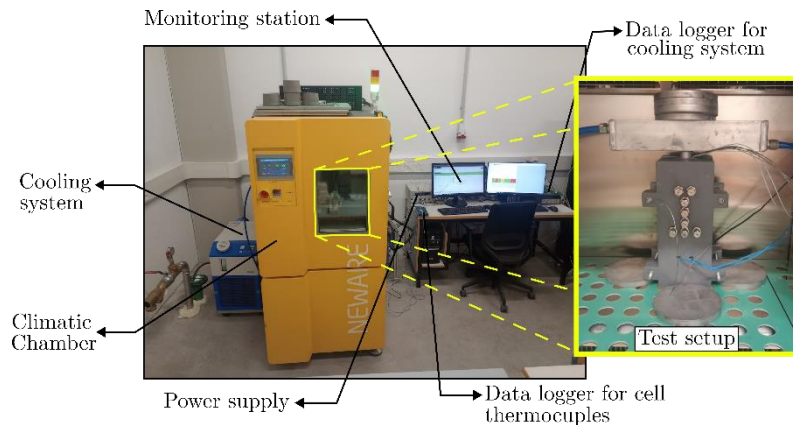


Figure 3: Laboratory equipment used in the experimental tests.

The experimental procedure applied during each test was as follows:

- (i) Prior to the thermal test, the cell was charged to 100% SOC using a constant-current–constant-voltage (CCCV) charging protocol.
- (ii) The cooling system and climatic chamber were stabilized at 25 °C. During this stage, the cell remained under thermal rest conditions, and the heater was kept switched off.
- (iii) The heater coupled to the base of the cell was then switched on using the power supply, applying an initial step of constant thermal power regulated through current control.

- (iv) The system was allowed to evolve until the temperatures recorded by all thermocouples attached to the cell reached a quasi-steady-state condition. The thermal stability criterion was defined as a temperature variation lower than $0.2\text{ }^{\circ}\text{C/h}$.
- (v) The thermal power supplied to the heater was increased, and the stabilization criterion described in step (iv) was applied again.
- (vi) Steps (iv) and (v) were repeated for a total of five power steps per test, ensuring that the maximum recorded temperature did not exceed the experimental limit of $80\text{ }^{\circ}\text{C}$.

Figure 4 illustrates the temperature evolution during a test with stepped thermal power under unidirectional axial heat flow in a cylindrical cell. Five successive power steps are observed, each leading to a temperature increase until a quasi-steady-state condition is reached. The final temperature of each step was used to determine the axial thermal conductivity based on different temperature gradients.

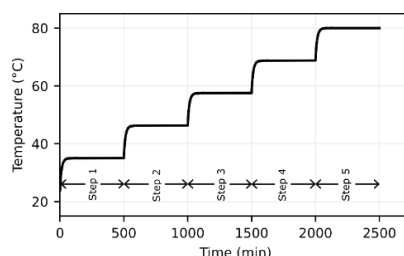


Figure 4: Representative stepwise temperature response of a cylindrical cell

3. RESULTS AND DISCUSSION

Figure 5 presents the temperature profiles recorded by the thermocouples during the tests performed on the six analyzed cells. The observed trend is consistent with the axial position of the thermocouples. The maximum temperature reached was $74.73\text{ }^{\circ}\text{C}$ for cell 2 of the NCA 5.0Ah format and $70.88\text{ }^{\circ}\text{C}$ for cell 1 of the NMC 5.3Ah format. The total duration of the tests ranged between 40 and 50 h. For each of the five thermal steps, the plots include dashed curves of lower intensity representing the temperature variation rate (dT/dt). The yellow shaded region indicates the proposed stabilization criterion of $0.2\text{ }^{\circ}\text{C/h}$, applied to all thermocouples connected on the cell surface. In all cases, thermal stabilization was achieved within approximately 4 h, with dT/dt values on the order of $0.1\text{ }^{\circ}\text{C/h}$ observed in some steps when the quasi-steady-state regime was maintained for a longer period. For the calculation of thermal conductivity, the last temperature value of each step was selected, after verifying that the thermal variation during the final hour was below the stabilization criterion. From the analysis, the NCA 5.0Ah cells exhibited higher temperatures at all thermocouple locations when compared to the NMC 5.3Ah cells, with relative differences on the order of 10%, and with thermocouple T_7 showing the largest relative difference, on the order of 20%. The temperature recorded at the heat exchanger plate coupled to the cell remained stable throughout all tests, with a temperature difference between the coolant inlet and outlet ranging from 0.05 to $0.10\text{ }^{\circ}\text{C}$. This behavior confirms that heat exchange occurred during the experiments.

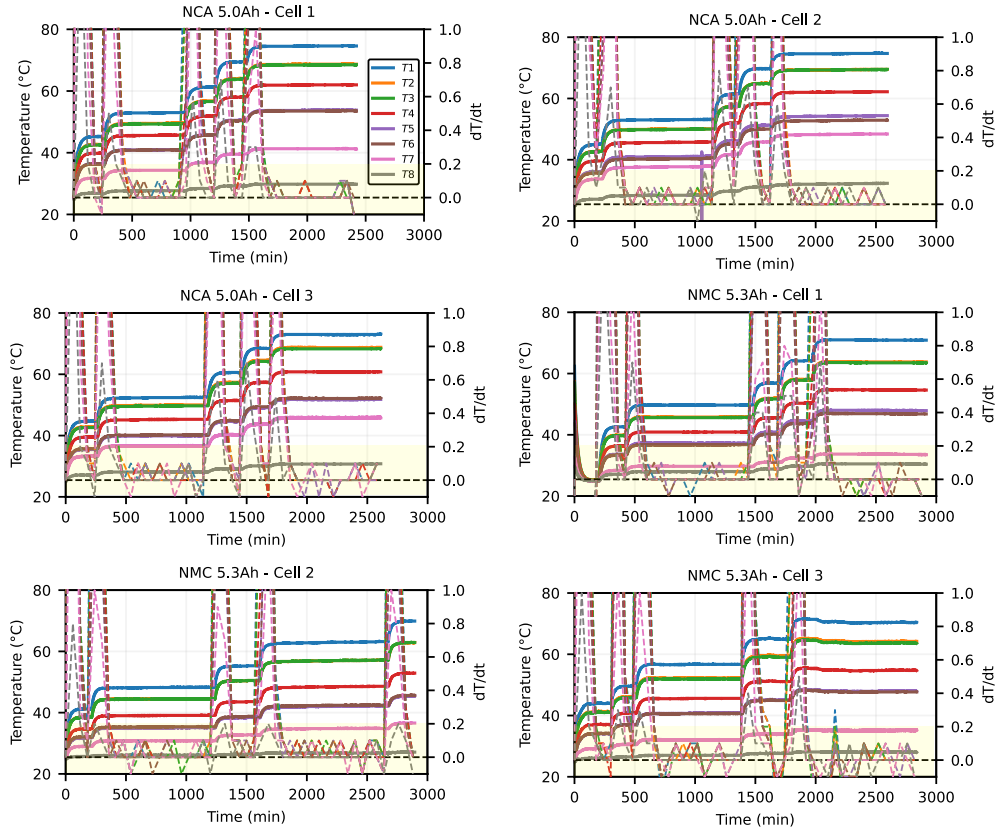


Figure 5: Temperature profiles and thermal stabilization criterion (dT/dt)

Figure 6 shows the electrical behavior of the heater used for cell heating during the thermal tests. Each subfigure presents the applied power, voltage, and current as a function of time for the analyzed cells. During the tests, gradual power increments were applied to generate the thermal steps observed in Figure 5. The applied power at each step, for all cells, was on the order of 0.94, 1.29, 1.67, 2.06, and 2.33 W, with a maximum deviation of 0.09 W observed in the last step for the NMC 5.3Ah cells. The voltage level did not exceed 3.2 V for either reference, while the current was limited to 0.75 A. A consistent electrical profile matching the thermal steps shown in Figure 5 was observed, ensuring comparable heating conditions among the tested cells. In the case of the NMC 5.3Ah - Cell 3, larger fluctuations in the electrical signals were observed. Nevertheless, this behavior did not have a significant impact on the thermal response, as the stabilization criterion of 0.2 °C/h was satisfied in all cases prior to increasing the next power step.

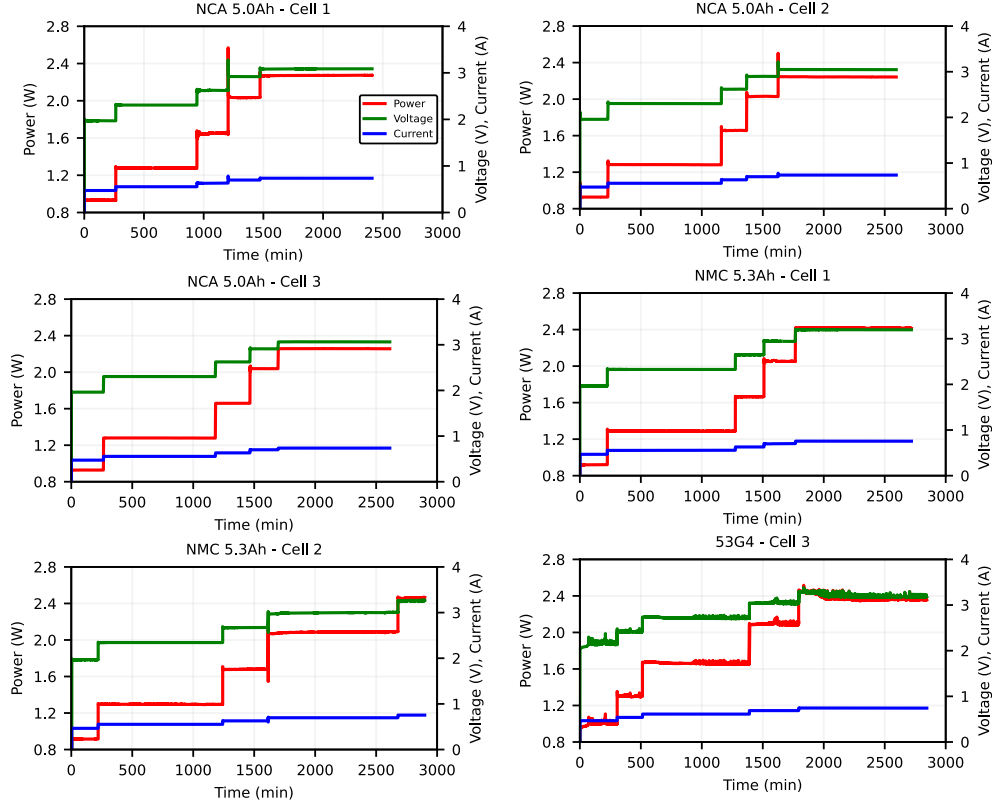


Figure 6: Electrical profile of the heater during the thermal tests

Based on the temperature steps, the axial thermal conductivity was calculated for the tested cells. Figure 7 shows the scatter plots of the axial thermal conductivity calculated using Equation (1) as a function of the temperature gradient for the lengths $L_{\Delta T_1}$, $L_{\Delta T_2}$, and $L_{\Delta T_3}$. The temperature considered for the calculation corresponds to the final value of each step obtained in Figure 5. Each plot shows three clusters, each consisting of five data points corresponding to the different power steps. The average value of each data group is also shown, together with the associated standard deviation. The maximum temperature gradient was 44.3 °C for cell 1 of the cylindrical NCA 5.0Ah format. This gradient corresponds to the temperature difference measured between thermocouple T1, located at the heater plate, and thermocouple T8 at the heat exchanger interface. Higher temperature gradients were not applied, as this would require increasing the heater temperature beyond the experimental limit of 80 °C established for the tests. This limit was selected to avoid operating conditions that could potentially trigger an exothermic event within the cell. The axial thermal conductivity values ranged between 10 and 20 W/mK. From the analysis, the thermal conductivity was found to depend on the considered axial length. This behavior is attributed to the anisotropy present along the axial direction, from the base of the cell (where thermocouple T₁ is located) to the measurement points corresponding to thermocouples T₅–T₈. The conductivity calculated for $k_{L_{\Delta T_1}}$ exhibited higher values due to the presence of the venting cap gap, where air ($k \approx 0.026$ W/mK) is present, introducing additional thermal resistance to heat

conduction. Among the evaluated cells, a higher dispersion of the results was observed, reaching up to 0.41 W/mK. In contrast, $k_{L\Delta T_2}$ exhibited higher thermal conductivity values, as the structural discontinuity present in $k_{L\Delta T_1}$ was not present along this length. Finally, the thermal conductivity calculated for $k_{L\Delta T_3}$ was the highest, since the rolled electrode layers extend up to this axial position.

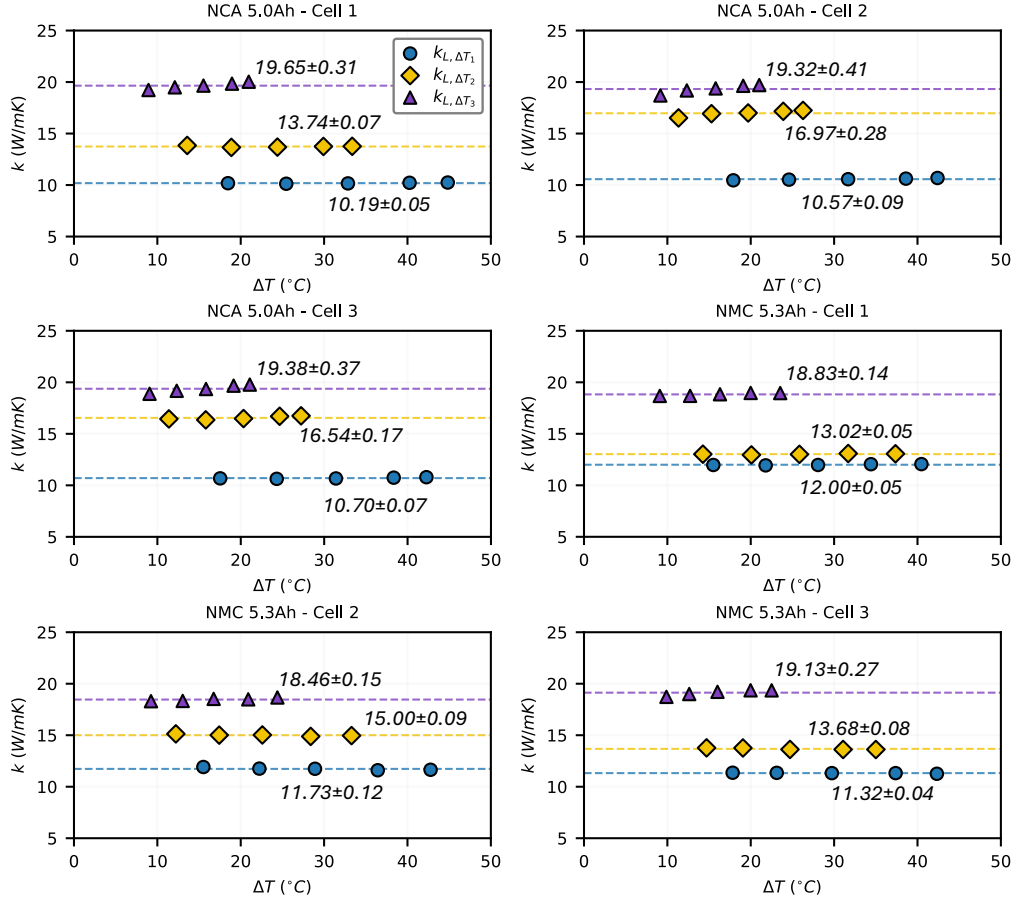


Figure 7: Axial thermal conductivity as a function of the temperature gradient

To compare the results presented in Figure 7, all calculated data were grouped, and the mean value and standard deviation were obtained for each cell. Figure 8 presents the axial thermal conductivity as a function of the temperature gradient for both cell references. As a result, the NCA 5.0Ah cells exhibited the lowest mean axial thermal conductivity for the length $L_{\Delta T_1}$, being 10.18% lower compared to the NMC 5.3Ah cells. In contrast, for the measurements performed at lengths $L_{\Delta T_2}$ and $L_{\Delta T_3}$, the NMC 5.3Ah cells showed, on average, lower thermal conductivity values by 11.7% and 3.3%, respectively, compared to the NCA 5.0Ah cells.

From this analysis, the results suggest that the NMC 5.3Ah cells exhibit improved heat conduction when the cathode-side region is considered, whereas the NCA 5.0Ah cells allow more effective thermal conduction at the axial positions corresponding to thermocouples T_5 , T_6 , and T_7 . Finally, a lower standard deviation was obtained for $k_{L\Delta T_1}$, with a maximum value of 0.30 W/mK recorded for the NMC 5.3Ah cells, while for $k_{L\Delta T_2}$ a higher standard deviation was observed, reaching up to 1.50 W/mK for the NCA 5.0Ah cells.

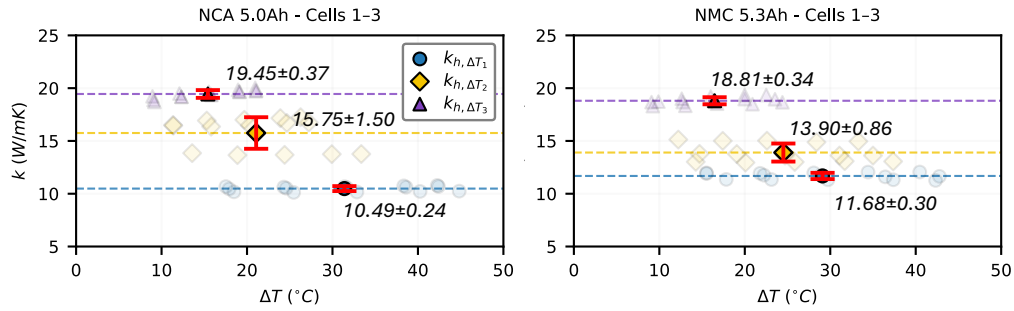


Figure 8: Mean axial thermal conductivity and standard deviation

In comparison, Huang et al. [23] reported an axial thermal conductivity of 11.5 W/mK for a cylindrical 18650 NCA cell, about 14.3% higher than the comparable value obtained for the NCA 5.0Ah cell in this study. However, their measurements were based on a single power step, representing only one operating condition. The use of multiple power increments in the present work allows a more robust evaluation of conductivity convergence.

Jiang et al. [24] reported axial conductivities between 13.95 and 14.10 W/mK for a similar cylindrical cell at different states of charge, up to 10.5% lower than the values obtained here. In their setup, the cell was surrounded by a POM shield with higher thermal conductivity than the insulation used in this study, which may have increased radial heat losses.

For NMC chemistry, previous studies report axial conductivity ranges between 10.37 and 45.83 W/mK for cylindrical and prismatic cells [25]. These values were derived from analytical evaluations of the internal battery structure rather than direct measurements, but they provide theoretical bounds consistent with the experimental results obtained in this work.

5. CONCLUSIONS

In this study, an experimental method was developed and applied to estimate the effective axial thermal conductivity of cylindrical lithium-ion batteries, based on a quasi-adiabatic system with axial heat flow and the application of five stepped thermal power levels. The results obtained showed good reproducibility among cells of the same reference, with a standard deviation of up to 1.50 W/mK, as well as compliance with the thermal stabilization criterion of 0.2 °C/h, which enabled measurements to be performed under controlled quasi-steady-state conditions. The use of stepped thermal power was demonstrated to be an effective strategy for evaluating the evolution of the thermal response of the cells. This approach allowed the assessment of

consistency in the determination of axial thermal conductivity and revealed a low data dispersion as successive temperature steps were applied, indicating improved stability of the estimated thermal conductivity with increasing thermal power levels.

The comparison between the NCA 5.0Ah and NMC 5.3Ah cells highlighted the relevance of thermocouple positioning in the calculation of axial thermal conductivity near the cell ends. The thermocouple connected to the cathode side exhibited lower thermal conductivity values when compared to the same axial position connected to the anode, which is attributed to the presence of material discontinuities.

Finally, the proposed method was implemented using conventional laboratory materials and equipment, facilitating its reproducibility and potential adoption in other experimental environments. Nevertheless, the present study is limited to quasi-steady-state conditions for axial heat conduction. Future work may extend the analysis to include radial heat transfer, variable states of charge, and cell aging. In addition, three-dimensional thermal simulations could be performed to quantify potential heat losses through the insulating foam boundaries.

6. ACKNOWLEDGMENTS

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CHARACTERIZATION OF HYDROGEN LEAKS AND FLAMMABILITY STUDY IN ZERO-EMISSION H₂-POWERED AIRCRAFT

Laura Vega
Fire Test Lab Manager
Fundación CTA - Miñano
España

Idurre Sáez de Ocáriz
Head of Science & Technology
Department
Fundación CTA - Miñano
España

Ane Errarte
Docente investigadora
Mondragon Unibertsitatea, MGEP -
Mondragon
España
M. Mounir Bou-Ali
Coordinador del Grupo de mecánica
de fluidos
Mondragon Unibertsitatea, MGEP -
Mondragon
España

Palabras clave: Safety, fire, H₂, aircraft, CFD.

1. MOTIVATION FOR THE STUDY

The aviation industry is essential to society and the economy as it drives economic growth [1], increases competitiveness and promotes cutting-edge technology. Passenger traffic demand is estimated to increase by 3.6% annually over the next 20 years [2], forecasting growth of 42% until 2040, reaching a total of 13.6M flights in Europe.

The aviation industry is developing the use of hydrogen as an alternative fuel for aircraft propulsion [3]. Hydrogen can be used in air propulsion in two ways: a fuel cell system that supplies electrical power to an engine or as fuel burned in a jet engine. The physico-chemical properties of hydrogen – wide flammability range, low minimum ignition energy, high flame speed and high diffusivity – introduce new risks associated with leaks, local accumulations and possible accidental ignitions.

Although the risks associated with hydrogen, in both ground and air applications, are not in themselves new, they are not currently explicitly addressed in the Federal Aviation Administration (FAA) or the European Aviation Safety Agency (EASA) airworthiness requirements. For this reason, the Hydrogen Fire & Explosion Research Steering Group (HFERSG) led by the FAA and EASA has been created, with the intention that other civil aviation authorities, as well as companies involved, contribute to the development and harmonization of regulatory material that addresses the use of hydrogen in transport aircraft, with special attention to the risk of fire and explosion.

This study presented here seeks to respond to some of the main challenges faced by the aeronautical sector for the development of future zero-emission aircraft, focusing on increasing the safety and reliability of new aircraft with hydrogen-based propulsion systems.

1.1 Test limitations using H₂

The presence of hydrogen in the aircraft can influence the behavior of materials in the presence of fire. This study seeks to analyze the influence of a hydrogen-rich atmosphere, assuming that there has been a propagation of gaseous hydrogen into the aircraft's ambient air.

For this reason, a series of tests have been designed to compare the results obtained in standard atmospheres and in atmospheres with a higher concentration of gaseous hydrogen (always below the lower flammability limit of H₂ (4% by volume)).

With the first tests, significant limitations arose. Firstly, the low density of H₂ favors its stratification and accumulation in the upper areas of the compartments. Second, the speed of mixing and sensitivity to ventilation conditions mean that small variations in airflow or chamber geometry can substantially alter the local hydrogen concentration.

1.2 Objectives of the study

In order to overcome these limitations, the objective of this study is to develop and validate a methodology that allows to reliably characterize flammability in atmospheres with the presence of hydrogen. The considered requirements have been to achieve the desired concentration in the shortest possible time and to maintain the desired concentration for the estimated duration of the test.

To this end, a strategy based on two complementary pillars is proposed: (i) numerical simulation using Computational Fluid Dynamics, CFD, to predict the spatial and temporal distribution of hydrogen in a vertical flammability test chamber, and (ii) experimental validation of numerical models by means of real tests in an instrumented HVFAA chamber.

2. VERTICAL FLAMMABILITY TESTS

Vertical flammability tests are one of the fundamental tools for the evaluation of the fire behavior of cabin interior materials used in an aircraft. The objective of these tests is to analyze the flame propagation, the post-combustion time and the generation of droplets or residues in materials exposed to a methane gas flame for 12 or 60 seconds, under controlled conditions.

The procedures and acceptance criteria for these tests are defined by international aviation safety regulations and manufacturer standards, including:

- **Aircraft Materials Fire Test Handbook, Chapter 1** – Provides detailed test methods and guidance.
- **CS-25 Appendix F [Amendment 25/17]** – European Aviation Safety Agency (EASA) requirements for large aeroplanes.

- **FAR 25 Appendix, Part I, §(b)(1)-(4)** – U.S. Federal Aviation Administration (FAA) equivalent standards.
- **AITM 2.0002A and AITM 2.0002B & Airbus ABD0031**– Airbus-specific test methods for vertical flammability. Internal Airbus specification that references AITM methods and additional requirements.
- **Easy Access Rules for Large Aeroplanes (CS-25)** – Consolidated EASA regulations for compliance.

These documents collectively establish the conditions, flame exposure times, and performance criteria that materials must meet to ensure safety in aircraft interiors.

Flammability tests were carried out in the FAA multi-function combustion box provided by Chongqing Gold Mechanical & Electrical Equipment Co.,Ltd. (Figure 1 (a)). The test chamber was adapted to inject the H_2 and insert the instrumentation. The test chamber has a big door that allows us to place the test samples in the holder. The two existing holes on the door have been used for insertion of instrumentation wires, and the second one has been modified to use it as H_2 inlet. For this purpose, a metallic plate with a central hole of 10 mm diameter was placed. The second hole has been used for the wire of the sensors. In order to ensure safety during the tests, an electric actuator has been incorporated that allows remote positioning of the pilot flame. Two internal fans have also been installed to accelerate the homogenization of the atmosphere.

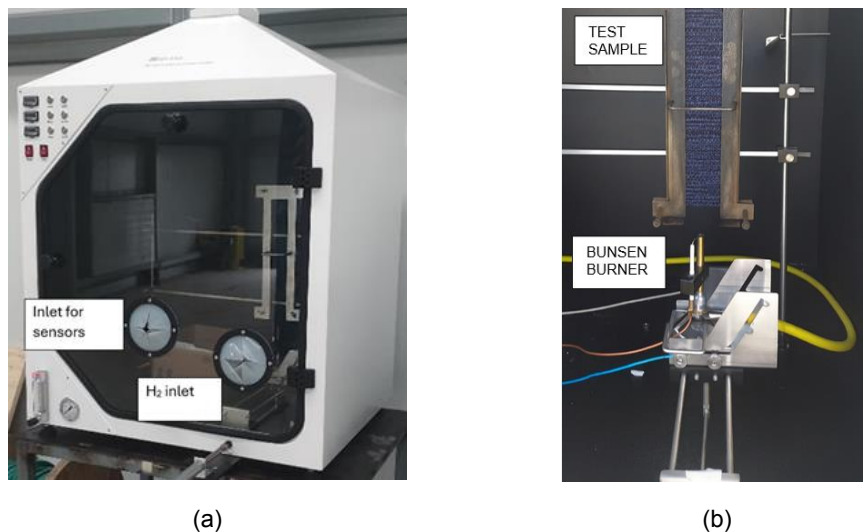


Figure 1: (a) Test chamber for vertical flammability tests. (b) Lay out for a vertical flammability test in the test chamber.

The test chamber external geometry is a cube with a pyramidal roof. Inside it has two closed boxes for the instrumentation (Figure 2). This is the geometry considered for the simulations.

The sample is placed in the sample holder (Figure 1 (b)) that ensures the correct position as defined by the standard. The sample is placed in an upright position, so that the flame hits the lower edge of the material. The Bunsen burner used to generate the flame moves along a rail, since prior to the application of the flame on the material under study, it must be calibrated both in height and appearance, as well as in temperature.

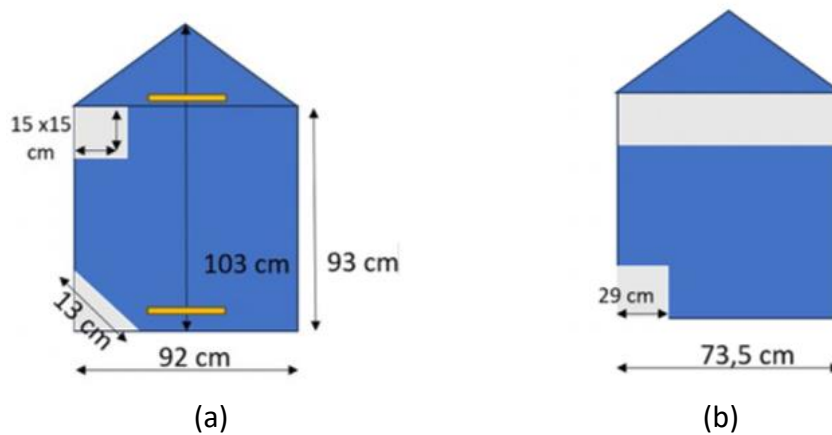


Figure 2: Test chamber geometry. (a) front view and (b) side view.

3. CFD SIMULATION

The Computational Fluid Dynamics (CFD) analysis enables a detailed prediction of flow patterns and mixing efficiency. In this study, we performed a non-reactive numerical experiment focused exclusively on the mixing of hydrogen within a controlled chamber. The objective is to evaluate the operating conditions and determine the optimal positioning of the agitators to generate a homogeneous hydrogen distribution. Achieving uniform mixing of H_2 is essential for conducting reliable flammability tests, which experimentally involve a diffusion flame interacting with the sample. CFD therefore serves as a predictive tool to identify the agitator configuration that ensures the most homogeneous pre-flammability conditions inside the chamber.

3.1 Numerical model

The three-dimensional CFD model was developed using ANSYS Fluent 2024-R1. The model addresses the fluid dynamics of the system by solving the Reynolds-Averaged Navier–Stokes (RANS) equations for turbulent flow. This approach incorporates the conservation equations of mass, momentum, and energy, enabling the simulation of both hydrodynamic behavior and heat transfer phenomena within the control volume.

In the RANS approach, the stress tensor requires closure through turbulence modelling. The $k-\omega$ Shear Stress Transport model was employed because it efficiently adapts to both free-stream

flows away from walls –characteristic of $k-\varepsilon$ models– and to the viscous sublayer near walls – characteristic of $k-\omega$ models.

Additionally, an equation of state is required to relate the density, pressure, and temperature of hydrogen. Since the maximum inlet pressure of hydrogen is below 1.0 bar, it can be modelled as an ideal gas [4]. As the analyzed chamber contains a transient mixture of air and hydrogen, the mixture is modelled as a single fluid phase without chemical reaction, where the fluid properties are calculated based on a perfect mixing model of ideal gases; the proportion of each component (air–hydrogen) in the mixture can be determined.

3.2 Computational domain

The computational domain corresponds to the inner volume of the chamber (Figure 3(a)), a multizone mesh with three mesh densities. The mesh grows in size starting from the hydrogen discharge point to accurately reproduce both the geometry and the fluid dynamics of the injection jet, and to avoid numerical diffusion that may occur due to the velocity gradients generated during the discharge. Thus, the size of the elements in the discharge zone ranges around 0.4 mm, while in the rest of the chamber the cell size increases up to 50 mm, resulting in a mesh composed of ~200000 elements (Figure 3(b)).

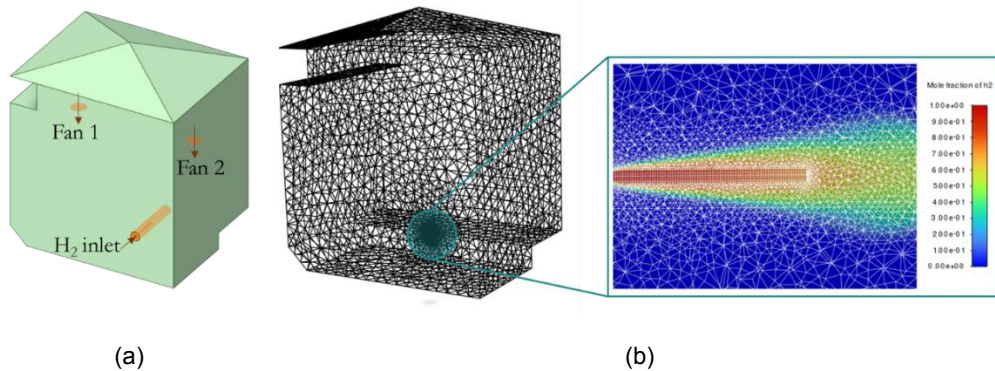


Figure 3: (a) Internal volume of the FAA multi-functional chamber, highlighting the hydrogen injection inlet, the cylindrical transition region used to smooth the mesh during injection, and the two central circular areas corresponding to the agitators. The arrows indicate the direction of the hydrogen flow. (b) Domain discretization (mesh) and representation of the adjusted hydrogen concentration -expressed as mole fraction- in the discharge area.

To analyze the H₂ dispersion, two observations have been made. On the one hand, the variation of the molar concentration has been tracked at three positions where the H₂ XEN-5320-ALU-CAN measurement sensors are located (see positions in Figure 4). On the other hand, the H₂ concentration has been graphically visualized by colourmaps in the injection plane at $x = 0.705$ m.

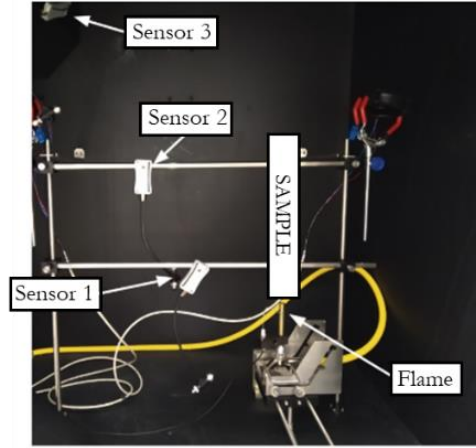


Figure 4: Position of the XEN-5320-ALU-CAN sensors inside the FAA chamber.

The image shows the internal setup of the measurement system, including the three XEN-5320-ALU-CAN sensors mounted at different heights and positions (Sensor 1, Sensor 2, and Sensor 3). The central vertical holder indicates the location of the sample. The flame source used for ignition tests is positioned at the lower right side, aligned with the sample.

3.3 Boundary conditions and solution methodology

The inlet boundary conditions were defined in terms of pressure and temperature, establishing a continuous injection of hydrogen into the chamber. The hydrogen stream was introduced at an average temperature of 298.15 K and a constant pressure of 0.5 bar, ensuring a steady inflow throughout the simulation. All remaining surfaces were treated as walls with no-slip and adiabatic conditions.

Pressure and velocity fields were solved using the SIMPLE algorithm combined with a second-order upwind discretization scheme. The convergence criterion was defined as a residual below 10^{-6} for energy and below 10^{-3} for velocity, continuity, turbulent kinetic energy k , turbulence dissipation rate ω , and species molar fraction. To ensure convergence, a variable time-step methodology was implemented, ranging from 10^{-6} s to 10^{-4} s throughout the simulation; the solver automatically adjusted the time-step based on the numerical error, which was limited to a maximum of 5%.

3.4 CFD results

The case involves injecting gaseous hydrogen into a closed cavity with a single injection point. The analysis focuses on the time required for the internal pressure of the cavity to equalize with the pressure of the injection line. As can be seen in Figure 5, the pressure in the cavity increases while the velocity in the inlet decreases.

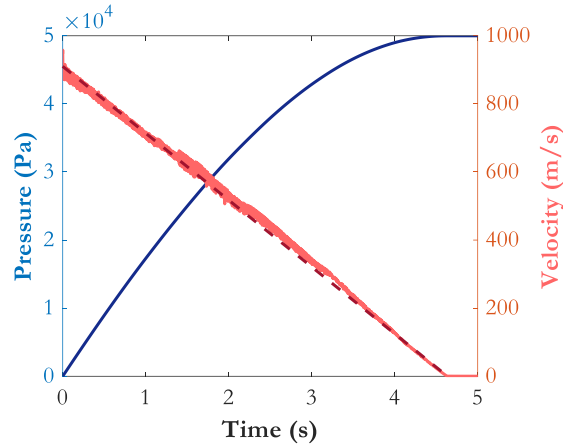


Figure 5: Temporal evolution of pressure (left) and velocity (right) during H₂ injection.

From that point onward, ~ 4.5 seconds, due to the absence of a pressure difference, it is no longer possible to introduce additional hydrogen into the cavity.

This section has been divided into two parts. First, the analysis of hydrogen distribution with and without agitators; second, the comparison between numerical and experimental cases.

The effect of agitators: CFD pursued to analyze the combustion chamber where the ignition process of different materials in the presence of hydrogen is tested; the spatial distribution was examined in order to identify the scenario where the distribution is as homogeneous as possible. In this context, Figure 6 shows the spatial distribution of H₂ -in volumetric fraction- across the four analyzed planes for the case of 0.5 bar inlet pressure, without and with agitators.

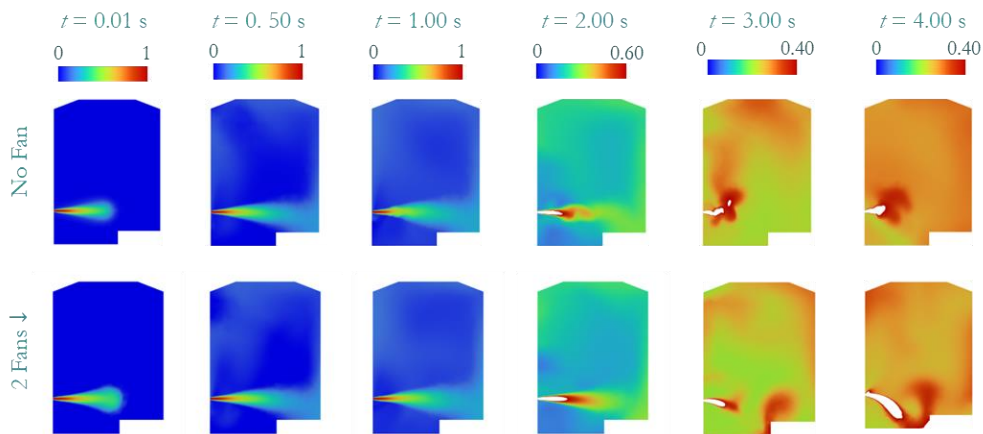


Figure 6: Spatial and temporal distribution of H₂ in molar fraction at the cross section of the combustion chamber inlet for the two simulated scenarios at a pressure inlet of 0.5 bar.

The jet develops rapidly once the H_2 injection begins. The concentration increases significantly near the injection point and quickly spreads throughout the entire cavity. As can be observed, the concentration inside the chamber exceeds the lower flammability limit of H_2 (4% in molar concentration) in less than one second, creating a highly explosive scenario. From this point onward, if a spark or ignition source is introduced, the mixture may ignite or explode.

The rapid diffusion of H_2 is due to two factors: the low density and high diffusivity of the gas, and the initial pressure gradient combined with the jet effect that promotes turbulent mixing. When comparing the two analysed scenarios, small differences can be observed, mainly in the upper part of the chamber. The agitators displace the H_2 toward the lower part of the cavity, where the sample is positioned, promoting homogenization within the central area of the chamber. Moreover, the consistency among simulations under different conditions has been verified by analysing the concentration inside the combustion chamber at the end of the simulation: 0.01575 kmol/m³ for the case without agitators and 0.01448 kmol/m³ for the case with the two agitators.

3.4 Experimental validation

The experimental validation of the CFD model has been carried out through the commissioning of a vertical flammability test chamber.

The CFD model was validated comparing the molar concentration variation in three points of the chamber. As it has been mentioned before, the experimental measurements were performed using the XEN-5320-ALU-CAN sensors, places at shown in Figure 3 in the following positions:

Table 1: Coordinates of the location of the three used H_2 measurement sensors.

	x (m)	y (m)	z (m)
Sensor 1	0.460	0.365	0.330
Sensor 2	0.380	0.365	0.530
Sensor 3	0.280	0.435	0.830

The FAA Multi-functional chamber was connected to a hydrogen storage cylinder at 200 bars. The alimentation tube was connected to the inlet hole (10 mm diameter) of the chamber by a 4.5 mm ID stainless steel tube; therefore, the diameter used in previous CFD analysis (results in Figure 5 / Figure 6) was reduced. For comparison purpose, the case without agitators was recalculated. Experiments were performed establishing constant injection pressure at 0.5 bar. Maximum liberation pressure is first limited in the outlet of the bottle, and the pressure is reduced to working conditions using a second manometer. Working pressure is measured before the injection point in the chamber. Figure 7 presents the comparison during the injection.

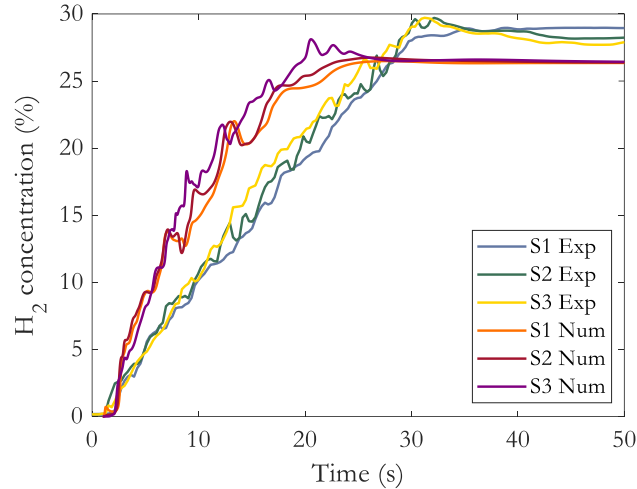


Figure 7: Numerical-experimental comparison at the three measured points for an inlet pressure of 0.5 bar.

The loading process in the numerical model saturates at ~27 seconds, when the chamber inlet pressure equals the inlet pressure. However, in the experimental case, the process and the rate of change in load concentration of H_2 are slightly slower, and the system does not saturate. This is due to various leaks in the chamber, specifically in the door, and the cable gland for the sensors and the flame igniter. We are currently working on two approaches: isolating the chamber and performing CFD simulations with small openings to the atmosphere.

The comparison between experimental and numerical results shows a good agreement in the temporal evolution of the hydrogen concentration, especially in the area close to the flame. However, discrepancies associated with non-idealized effects in the model have been identified, such as small leaks, thermal disturbances and variations in the actual performance of the fans.

Among the main limitations detected are the difficulty in accurately reproducing the boundary conditions of the CFD model and the sensitivity of the system to small variations in ventilation. These questions highlight the inherent complexity of studying hydrogen flammability and the need for integrated approaches.

4. CONCLUSIONS AND FUTURE WORK

The present work has developed a combined CFD simulation and experimental validation methodology for the study of flammability associated with hydrogen leaks in zero-emission aircraft. The results obtained demonstrate the ability of the numerical model to predict the distribution and temporal evolution of the concentration of H_2 in a vertical flammability test chamber, as well as its usefulness for the design and interpretation of experimental tests.

It has been observed that the concentration of hydrogen in the vicinity of the flame increases rapidly after the start of the injection, with characteristic times depending on the inlet pressure. Despite the initial differences, the concentration values tend to converge, suggesting an effective homogenization of the atmosphere under the conditions studied.

Among the main limitations of the study are the uncertainties associated with the reproduction of experimental conditions in CFD models. As the test chamber is not watertight, the CFD conditions and the real conditions are not the same. So, this is one of the next steps that should be taken: modify the conditions for the CFD study to include some opening of the test chamber to the atmosphere.

Finally, preliminary tests of complete tests on specimens have been carried out. As a future work, it is proposed to deepen the study of different ventilation configurations, carry out tests on some of the most characteristic materials of this type of test and develop specific test procedures for hydrogen-rich atmospheres.

5. ACKNOWLEDGEMENTS

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APPLICATION OF MACHINE LEARNING TO ELECTRIC VEHICLE OCCUPANCY PREDICTION AND SAFETY ANALYSIS

Álvaro Ramos

Bachelor's Degree in Architecture, University of Navarra, Spain

César Martín-Gómez

Full Professor, University of Navarra, Spain

Judith Blanco

Head of Parking, Concessions and Curb Cuts Service, Pamplona City Council

Mohd Zahirasri Mohd Tohir

Associate Professor, Dept. of Chemical and Environmental Engineering, Faculty of Engineering,
Universiti Putra Malaysia, Malaysia

Keywords: Prediction, artificial intelligence, fire safety, electric vehicles, underground parking

1. INTRODUCTION

1.1. Context and motivation

The accelerated growth of electric mobility poses unprecedented safety challenges, especially in confined environments such as underground parking facilities. According to the European Environment Agency, 2.4 million new electric vehicles were registered in the EU in 2023, representing a 37% increase over the previous year (1).

Fires caused by lithium-ion batteries present unique characteristics that differentiate them fundamentally from fires in internal combustion vehicles (2, 3). The thermal runaway phenomenon can generate temperatures exceeding 1000°C, rapid energy release over time, toxic gas emissions, and spontaneous reignitions up to 72 hours after the initial incident, as evidenced by documented cases in cities such as Madrid, Barcelona, and Seoul.

Existing fire protection approaches rely predominantly on reactive mechanisms: smoke detectors, heat sensors, and computer-vision-based systems can only respond once combustion is already underway (4). For a thermal runaway event, this is structurally too late — by the time a ceiling sensor perceives sufficient smoke or heat, the battery has already entered an irreversible decomposition phase. This latency gap defines the frontier where predictive tools become necessary.

Despite the growing presence of electric vehicles in the automotive fleet, there is a notable absence of specific regulations adapted to this new reality (5). Most current frameworks were designed for combustion vehicles, creating regulatory gaps in safety distances, early detection systems, evacuation protocols, and emergency team training.

1.2. Theoretical framework: the EVRISK project

This work is framed within the EVRISK project (Electric Vehicle Fire Hazard Assessment and Risk Reduction), an initiative funded by the European Union through the Marie Skłodowska-Curie Actions (MSCA) program under Horizon Europe. The main objective of the project is to develop a comprehensive framework for fire risk assessment in electric vehicles, with special emphasis on enclosed parking facilities.

EVRISK adopts a multidisciplinary approach that integrates chemical engineering, architecture, fire science, and data analysis. The project combines experimental research on the thermal behavior of lithium batteries, computational modeling of fire propagation, and development of risk management tools. The tool presented in this work, called SafeParkForecast, constitutes one of the applied developments of the project, specifically oriented towards prediction and preventive analysis of risk scenarios.

1.3. Objectives of the work

The main objective of this work is to develop a predictive tool based on artificial intelligence that allows anticipating risk configurations in parking facilities through the analysis of electric vehicle occupancy patterns (Fig. 1). SafeParkForecast does not aim to replace detection or suppression systems; rather, it operates as a complementary upstream component, shifting the point of intervention from reaction to prediction. Specifically, the following objectives are proposed:

- Develop a machine learning model capable of accurately predicting future parking space occupancy based on historical data.
- Implement a critical scenario detection system that identifies high-risk configurations for fire propagation.
- Generate visual representations of predicted scenarios that facilitate interpretation by managers and emergency services.
- Provide exportable data compatible with fire simulation systems for advanced analyses.
- Establish the foundations for future developments that integrate IoT sensors and early detection of pre-fire conditions.

With adequate progress in terms of data, calibration, and sensor integration, the tool will evolve from predicting occupancy scenarios to anticipating conditions conducive to a fire, enabling early warnings and more effective emergency responses.



Figure 1: Research outline

2. APPLICATION CONTEXT: ELECTRIC VEHICLE SAFETY IN PUBLIC PARKING INFRASTRUCTURE

The relevance of a predictive occupancy tool is best understood through the operational reality faced by public administrations managing underground parking facilities. The rapid proliferation of electric vehicles in urban fleets requires immediate adaptation of safety protocols, resource allocation strategies, and regulatory frameworks (1, 5).

From an operational perspective, SafeParkForecast can support decision-making on the dynamic allocation of surveillance and emergency resources. Knowing in advance the hours of greatest risk concentration, fire services can pre-position teams or plan optimized response routes. The identification of specific critical spaces allows evaluating the selective installation of early detection sensors or automatic extinguishing systems in strategic locations, optimizing safety investment (4) — informing where and when they matter most, without substituting them.

The tool also offers a solid technical basis for updating municipal ordinances on parking safety, particularly relevant given the regulatory gaps identified in existing frameworks (5). It can support decisions on charging point distribution, evacuation route signage, and the dimensioning of detection and extinguishing systems. Historical data accumulated by the system can also feed long-term urban planning studies, informing decisions on new parking locations or modifications to existing infrastructure.

The project has attracted the interest of Pamplona City Council, which has expressed willingness to explore practical applications of SafeParkForecast in its municipal parking facilities, exemplifying the potential for knowledge transfer from university research to effective municipal management.

3. BACKGROUND AND STATE OF THE ART

3.1. Specific risks: thermal runaway

Thermal runaway is an autocatalytic exothermic phenomenon that occurs when an electric vehicle battery cannot dissipate the heat it generates, causing a progressive accumulation of temperature (Fig. 2) (2, 6). This process can be triggered by various causes: overcharging, manufacturing defects, mechanical damage from impact, internal short circuits, or exposure to extreme temperatures.

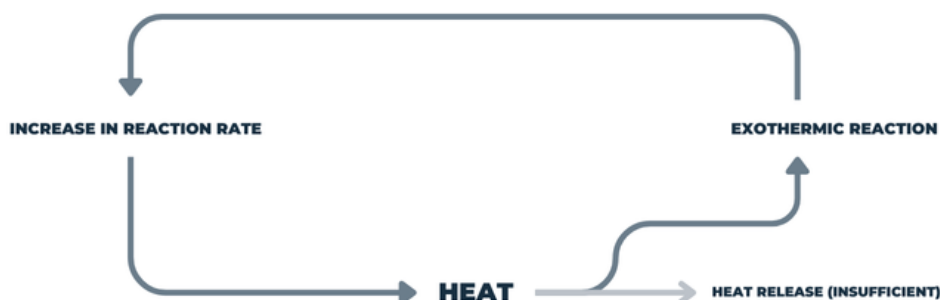


Figure 2: Diagram of the thermal runaway process in a battery

Lithium-ion batteries, widely used in electric vehicles for their high energy density, are composed of reactive electrodes (anode and cathode) and flammable organic electrolytes. During thermal runaway, the temperature can reach values between 800–1000°C, producing electrolyte decomposition and the release of combustible gases such as hydrogen, methane, and carbon monoxide (6). This combination of high temperature and flammable gases can generate explosions and rapid fire propagation.

Recent studies using ARC (Accelerating Rate Calorimeter) calorimetry and oven tests have demonstrated that thermal behavior varies significantly depending on the battery's state of charge (6). Fully charged batteries present greater severity in thermal runaway, with shorter development times and greater energy release. Additionally, the phenomenon of spontaneous reignition up to 72 hours after the initial incident has been documented, which significantly complicates extinguishing efforts and requires specific post-incident monitoring protocols (2, 4).

3.2. Predictive models in parking management

The application of machine learning techniques to predict parking occupancy is not new (7, 8, 9). Cities like Barcelona have implemented predictive systems to optimize the search for parking in blue zones, while Hong Kong has developed methodologies for grouping parking facilities according to similar usage patterns to make data collection more efficient (9).

Various comparative studies have evaluated the performance of different prediction algorithms, including linear regression, decision trees, neural networks, and Random Forest (7, 8). The results consistently demonstrate that Random Forest (Fig. 3) offers the best balance between precision, robustness, and ability to handle large volumes of data, achieving R^2 values above 0.85 and MAE errors below 0.10 in most evaluated scenarios (8).

However, existing implementations of predictive parking systems focus exclusively on optimizing user experience or operational efficiency. None address the spatial distribution of occupancy from a fire propagation perspective. SafeParkForecast represents a significant reorientation: rather than operating downstream of a fire event alongside detection and suppression systems, it operates upstream, identifying the configurations that make propagation possible before any incident occurs. In this sense, it occupies a distinct and currently unaddressed position in the fire safety ecosystem for EV parking facilities.

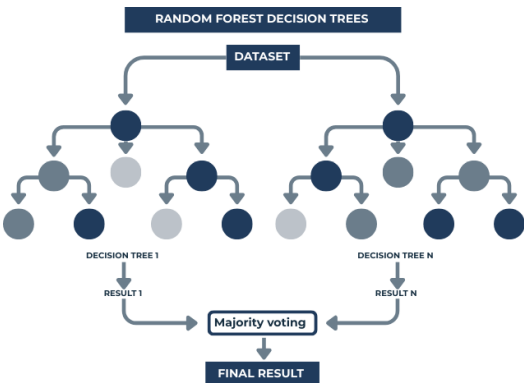


Figure 3: Random forest diagram

4. METHODOLOGY

4.1. General system architecture

SafeParkForecast is structured in two main interconnected modules. The first module handles occupancy prediction using a Random Forest model trained with historical data. The second module takes the generated predictions and analyzes them to identify and visualize risk scenarios (Fig. 4). This modular architecture allows independent updating of each component and facilitates future system extensions. The workflow begins with the collection and preparation of historical parking occupancy data. These data include temporal information (year, month, day, day of the week, hour, and minute), space identification, weather conditions, and occupancy status. Once processed and validated, the data feed the predictive model training.

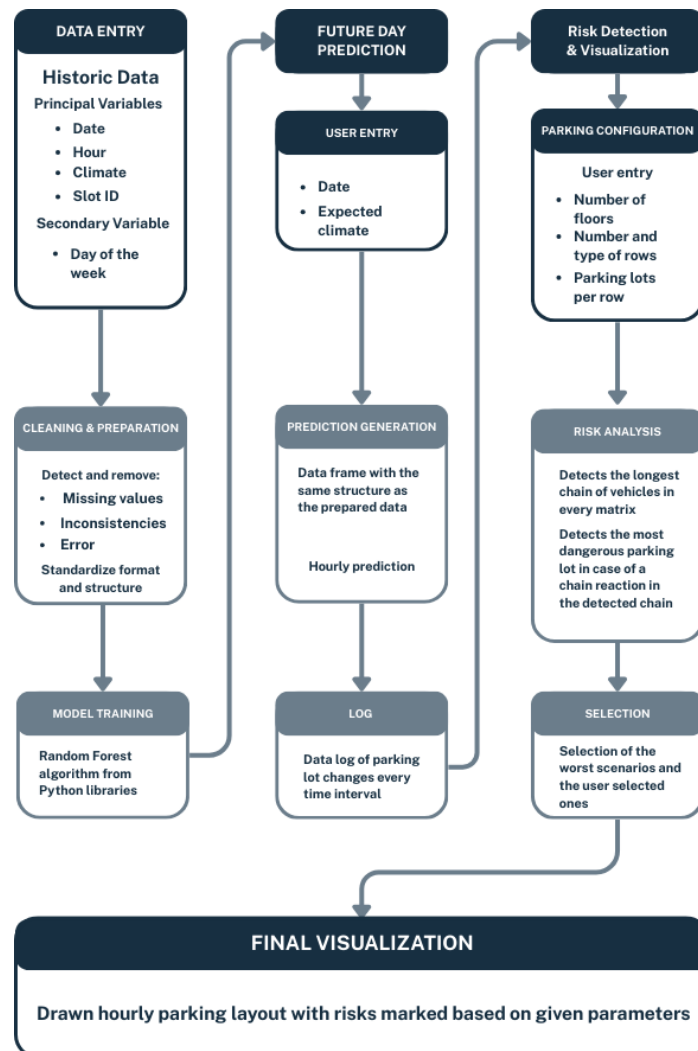


Figure 4: SafeParkForecast workflow

4.2. Data collection and preparation

For the prototype development, the CNRPark+EXT dataset was used, which records parking occupancy in Italy with measurements every 5 minutes, including space identification, complete timestamp, and weather conditions categorized into three states (sunny, cloudy, rainy) (Fig. 5).

The data preparation phase includes several critical steps: integrity validation (detection of missing or inconsistent values), format standardization (especially in space numbering), enrichment through derived variables (such as day of the week calculated from the complete date), and normalization of categorical values. This cleaning and transformation process is fundamental to ensure the quality of subsequent predictions.

CNRPark+EXT A Dataset for Visual Occupancy Detection of Parking Lots Giuseppe Amato, Fabio Carrara, Fabrizio Falchi, Claudio Gennaro, Claudio Vairo							
YEAR	MONTH	DAY	HOUR	MINUTE	CLIMATE	SLOT ID	OCCUPANCY
2015	7	3	8	05	S	1	1
2015	7	3	8	05	S	5	0
2015	7	3	9	05	S	3	1
2015	7	3	9	05	S	5	1

Figure 5: Example of data used from CNRPark+EXT study

The inclusion of weather conditions as a predictor variable is justified by empirical evidence suggesting that adverse weather correlates with increased demand for covered parking: rainy or cold conditions discourage surface parking and short-stay alternatives, thus driving occupancy in underground structures (7, 8). This hypothesis is supported by the feature importance analysis, which confirmed that while temporal variables are the dominant predictors, weather conditions constitute a relevant secondary predictor, contributing approximately 8% to the overall predictive importance. The complete ranking, from most to least influential, is: hour > day_of_week > slot_id > month > climate.

4.3. Prediction model: Random Forest

Random Forest is an ensemble learning algorithm that combines multiple decision trees, training each on a random data sample and subset of variables at each split, reducing overfitting and improving generalization capacity.

The CNRPark+EXT dataset was divided using an 80/20 chronological train-test split — rather than random — to ensure temporal representativeness and avoid data leakage, so that the test set always corresponds to time periods subsequent to those in the training set. The model's hyperparameters were optimized through GridSearchCV cross-validation across 5 folds, yielding the following final configuration: n_estimators = 200, max_depth = 20, min_samples_split = 5, min_samples_leaf = 2, and max_features = sqrt. The developed model achieved 92% accuracy in occupied/vacant binary classification, with an MAE of 0.0849 and an R² of 0.6563.

4.4. Critical scenario detection algorithm

Once occupancy predictions are generated for each space at 5-minute intervals throughout the selected day, the system builds a matrix representation of the parking facility that reflects its physical distribution. This matrix is updated for each time interval, marking occupied and vacant spaces according to the predictions.

The implemented risk detection algorithm is based on the concept of propagation chains. A chain is defined as a set of occupied spaces connected to each other by neighborhood relationships (considering horizontal, vertical, and diagonal neighborhood). The algorithm recursively explores each occupied space and its neighbors, constructing all chains present in each temporal scenario. For each identified chain, the system calculates a criticality indicator based on an expansion level analysis.

Starting from each space in the chain, it evaluates how many 'turns' or propagation levels would be necessary to reach all other spaces in the chain. The space that requires the fewest turns is identified as the 'critical center' of the chain, representing the point from which a fire would spread most rapidly to the rest of the connected vehicles (Fig. 6).

The algorithm's output is therefore inherently temporal: rather than producing a single static risk map, it generates a sequence of hourly risk states throughout the day, allowing managers to anticipate not just where risk concentrates, but when.

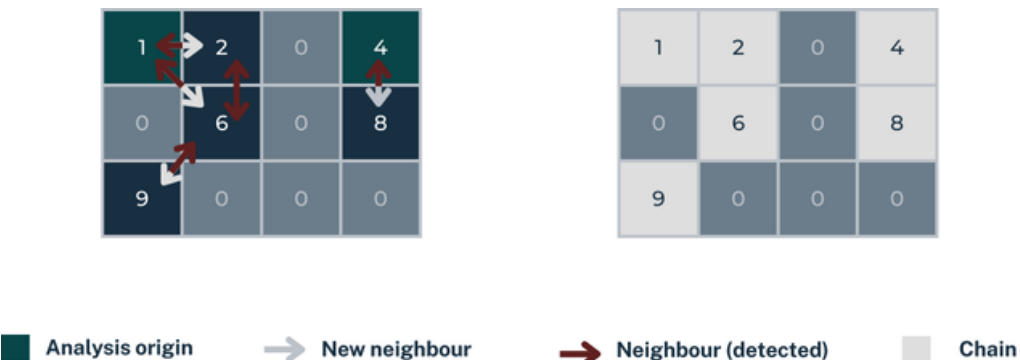


Figure 6: Neighbors detection diagram (Example, not a parking scenario)

It is important to note that the current version of the neighborhood detection algorithm operates on a purely geometric basis: two spaces are considered neighbors if they are spatially adjacent in the parking matrix, regardless of the presence of architectural obstacles between them. Structural elements such as reinforced concrete pillars, fire-rated walls, or ventilation shafts that could physically interrupt a thermal propagation chain are not yet encoded in the model.

The practical implication is that the algorithm may overestimate chain length in parking facilities where such barriers exist. Future development (see Section 7.3) will incorporate the import of CAD-format plans that explicitly encode these architectural features, enabling the chain detection algorithm to respect physical propagation boundaries and produce more realistic risk assessments.

The system prioritizes scenarios according to the length of the longest chain in each time interval, thus identifying the hours of the day with the greatest propagation potential. This information allows managers to concentrate on preventive measures at times of greatest vulnerability.

4.5. Visualization and export system

SafeParkForecast generates two types of complementary outputs. On one hand, it produces graphical representations of the parking facility that uses a color code to differentiate vacant spaces, occupied spaces, vehicles belonging to the longest chain, and the space identified as the critical center. These visualizations allow an intuitive and immediate understanding of risk distribution (Fig. 7)

1	2	3	4	5	6	7	8	9	10	11
0	0	0	0	0	0	0	0	0	0	0
12	13	14	15	16	17	18	19	20	21	22
23	24	25	26	27	28	29	30	31	32	33
0	0	0	0	0	0	0	0	0	0	0
34	35	36	37	38	39	40	41	42	43	44

Figure 7: SafeParkForecast prediction and detection example

On the other hand, the system exports the data in structured Excel format, including for each time interval: list of occupied spaces, identification of all detected chains, length of each chain, and identified critical space. This structured export facilitates subsequent analysis with other tools, integration with existing management systems, and feeding more advanced fire simulation models.

5. SAFEPARKFORECAST DEVELOPMENT

SafeParkForecast has been developed in Python using a modular architecture that separates data loading, model training, prediction generation, chain detection, and visualization output. The user interacts through a command-line interface: after entering the target date, expected weather conditions, and the physical configuration of the parking facility (floors, rows, and spaces per row), the system generates predictions for each 5-minute interval within opening hours, executes the chain analysis, and identifies the most critical scenarios. Results are delivered as color-coded parking layout visualizations and exportable Excel files compatible with existing management systems and fire simulation software.

The current implementation marks a first step in a broader trajectory: from a tool that predicts occupancy patterns and flags dangerous spatial configurations, towards a system capable of anticipating the conditions that precede a fire before any visible sign appears. With the integration of IoT sensors monitoring temperature, gas concentrations, and battery state, SafeParkForecast will evolve from predictive occupancy analysis into real-time pre-fire condition detection — shifting emergency management from a reactive to a genuinely preventive paradigm.

6. RESULTS AND VALIDATION

6.1. Predictive model performance

The Random Forest model evaluation through cross-validation yielded very satisfactory metrics. The overall accuracy achieved was 92%, with a recall of 94% for the 'occupied' class and 91% for the 'vacant' class. This indicates that the model has a high capacity to correctly identify both spaces that will be occupied and those that will remain vacant.

The mean absolute error (MAE) of 0.0849 and mean squared error (MSE) of 0.0849 confirm the consistency of predictions. The coefficient of determination R^2 of 0.6563, although moderate, is adequate for a binary classification problem with high intrinsic variability such as parking occupancy, where external random factors can significantly influence.

The confusion matrix reveals that false positives (predicting occupied when vacant) represent only 9% of predictions, while false negatives (predicting vacant when occupied) are even less frequent, at 6%. This asymmetry is beneficial from a safety perspective, as it is preferable to overestimate occupancy than to underestimate it — a conservative bias that aligns with the preventive objectives of the tool.

6.2. Critical scenario detection capability

Tests performed on various synthetic and real scenarios demonstrate that the chain detection algorithm correctly identifies all risk configurations according to established criteria. In a test parking facility with 44 spaces distributed in 2 double rows, the system was able to detect chains of up to 8 connected vehicles and accurately identify the critical center of each chain.

The comparison between different times of day shows clear variability in risk level. Typical analyses reveal that peak occupancy hours (generally between 10:00-14:00 in commercial parking facilities) do not always coincide with the hours of greatest propagation risk. Occasionally, partial occupancies generate more dangerous spatial distributions than almost complete occupancies, where saturation paradoxically limits chain length.

This counterintuitive finding underscores the value of temporal risk analysis over static occupancy thresholds and supports the case for continuous monitoring rather than point-in-time assessments.

6.3. Export and interoperability

The generated Excel files have been successfully imported into data analysis tools (Python, R) and fire simulation software, confirming the compatibility and interoperability of the export format. This integration capability is fundamental to allow researchers and professionals to use SafeParkForecast predictions as input data for more sophisticated analyses, including CFD (Computational Fluid Dynamics) simulations of smoke and heat propagation. The compatibility with standard fire simulation formats positions SafeParkForecast as an upstream data provider within broader fire safety workflows, rather than an isolated tool.

7. FUTURE DEVELOPMENT LINES

7.1. IoT sensor integration

As part of future development, the incorporation of a sensor network based on Internet of Things (IoT) technologies is planned, capable of monitoring in real-time key parameters such as ambient temperature, vehicle surface temperature, gas concentrations (CO, CO₂, volatile organic compounds), relative humidity, and structural vibrations.

This integration will allow linking physical environmental data with the occupancy predictive model, creating a hybrid system that combines medium-term predictions based on historical patterns with real-time anomaly detection. A sudden temperature increase in a specific parking area, correlated with the prediction of high occupancy in that area, would generate automatic priority alerts — bridging the predictive layer described in this work with active monitoring systems.

7.2. Refinement of risk criteria

The current risk detection criterion based solely on the length of connected vehicle chains, although useful as a first approximation, is deliberately simplified. Future developments must incorporate more sophisticated criteria that consider: vehicle type and battery capacity (not all electric vehicles present the same risk), battery state of charge (information potentially accessible from smart charging points), proximity to critical structural elements, distance to emergency exits, and presence of active protection systems in each zone.

Collaboration with fire science and structural safety experts will be fundamental to validate and refine these criteria. The integration of CFD simulation results from real electric vehicle fire scenarios will allow calibrating detection algorithms to more accurately reflect the real physics of fire propagation in enclosed parking facilities. A priority development is the integration of architectural data (CAD plans encoding structural pillars, fire-rated walls, and physical compartmentalization) into the chain detection algorithm. These elements fundamentally alter the propagation dynamics of a thermal runaway event in a realistic parking structure (2, 4).

7.3. Extension to complex geometries

The current version of SafeParkForecast is limited to parking facilities with regular geometries (parallel rows and uniform spacing). A priority extension consists of allowing the configuration of parking facilities with arbitrary geometries through the import of CAD format plans or manual definition of occupancy matrices that faithfully represent the actual distribution of spaces, including variable orientations, different aisle widths, and the presence of columns or obstacles.

This capability would significantly expand the tool's applicability range, allowing its use in most existing urban parking facilities, which rarely present completely regular distributions. The user interface could evolve towards a graphical application that allows drawing or importing the parking plan, assigning numbering to spaces, and visualizing results directly on the real plan. This extension would transform SafeParkForecast from a prototype calibrated on a specific dataset into a general-purpose tool deployable across the diversity of real urban parking infrastructure.

7.4. Automatic weather data retrieval

Currently, the system requires the user to manually enter expected weather conditions. A planned development consists of integrating automatic consultation of online meteorological services (APIs such as Visual Crossing Weather, WeatherAPI.com, or Open-Meteo) that provide both future forecasts and historical data. This would eliminate the need for manual intervention and allow generating multiple scenarios considering different probable weather conditions, quantifying the uncertainty associated with climate variability.

8. CONCLUSIONS

This work has demonstrated the technical feasibility and practical utility of applying machine learning techniques to the prediction of risk scenarios in parking facilities with electric vehicle presence. SafeParkForecast represents a first functional approach that occupies a currently unaddressed position in the fire safety ecosystem: operating upstream of detection and suppression systems as a predictive layer that anticipates dangerous occupancy configurations before any fire event occurs.

The obtained results validate the effectiveness of the Random Forest model for predicting occupancy with 92% accuracy, trained on an 80/20 chronological split of the CNRPark+EXT dataset and optimized through GridSearchCV cross-validation ($n_estimators = 200$, $max_depth = 20$). Feature importance analysis confirms that temporal variables are dominant predictors, with weather contributing approximately 8% of predictive importance, justifying its inclusion as a secondary variable. The algorithmic detection of critical configurations based on propagation chains provides a useful tool for identifying high-risk scenarios, with the acknowledged limitation that the current prototype does not yet account for architectural obstacles such as structural pillars or fire-rated walls.

The visualization and export capabilities facilitate result interpretation and integration with fire simulation tools. The future incorporation of real-time IoT data, the refinement of risk criteria through collaboration with fire science experts, and the extension to complex geometries will transform this initial tool into a robust predictive safety management system. The interest expressed by Pamplona City Council underscores the potential for transferring this technology to real municipal applications. The collaboration between universities, public administrations, and European research projects like EVRISK exemplifies the development model of evidence-based solutions to address the emerging challenges of the transition to electric mobility.

9. ACKNOWLEDGMENTS

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Session 6

Sesión 6

Sessão 6

**FROM CFD TO FORECAST: LSTM-BASED MODELING OF
BACKLAYERING EVOLUTION IN LONGITUDINALLY VENTILATED
TUNNEL FIRES**



Pablo Ayala*
Professor
Comillas (ICAI)- IIT
Spain



Luis Amo†
Student
Comillas (ICAI)
Spain



Alexis Cantizano‡
Professor
Comillas (ICAI)- IIT
Spain

Abstract:

Smoke backlayering is one of the most critical phenomena in longitudinally ventilated tunnel fires because it governs the upstream extent of smoke and hot gases, directly affecting tenability, evacuation, and the effectiveness of ventilation control. High-fidelity Computational Fluid Dynamics (CFD) can reproduce backlayering dynamics with good physical detail, but its computational cost limits real-time use and large parametric assessments. This study proposes a reduced-order, data-driven forecasting framework that predicts the time evolution of backlayering length from early ceiling-temperature histories. A dataset of 405 large-eddy CFD simulations was generated with Fire Dynamics Simulator (FDS v6.8.0) for a 2,000 m tunnel, varying heat release rate (5–50 MW), longitudinal ventilation (1–5 m/s), and tunnel cross-sectional dimensions (width 6–12 m; height 4–8 m). Ceiling temperatures sampled along the tunnel were compressed using Principal Component Analysis (PCA); 32 modes provided accurate reconstruction while greatly reducing dimensionality. The forecast model is a sequence-to-vector LSTM network that maps a history window of PCA-encoded temperature fields to a compact vector of future backlayering values defined on a logarithmically spaced time grid. Forecast skill improves systematically as the available history increases from 30 s to 240 s, with diminishing returns beyond ≈ 180 s. Validation error decreases from $\text{RMSE} \approx 58.9$ m ($R^2 \approx 0.75$) at 30 s to $\text{RMSE} \approx 22.5$ m ($R^2 \approx 0.97$) at 180 s and $\text{RMSE} \approx 21.2$ m ($R^2 \approx 0.97$) at 240 s. Error propagation analysis shows that longer input windows substantially reduce long-horizon uncertainty and

* Pablo Ayala — Institute for Research in Technology, ICAI, Comillas Pontifical University, C/ Alberto Aguilera 25, 28015, Madrid (Spain).

Telef.: +34 5422800, E-mail: pablo.ayala@iit.comillas.edu

† Luis Amo — ICAI, Comillas Pontifical University, C/ Alberto Aguilera 25, 28015, Madrid (Spain).

Telef.: E-mail: luis.amo@alu.icaei.comillas.edu.

‡ Alexis Cantizano — Institute for Research in Technology, ICAI, Comillas Pontifical University, C/ Alberto Aguilera 25, 28015, Madrid (Spain).

Telef.: +34 5422800, E-mail: alexis.cantizano@iit.comillas.edu

outliers. A temporal occlusion (SHAP-style) perturbation study indicates that the model relies primarily on the most recent portion of the temperature history (roughly the last 40–50 time steps), consistent with the physical role of near-instantaneous upstream thermal stratification in controlling backlayering. Overall, the proposed PCA–LSTM approach offers a fast surrogate for transient backlayering forecasting that can support rapid safety assessment and real-time decision support.

Keywords: Tunnel fires; Backlayering length; Long Short-Term Memory (LSTM); Data-driven forecasting.

1. INTRODUCTION

Tunnel fires pose a major safety risk because confined spaces, limited escape routes, and ventilation strongly affect smoke movement. In longitudinally ventilated tunnels, airflow can limit downstream smoke spread, but if it is too weak to overcome buoyancy, smoke and hot gases move upstream, causing backlayering. This upstream spread, measured by the backlayering length, defines the area exposed to high temperatures, poor visibility, and toxic gases. Predicting its development, especially in the early fire stage, is therefore essential for evacuation, emergency response, and ventilation control.

Tunnel fire assessment often relies on empirical correlations, simplified engineering models, and CFD. However, CFD is computationally expensive, making large scenario studies and real-time prediction impractical. This motivates data-driven surrogate models that preserve CFD-level predictive value while enabling much faster evaluation.

In recent years, machine learning has increasingly been explored for fire-related applications, including surrogate modeling of CFD outputs, rapid estimation of smoke layer properties, and prediction of fire-induced flow variables. However, many existing approaches either (i) focus on steady outputs rather than transient trajectories [1], [2], (ii) use low-dimensional scalar inputs that may not capture the evolving spatial structure of the thermal field [3], [4], or (iii) lack interpretability regarding which portions of the observed fire history drive the predictions [5], [6]. For tunnel fire problems, where the upstream ceiling-temperature profile encodes information about plume development, stratification, and the location of the backlayering front, leveraging spatiotemporal temperature information offers a promising path toward reliable forecasting, provided the dimensionality of the input data can be handled efficiently.

Recurrent neural networks, and in particular Long Short-Term Memory (LSTM) architectures, are well suited to this task because they are designed to learn dependencies in time-ordered sequences while mitigating vanishing-gradient issues that limit basic recurrent models [5]. An LSTM can, in principle, infer hidden state variables that summarize the evolving fire–ventilation interaction and can therefore forecast future backlayering behavior from early measurements. At the same time, directly ingesting raw ceiling-temperature fields sampled at thousands of spatial locations is inefficient and can hinder training. A natural remedy is to combine LSTMs with dimensionality reduction, such as Principal Component Analysis (PCA), which can compress the temperature field into a small number of orthogonal modes capturing most of the variance while preserving the spatial patterns relevant to backlayering dynamics (e.g., the temperature rise near the upstream backlayering front and the downstream decay region).

This work presents a PCA–LSTM forecasting framework to predict the transient evolution of backlayering length in longitudinally ventilated tunnel fires from ceiling-temperature histories. The

model is trained on 405 FDS simulations covering different heat release rates, ventilation velocities, and tunnel dimensions. Ceiling temperature fields are reduced using PCA, and a LSTM sequence-to-vector model predicts future backlayering values. A logarithmic time mapping is used to better capture the rapid early stages of fire development.

The paper first describes the CFD database and fire scenarios, then the PCA–LSTM workflow, including model architecture and training. It then evaluates reconstruction accuracy, forecasting performance, error over time, representative predictions, and temporal dependence, before presenting the main conclusions.

2. CFD DATASET

A total of 405 CFD simulations were performed with Fire Dynamics Simulator (FDS) v6.8.0. Combustion was modeled using the Eddy Dissipation Concept (EDC) coupled with a thermal extinction model. Turbulence was resolved with the Deardorff LES formulation using a constant $C_v = 0.1$. Radiative heat transfer was included by solving the radiative transport equation with 100 angular discretizations. To improve numerical robustness for the long computational domain and the highest heat release rates, the maximum number of iterations in the Poisson solver was increased to 100.

The parametric campaign investigated the influence of Heat Release Rate (HRR), longitudinal ventilation velocity, and tunnel cross-section (width and height). The tunnel length was kept constant at 2,000 m, with the fire source located 500 m from the upstream portal and positioned at a height of 1.2 m above the floor. The HRR per unit area ranged from 1,300 to 1,800 kW/m², with the selected value in each case adjusted according to mesh resolution. Gas temperature and velocity were sampled every 1.0 m along the tunnel, 0.4 m below the ceiling and 0.4 m from the side wall. The set of simulated scenarios is summarized in Table 1.

The numerical setup follows previous tunnel-fire modelling approaches that were validated against full-scale experiments [7], [8]. A uniform cell size of ($\Delta = 0.4$ m) provides adequate resolution in both the near- and far-field regions and satisfies the FDS resolution criterion based on the non-dimensional parameter ($R = D^*/\Delta$), with ($5 \leq R \leq 20$). The characteristic fire diameter, (D^*), is computed from:

$$D^* = (\dot{Q}/(\rho_\infty C_{p,\infty} T_\infty \sqrt{g}))^{2/5}$$

where $\dot{Q}$ is the HRR, ρ_∞ is the air density, $C_{p,\infty}$ is the air specific heat at constant pressure, T_∞ is the air temperature, and g is the gravity acceleration modulus [9].

Table 1 Summary of the values considered for the 405 simulations

N° Simulations	HRR	Fire Area	Ventilation Velocity	Tunnel Dimensions	
	(MW)	(m ²)	(m/s)	Width (m)	Height (m)
1-81	5	2.4 x 1.6	1 / 1.5 / 2 / 2.5 / 3 / 3.5 / 4 / 4.5 / 5	6 / 8 / 12	4 / 6 / 8
82-162	10	3.2 x 2.0	1 / 1.5 / 2 / 2.5 / 3 / 3.5 / 4 / 4.5 / 5	6 / 8 / 12	4 / 6 / 8
163 -243	20	4.8 x 2.8	1 / 1.5 / 2 / 2.5 / 3 / 3.5 / 4 / 4.5 / 5	6 / 8 / 12	4 / 6 / 8
244-324	30	6.4 x 3.2	1 / 1.5 / 2 / 2.5 / 3 / 3.5 / 4 / 4.5 / 5	6 / 8 / 12	4 / 6 / 8
325-405	50	8.8 x 3.2	1 / 1.5 / 2 / 2.5 / 3 / 3.5 / 4 / 4.5 / 5	6 / 8 / 12	4 / 6 / 8

3. METHODOLOGY

In this section, a data-driven forecasting model is developed to predict the evolution of backlayering length during longitudinal tunnel fires using a sequence-to-vector neural network based on Long Short-Term Memory (LSTM) units. The model is designed to capture temporal dependencies in fire dynamics using temperature field data derived from high-fidelity CFD simulations. By learning from historical patterns in these simulations, the model offers a computationally efficient alternative to full CFD evaluation for real-time or large-scale fire safety assessments.

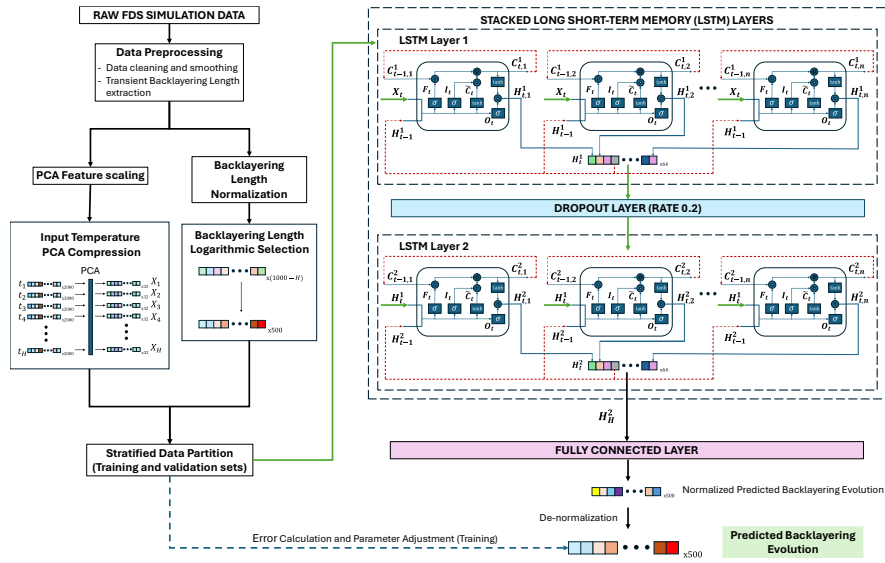


Figure 1. Schematic and process-flow of the proposed model.

Figure 1 presents the comprehensive framework of the proposed methodology, divided into two primary processing streams: the data preprocessing and feature engineering pipeline (left panel), and the stacked LSTM network architecture (right panel).

As illustrated in the left panel of Figure 1, the process begins with the extraction of raw simulation data. The input to the model consists of a time-ordered sequence of temperature fields, sampled at one-second intervals from the start of the fire scenario. Each field corresponds to the temperature at 2,000 spatial locations distributed along the tunnel's length.

To manage the high dimensionality of this spatial data, PCA is applied to the complete set of temperature snapshots. This yields a fixed linear transformation that projects each snapshot onto a reduced orthogonal basis, capturing the dominant modes of variance. By retaining 32 principal components, the system achieves an effective trade-off between data compression and information retention. Consequently, the input sequence is represented as a matrix where rows denote time steps and columns correspond to principal spatial modes.

The forecasting target is the backlayering length, predicted from the end of the input window onward. Rather than using uniformly spaced output points, which can overrepresent low-variation regions in the later stages of the fire, the forecast vector is defined using logarithmic time mapping. This allows denser sampling of early time points, where backlayering changes rapidly, and

sparser sampling later, reflecting the natural slowing of fire evolution. The output of the model is thus a compact vector of future backlayering values sampled over a non-uniform time grid. Before training, all targets are normalized using the global mean and standard deviation of the entire dataset to enhance numerical stability. Finally, the processed data undergoes a stratified partition into training and validation sets to preserve the distribution of samples with significant backlayering between both sets.

The right panel of Figure 1, details the machine learning model architecture. The model employs a stacked configuration, processing the sequence of PCA-encoded temperature vectors through two distinct LSTM layers comprising 64 units each.

The core of the network is the LSTM unit, designed to regulate the flow of information over time through a series of interacting gates. As detailed in the cell insets of Figure 1, at each time step t , a unit receives an input vector, the previous hidden state H_{t-1} , and the previous cell state C_{t-1} . These are processed through a series of gates with learned parameters:

- Forget Gate (F_t): This gate determines which parts of the previous memory C_{t-1} should be discarded. It combines X_t and H_{t-1} , utilizes a sigmoid activation function σ , and multiplies the result with C_{t-1} .
- Input Gate (I_t) and Candidate Memory ($\tilde{C}_t$): The input gate, also based on a sigmoid function, determines which parts of new information is incorporated. A separate tanh layer generates $\tilde{C}_t$, a candidate update. The actual update to the memory is $I_t \cdot \tilde{C}_t$.
- Memory Update (C_t): The new memory is calculated by combining retained old memory and new information: $C_t = F_t \cdot C_{t-1} + I_t \cdot \tilde{C}_t$.
- Output Gate (O_t) and Hidden State (H_t): The output gate decides which parts of the memory is exposed. The final hidden state H_t is computed by applying a tanh activation to C_t , then multiplying elementwise with O_t .

This gated architecture allows each LSTM unit to maintain a persistent internal memory over long sequences, selectively updating or retaining information based on temporal context. It is particularly well-suited to modelling fire development, where early conditions may influence later behavior in complex, nonlinear ways.

The network structure integrates these units into a cohesive flow. The first LSTM layer receives the PCA-compressed temperature distribution X_t as its input vector and outputs a sequence of hidden states (H_t^1), capturing both short- and long-term temporal dependencies which serve as input to the second layer. To prevent overfitting, a Dropout layer with a rate of 0.2 is applied between the LSTM layers, randomly dropping a fraction of units during training. The second LSTM layer processes the sequence to produce a final hidden state (H_H^2) that summarizes the entire input window. Finally, a Fully Connected layer transforms this context vector into the forecast vector which, after de-normalization, corresponds to the logarithmically spaced future backlayering length time points.

Each training sample consists of a pair: a sequence of past temperature fields and a vector of future backlayering values. The network is trained using the Adam optimization algorithm, which leverages adaptive learning rates to accelerate convergence. During the training phase, loss gradients are backpropagated through time to adjust the weights of the recurrent and dense layers.

Multiple models are trained with varying input sequence lengths (H) to evaluate the impact of historical information on predictive performance. Post-training performance is assessed using three standard regression metrics: Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and the coefficient of determination R^2 .

4. RESULTS AND DISCUSSION

4.1 PCA-Based Compressibility and Mode Selection for Ceiling Temperatures

The ceiling temperature fields are analyzed using PCA to determine their intrinsic dimensionality and to assess the feasibility of reduced-order representations. The cumulative explained variance demonstrates that the temperature distributions are highly compressible: more than 96% of the variance is captured by the first four components, and the 99–99.9% range is already reached with 8–32 components. This indicates that the dominant thermal structures governing the ceiling flow are governed by a very low-dimensional manifold.

The reconstruction performance highlights the PCA behavior across three ceiling-domain subsets. The RMSE over all ceiling points measures global accuracy and drops below about 2 °C with 16–32 components, showing that the large-scale temperature field is captured with relatively few modes. The activity-weighted RMSE, which emphasizes hotter regions, is initially higher, indicating that low-dimensional reconstructions miss localized plume structures. As more components are added, it approaches the global RMSE, suggesting that modes beyond roughly the 8th–16th capture thermal features relevant to backlayering. Similarly, the RMSE restricted to points above 12 °C confirms that about 16–32 components are needed to reproduce the fire-heated layer accurately.

The qualitative comparison in Figure 2 supports the previous numerical results. Differences between reconstructions mainly appear in regions with strong temperature gradients, while far from the fire the number of components has little effect. Downstream, profiles are nearly identical beyond 30 m, whereas upstream differences extend up to 150 m because of backlayering. Reconstructions with 16–32 components closely match the original profiles, including the peak temperature and downstream decay, while the sharp backlayering front is progressively recovered as more components are retained.

Overall, the PCA analysis indicates that the ceiling temperature fields are governed by a compact, low-dimensional structure, and that representations using 32 PCA modes are sufficient to reproduce both the global temperature distribution and the localized features most relevant for backlayering dynamics. This provides a strong foundation for PCA-based data reduction in subsequent modeling and sensitivity analyses.

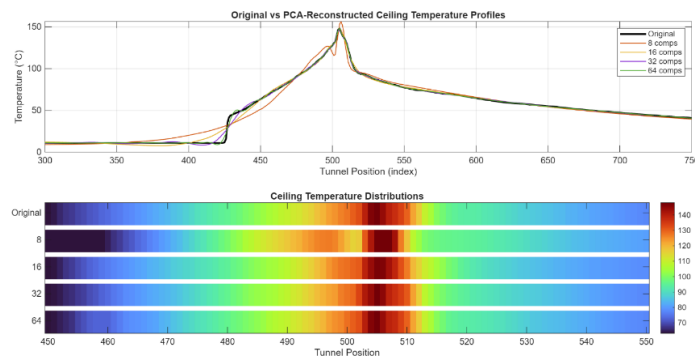


Figure 2. Ceiling temperature distribution sample for simulated and PCA-reconstructed for different number components: Temperature profiles along longitudinal tunnel section and Temperature graphical distribution detail.

4.2 Impact of Observation Window Length on LSTM Generalization Performance

To evaluate the impact of input sequence duration on forecasting performance, a series of LSTM models were trained using different lengths of historical temperature data. Specifically, the duration of available input data was varied from 30 to 240 s, in order to assess how early into a fire event accurate backlayering predictions can be made. This analysis aims to identify how much prior information is required for reliable forecasting, and whether longer observation windows consistently lead to better predictive accuracy. By systematically testing models with increasing historical context, the study also seeks to quantify the trade-off between early inference capability and forecasting precision.

To ensure a robust and statistically representative evaluation across different input configurations, each model corresponding to a given input history length (ranging from 30 to 240 s) was trained over 200 epochs. This process was independently repeated 50 times to account for variability due to random initialization and stochastic gradient descent. From each group of 50 trials, the model yielding the lowest validation RMSE was selected for analysis. This procedure ensures that performance comparisons are based on the best-achievable configuration under consistent training conditions.

The LSTM forecasting performance was assessed as a function of the available input history by varying the input window from 30 to 240 s (six steps) and training all models under identical conditions to isolate the effect of history length. Predictive skill was quantified using MAE, RMSE, and R^2 , reported for training, validation, and the full dataset.

Accuracy improves steadily as longer histories are provided. With only 30 s of input, the model shows limited capability (validation RMSE 58.9 m, R^2 0.75), whereas extending the window to 120 s yields a marked improvement (RMSE 32.5 m, R^2 0.94). Further increases to 180–240 s provide smaller additional gains (RMSE 22.5–21.2 m; $R^2 \approx 0.97$), indicating diminishing returns and suggesting that most of the relevant dynamic information is concentrated in the initial stages of the fire, particularly within the first 2–3 minutes. This result is consistent with the high variability during early smoke and heat propagation and the relative stabilization that follows under the influence of ventilation.

Validation errors remain higher than training errors but the gap is controlled across all cases, indicating good generalization. Overall, input windows of roughly 120–180 s offer a practical trade-off between early warning and robust accuracy for tunnel-fire backlayering forecasts.

4.3 Temporal Evolution of Prediction Error Distributions

To complement the aggregate performance metrics and explore the temporal dynamics of error propagation, Figure 3 presents a series of boxplots showing the distribution of prediction errors at specific forecast times, for each tested history length. Each subplot corresponds to a different input history window (H), and the boxplots capture the prediction error at discrete time points throughout the forecast interval.

This representation provides valuable insight into both the magnitude and variability of prediction errors as a function of forecast lead time and input duration. Several important trends are evident. For the shortest history length (30 s), the prediction error increases substantially as the model attempts to forecast further into the future. While the median error remains relatively centered in the early stages, the spread, which is indicated by the interquartile range and the prevalence of outliers, widens rapidly beyond 240 s. By 600 to 900 s, errors become heavily skewed, with

frequent underpredictions exceeding 200 m in magnitude. This indicates that with minimal historical context, the model lacks the temporal information necessary to produce stable long-range forecasts, particularly as system dynamics evolve under ventilation influence. As the input history increases, performance improves markedly. For 60 and 90 s of input, the error variance still grows with forecast horizon but is significantly reduced, particularly in the early to mid-range time steps (up to ~480 s). Importantly, systematic bias begins to diminish, as evidenced by boxplots becoming more centered around zero, and the magnitude of outliers decreases.

At 120 s of input, error distributions become significantly more compact and symmetric, even at longer forecast horizons. This suggests the model has acquired sufficient temporal information to generalize well over both short and medium-term predictions. Beyond 180 s of input, the improvements are primarily in consistency rather than magnitude: while the central tendency of the error remains close to zero throughout, the interquartile spread and the number of extreme outliers are minimized across all forecast horizons. The model achieves robust predictive behaviour not only at early time points but also during the more stable phases of the backlayering process.

Overall, these results validate the hypothesis that extended temporal context allows the model to more accurately infer the underlying dynamics and better anticipate future system states. The benefits of longer input windows are particularly evident at mid-to-long-term forecasts, where physical processes such as thermal stratification and airflow interactions become more dominant. The transition from wide, asymmetric error distributions to compact, balanced ones clearly illustrates how historical depth contributes to model stability and confidence across the entire prediction timeline.

These findings, taken together with the global performance metrics previously discussed, strongly support the use of LSTM models for forecasting backlayering evolution and highlight the critical role of temporal context in improving both precision and reliability.

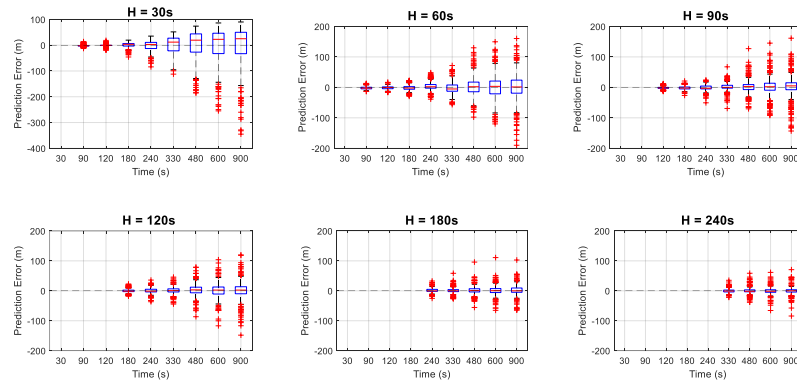


Figure 3. Error distribution evolution over prediction time for different input history windows (H).

4.4 Sample-Level Backlayering Evolution Predictions

Figure 4 illustrates forecast trajectories for four representative samples, with varying backlayering evolutions and cases with and without backlayering, providing qualitative insight into the influence of input history length. Each subplot compares the true backlayering evolution to predictions generated by models trained with different historical input durations, with the vertical dots

representing the time in which input set ends and predictions start for each model. These qualitative examples offer further insight into how input history influences forecast shape and fidelity throughout the event timeline.

With short histories (e.g., 30 s), the model often fails to anticipate continued backlayering growth and tends to plateau early, leading to systematic underestimation in cases with strong backlayering. In addition, the 30 s model produces similar trajectories for otherwise distinct samples, indicating insufficient temporal information to discriminate longterm evolution, which is consistent with the large underprediction outliers observed in Figure 3. As the input history increases, predictions better reflect the event dynamics, capturing both growth rate and final extent.

Histories of roughly 90–180 s yield close qualitative agreement with the simulated trajectories, including nonlinear growth and stabilization. Extending to 240 s is typically only marginally better than 180 s and can occasionally introduce slight smoothing, reinforcing the diminishingreturn trend and supporting 120–180 s as a practical compromise between accuracy and efficiency. Overall, these examples provide a visual complement to the statistical analysis, reinforcing the conclusion that richer temporal context substantially enhances forecast reliability. They highlight the model's strength in extrapolating from early input data to longhorizon predictions, a critical capability for anticipatory safety measures in tunnel fire incidents.

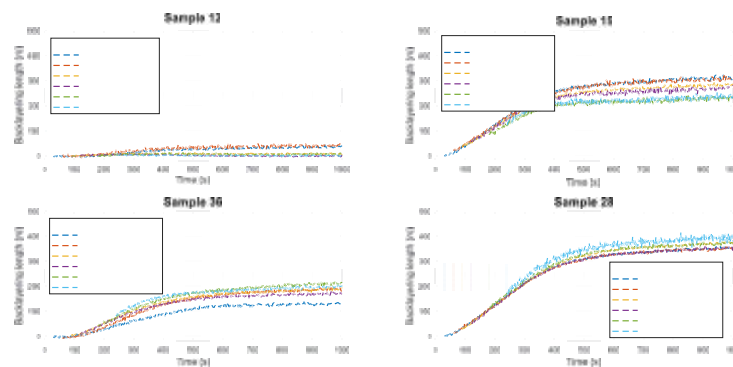


Figure 4. Sample cases for backlayering evolution prediction for different input history windows (H).

4.4 Interpreting Temporal Dependence via Occlusion Perturbations

To assess how different portions of the ceilingtemperature history influence the predicted backlayering distance, a temporal occlusion analysis was performed. Although not a gradientbased SHAP method, the procedure is conceptually equivalent to a SHAPstyle perturbation approach: small windows of the historical input sequence are systematically removed, and the resulting change in predicted backlayering distance is interpreted as the importance of that temporal region. The combined plot shown in illustrates two complementary indicators of temporal influence. The mean $\pm$ standard deviation of the L2 prediction change for each occluded window can be observed in. This reflects the absolute sensitivity of the model to perturbations at a given point in the sequence. The results show a strong increase in sensitivity towards the later part of the

temperature history (approximately the last 40–50 time steps). Occluding early parts of the sequence produces a negligible impact, indicating that the model places minimal reliance on distant historical information. In contrast, the highest sensitivity occurs at the very end of the 180 s history window, suggesting that the model primarily leverages the most recent thermal state to determine the extent of backlayering. Overlaying this, b) also includes a normalized importance representation, which highlights the relative distribution of influence across the full history. The steep rise near the final segment of the sequence implies that the reconstruction of the instantaneous backlayering front and the shape of the ceiling temperature profile immediately upstream are the dominant drivers of the model's predictions. Training and validation sets show nearly identical patterns, indicating stable and generalizable temporal dependence.

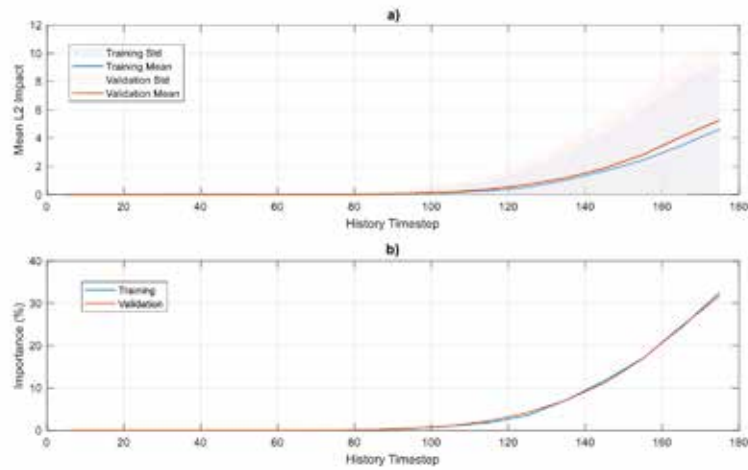
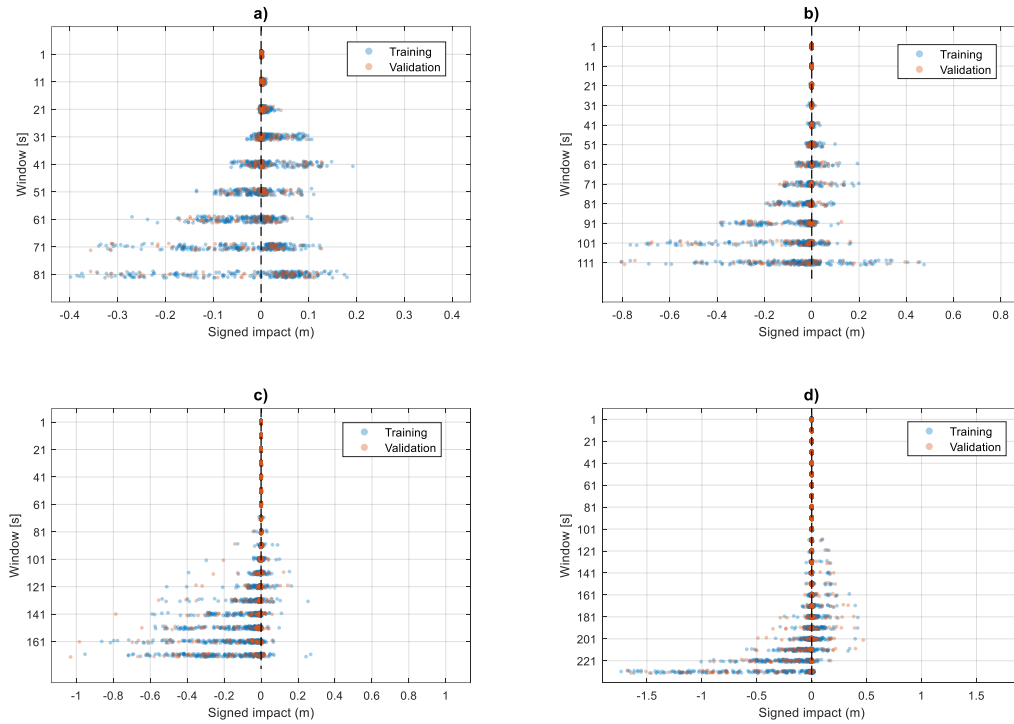


Figure 5. Temporal influence of the occlusion intervals for the input history windows $H = 180$ s. a) Mean and standard deviation of the L2 prediction change; b) Normalized importance of the window occlusion.

The sample level signed impacts depicted in Figure 6 provide additional insight for different input history windows. Each point represents the direction and magnitude of prediction change for a specific sample and occluded window. Negative values indicate reductions in the predicted backlayering distance when the window is removed (i.e., the removed thermal information originally pushed the prediction upward), while positive values imply that the occluded region caused an overprediction. The results show that most windows in the final portion of the history consistently produce negative signed impacts when removed, demonstrating that the recent thermal rise upstream of the fire predominantly increases the predicted backlayering distance. Earlier windows exhibit impact values clustered tightly around zero, reinforcing their limited relevance. The distribution also shows minimal systematic bias between training and validation datasets, indicating that the temporal response behaviour is consistent across unseen data.

Taken together, these results show that the model relies heavily on the latehistory thermal pattern, especially the shape and magnitude of the ceilingtemperature rise close to the backlayering front, while earlier portions of the time series provide very limited predictive utility.

The occlusion-based SHAP-style approach therefore confirms the physical expectation that backlayering behaviour is governed primarily by the most recent upstream temperature conditions



rather than long-range historical information.

Figure 6. Sample-level signed impacts for the input history windows: a) $H = 90$ s; b) $H = 120$ s; c) $H = 180$ s; and d) $H = 240$ s

5 CONCLUSIONS

This study developed and evaluated a PCA–LSTM framework to forecast backlayering-length evolution in longitudinally ventilated tunnel fires using a large CFD database (405 FDS simulations spanning 5–50 MW HRR, 1–5 m/s ventilation, and multiple tunnel cross-sections). PCA showed that ceiling-temperature fields are strongly compressible: retaining roughly 16–32 components preserves the dominant thermal structures while substantially reducing input dimensionality, enabling efficient sequence learning without discarding features relevant to backlayering.

Forecast skill increased consistently with the length of the historical input window. The largest improvements occurred when extending the history from 30 s to ~120 s, while longer windows (180–240 s) provided smaller additional gains, indicating that most predictive information is contained within the first 2–3 minutes of temperature evolution. Consistently, longer histories reduced error growth at longer horizons, yielding tighter and less biased error distributions and more faithful reproduction of the non-linear growth and stabilization of backlayering.

Temporal occlusion analysis indicated that predictions are driven primarily by the most recent segment of the input sequence, with early-time information contributing little—consistent with the

physics that link backlayering to the instantaneous upstream stratification and local ceiling heating near the backlayering front.

Overall, the proposed reduced-order, data-driven framework offers a promising fast surrogate for real-time backlayering prediction from ceiling-temperature measurements or reduced-order CFD outputs, supporting rapid decision-making and scenario screening in tunnel fire safety.

6. ACKNOWLEDGMENTS

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ANÁLISIS PRESTACIONAL DE UN FALSO TÚNEL URBANO FRENTE A LA ACCIÓN DEL INCENDIO. CASO DE ESTUDIO



Alejandro Torres
MSc Ing. Industrial
JVVA
España



Roberto Cerdeiriña
MSc Ing. Industrial
EUR-ING FEANI
JVVA
España



Alberto López
MSc Ing. Industrial
JVVA
España

Palabras clave: Estructura, Fuego, Túnel, PBD, Reutilización.

INTRODUCCIÓN

En el corazón de la ciudad de Málaga, bajo un parque urbano y una de las principales arterias de tráfico, se localiza el falso túnel Ortega Prado. Construido en 1995, este elemento de infraestructura soporta diariamente el tránsito de miles de vehículos y constituye un punto crítico para la movilidad urbana de la ciudad.

El proyecto original fue desarrollado en 1995 por el Dr. Luís Cánovas del Castillo Fraile. Posteriormente, se llevó a cabo una intervención de rehabilitación integral y mejora estructural dirigida por los ingenieros estructurales Prof. Dr. Juan J. Arenas de Pablo y Prof. Dr. Marcos J. Pantaleón Prieto, fundadores de la reconocida consultora de ingeniería estructural Appia XXI.

La relevancia estratégica del túnel implica que cualquier fallo estructural o una intervención prolongada tendría consecuencias inmediatas, tales como el colapso del tráfico en la zona occidental de la ciudad, un impacto económico significativo sobre servicios esenciales y una alteración directa de la actividad cotidiana de los ciudadanos.

En este contexto, el presente caso de estudio se concibió como una intervención crítica cuyo objetivo fue adaptar la infraestructura a la normativa vigente y al estado del arte en materia de Ingeniería Estructural frente al Incendio (Structural Fire Engineering, SFE, de ahora en adelante), mediante un enfoque basado en prestaciones. En particular, se evaluó el comportamiento estructural del falso túnel frente a escenarios de incendio natural mediante con el objetivo de analizar si el sistema estructural necesite o no protección pasiva.

Este caso de estudio se desarrolló dentro del marco del Diseño Estructural frente al Fuego Basado en Prestaciones (Performance-Based Structural Fire Design [1], PBSFD, de ahora en adelante), combinando técnicas de Dinámica de Fluidos Computacional (Computational Fluid Dynamics, CFD) con análisis termo-mecánicos avanzados mediante el Método de los Elementos Finitos (Finite Element Method, FEM).

DESCRIPCIÓN DEL SISTEMA ESTRUCTURAL

La estructura principal del falso túnel consta de 42 vigas en cajón mixtas de sección trapezoidal variable acero-hormigón, de 700 mm de canto en apoyo y 1400 mm a partir de un octavo de luz. El ancho del ala superior es constante de 2.4 m y de 1.6 m en el inferior salvando un vano aproximado de 34 m. En la figura 1 puede observarse una vista en alzado de la sección longitudinal de la viga del túnel.

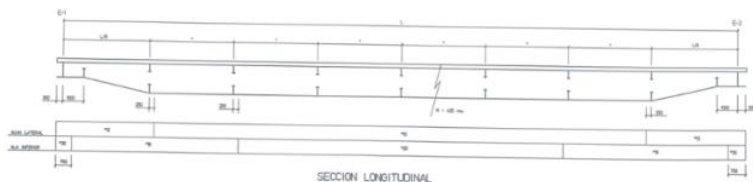


Figura 1: Sección en alzado de la viga

La sección mixta se completa mediante una losa de hormigón armado de 0,18 m de espesor, solidariamente conectada a la estructura metálica a través de conectores soldados movilizandoo conexión total al ala superior de las vigas de acero. Por otra parte, la sección de la viga está rigidizada internamente cada $L/8$ como puede verse en la figura 2.

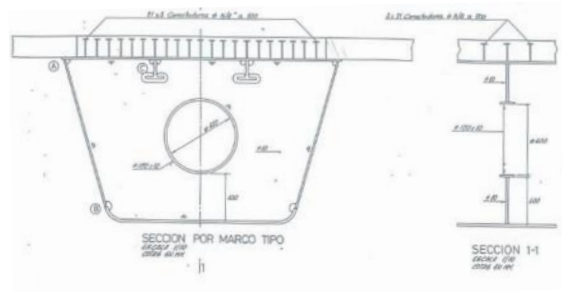


Figura 2: Sección en alzado de la viga

Su única conexión al terreno se realiza en los estribos a través de apoyos elastoméricos, donde se aprovecha la pantalla de hormigón existente, que se constituye en su cimentación, directamente en el estribo derecho y mediante un cargadero en el estribo izquierdo. El detalle de la sección transversal en la posición de los apoyos se muestra en la figura 3.

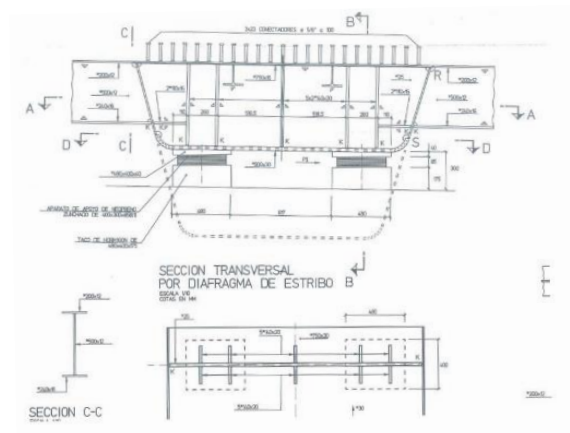


Figura 3: Sección en alzado de la viga

La estabilidad lateral se consigue a través de un efecto diafragma de la losa superior que configura la sección mixta actuando como en su conjunto con las alveoladas prefabricadas como se ve en la figura siguiente. Cada viga del tablero se encuentra unida por sus extremos a través de unas vigas armadas configurando una continuidad estructural al conjunto en las secciones de apoyo (figura 4).

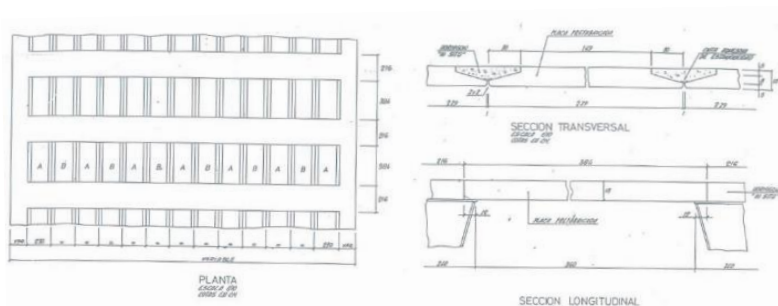


Figura 4: Sistema de losa superior

CRITERIO DE CUMPLIMIENTO PROPUESTO

De acuerdo con los requisitos mínimos de seguridad en los túneles de carreteras del Estado [2], no existe ningún requisito de resistencia estructural para túneles como el evaluado. Sin embargo, los sistemas de protección contra incendios del túnel sí deben asegurar tanto la seguridad de los usuarios como de los equipos de intervención para el incendio de diseño. Por tanto, como criterios de análisis se adopta evitar el colapso progresivo y evitar la afección a los sistemas de seguridad del túnel (ventilación y comunicaciones) durante la posible intervención.

Por otra parte, la ubicación del túnel bajo un parque hace importante asegurar que al menos se garantice un tiempo razonable para la evacuación del parque en condiciones de seguridad, y además, un posible colapso del túnel resultaría muy perjudicial para la circulación al tratarse de un acceso principal de la ciudad.

El tráfico no está restringido a vehículos ligeros, aunque el tráfico de vehículos pesados está entre el 5 y el 7%, según el sentido de circulación [3]. La probabilidad de ocurrencia de un incendio de vehículo ligero (en caso de incendio relevante) según la metodología MARTE [4] (E1, 8 MW) está en el orden del 85% para este túnel.

Según las recomendaciones de PIARC [5], tampoco resulta estrictamente necesario garantizar la resistencia estructural de este tipo de túneles más allá de evitar el colapso progresivo. En caso necesario se propone asegurar un valor de entre R60 y R120 según la curva de fuego normalizada ISO-834.

Aplicando normativa nacional de aplicación a edificios [6], el valor estaría en ese mismo orden de magnitud, entre R60 y R120. Asimilándolo a un aparcamiento, el valor propuesto en el CTE DB-SI es R90.

Se propone por tanto el siguiente análisis para definir la resistencia estructural requerida por el túnel:

- Evaluar el comportamiento estructural para el escenario de incendio de diseño, definido de acuerdo con el Escenario E4 de la MARTE (30 MW), mediante técnicas de simulación computacional (análisis prestacional).
- En función del resultado (colapso o daño significativo, tiempo hasta alcanzarlo) definir un valor de resistencia y estabilidad estructural coherente con los valores definidos en las distintas normativas.

Con lo expuesto anteriormente, se define como objetivo que el sistema estructural deba mantener su estabilidad y capacidad portante para evitar el colapso progresivo durante al menos 90 minutos no afectando a la operación del falso túnel.

METODOLOGÍA EMPLEADA

El estudio prestacional de ingeniería del incendio y estructural objeto del caso de estudio tiene el objetivo de justificar que el sistema estructural garantiza la estabilidad y resistencia adecuada adaptándose a los requisitos prescriptivos de normativa de posible aplicación. Para llevar a cabo dicho análisis, se implementará la metodología definida en los Eurocódigos que son de aplicación [7]. La metodología PBSFD combina dinámica de fluidos computacional (CFD) y análisis estructural termo-mecánico avanzado mediante la técnica de los elementos finitos (FEM).

La herramienta de cálculo para la modelización del incendio se ha desarrollado con el programa de CFD Fire Dynamics Simulator (FDS) [8] [9]. El pre/post procesado de las simulaciones se ha realizado con el software PyroSim, desarrollado por Thunderhead Engineering de forma específica para su uso con FDS.

Como herramienta de cálculo del problema acoplado termo-mecánico se utilizó el software SAFIR [10], desarrollado en la University of Liège (Bélgica), para la obtención del campo de temperatura no uniformes en la sección transversal y posteriormente, el análisis del sistema estructural. Este software permite realizar cálculos térmicos de transferencia de calor mediante el Método de los Elementos Finitos (FEM), así como análisis estructurales no lineales en dos y tres dimensiones. Asimismo, posibilita el análisis de inestabilidades locales considerando la torsión no uniforme (alabeo) de secciones y la inclusión de las masas correspondientes para la resolución del problema dinámico.

La evaluación del comportamiento del sistema estructural se llevó a cabo mediante un procedimiento de tres pasos, descritos a continuación.

Paso 1. Definición y análisis de escenarios de incendio. Se seleccionaron tres escenarios representativos, coherentes con la metodología de análisis de riesgos en túneles MARTE: 30 MW (E4 MARTE) en el centro del vano y en zona de apoyo como incendio máximo previsible (escenarios de diseño, SC1, SC2) y 8 MW (E1 MARTE) de fuego en el centro del vano como escenario crítico más probable (SC3). Fueron modelados utilizando la técnica CFD, empleando los parámetros propuestos en la Metodología ATC [11].

Para poder trasladar los resultados del modelo CFD al modelo de cálculo térmico estructural hay que obtener los flujos térmicos que afectan a la estructura. Una forma de hacerlo es mediante el concepto de Temperatura Superficial Adiabática (T_{AST}) definido por Wickström [12]. Esta temperatura ficticia sería aquella para la cual el flujo de calor neto es nulo, de acuerdo con la siguiente fórmula:

$$\varepsilon(\dot{q}_{inc}'' - \sigma T_{AST}^4) + h(T_g - T_{AST}) = 0 \quad (1)$$

Donde ε es la emisividad de la superficie, h el coeficiente de transferencia de calor por convección, $\dot{q}_{inc}''$ el flujo de calor por radiación incidente en la superficie, y T_g la temperatura del gas que envuelve el sólido.

Este concepto permite incorporar los flujos de calor convectivo y radiante en un único valor. Al aplicar este campo de temperaturas a los elementos sólidos del modelo térmico-estructural se estarían introduciendo los efectos del incendio sobre la estructura tanto por el efecto de la temperatura del gas como por la propia radiación del incendio.

Paso 2. Análisis Seccional Térmico (FEM) de la transmisión de calor en la sección estructural, evaluándose tanto la velocidad de calentamiento como la evolución y distribución del campo de temperaturas no uniforme en el interior de la sección.

Paso 3. Análisis Estructural (FEM). A partir de los resultados térmicos obtenidos en la fase anterior, se realizó un análisis termo-mecánico acoplado, no lineal y avanzado del sistema estructural en el dominio del tiempo y de la resistencia. Este paso es imprescindible para evaluar el comportamiento real del sistema estructural, ya que permite considerar la interacción entre los distintos elementos estructurales y los efectos acoplados asociados. Dicha interacción incluye la redistribución de esfuerzos internos, así como la interacción térmica entre los elementos sometidos a mayores temperaturas y aquellos más fríos. El análisis de la evolución de la configuración deformada resulta igualmente un aspecto fundamental que proporciona respuestas relevantes sobre los posibles modos de comportamiento.

Los resultados obtenidos se evaluaron mediante la aplicación de criterios de aceptación acordes con el estado del arte en el análisis basado en prestaciones a nivel internacional, considerando límites de deformación [13], estabilidad y resistencia [7]. De este modo, se contrastó el comportamiento del sistema estructural frente a los objetivos de desempeño y los requisitos reglamentarios establecidos.

RESULTADOS

Paso 1. Resultados del análisis CFD

Se ha generado un modelo CFD de longitud suficiente para recoger de forma adecuada las temperaturas de todas las vigas afectadas por el incendio (60 m, 10 vigas). No se ha considerado la activación de la ventilación ni tiro natural en el túnel, quedando así del lado de la seguridad con

respecto a las temperaturas alcanzadas por la estructura. Se han considerado condiciones ambientales medias anuales, estimado representativo del estado en el interior del túnel. Se ha empleado un mallado de 0.2 m, considerado suficiente para la representación del incendio empleado de acuerdo con la experiencia del consultor y la documentación del software [9]

En la superficie de las diferentes vigas del túnel se han colocado sensores para capturar la evolución de la temperatura del incendio. Estos dispositivos se han colocado en cada sección transversal con un espaciamiento entre secciones de 1000 mm. Estos sensores se han distribuido tanto en las caras exteriores como en interiores de almas laterales, ala inferior y superior, así como en los rigidizadores interiores. Por cada escenario de incendio y viga, se ha analizado un total de 32 secciones transversales con sus sensores correspondientes.

En la figura 5 se observan los diferentes dispositivos empleados para cada sección de las vigas del túnel, así como el modelo CFD empleado:

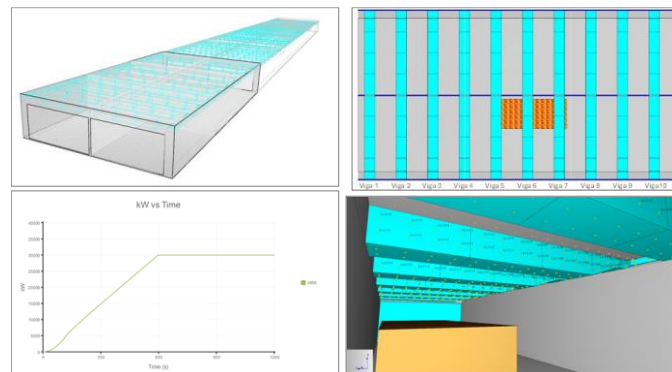


Figura 5: Imágenes del modelo CFD (SC1). Arriba izqda., vista 3D; arriba dcha., vista en planta; abajo izqda., HRR (30 MW pico); abajo dcha., sensores de T_{AST}

Los resultados obtenidos se pueden observar en la figura 6 y 7:

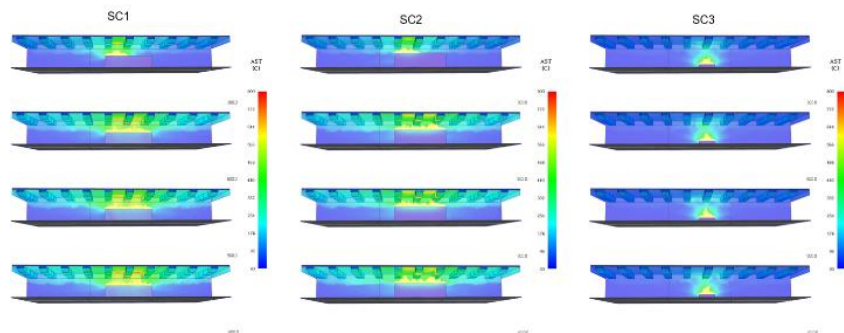


Figura 6: Resultados del análisis CFD

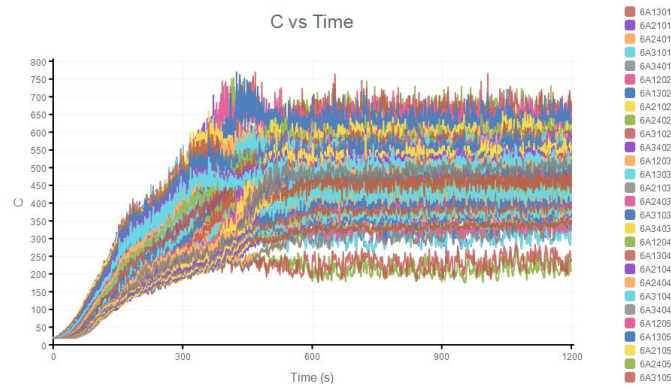


Figura 7: Escenario SC1. Ejemplo de resultados de sensores de T_{AST} (viga 6)

En los escenarios SC1 y SC2, la temperatura adiabática máxima en la superficie de las vigas del túnel se alcanza en torno a los 1200 s (20 min). La viga situada directamente sobre el foco del incendio alcanza valores máximos en el contorno de la sección de acero trapezoidal del orden de 800 °C, mientras que las vigas adyacentes registran temperaturas máximas cercanas a 600 °C.

En el escenario de incendio SC3, la temperatura adiabática máxima en la superficie de las vigas del túnel también se alcanza a los 1200 s (20 min), con un valor máximo aproximado de 450 °C. En este caso, las vigas adyacentes alcanzan temperaturas máximas del orden de 250 °C.

La evolución temporal de los registros de estos sensores se traslada al modelo de cálculo estructural como condiciones de contorno para la evaluación del comportamiento de la estructura sometida a los escenarios de incendio presentados. La simulación se ha corrido hasta alcanzar un estado estacionario en temperaturas, extrapolando los valores de T_{AST} a partir de ese momento para alimentar el modelo de análisis estructural. No se ha considerado el posible decaimiento de la potencia de incendio según la MARTE, quedando del lado de la seguridad y considerando que dicho decaimiento no está garantizado.

Paso 2. Resultados de análisis seccional térmico

Para ser consistentes con el análisis anterior, la viga mixta se ha discretizado en tramos de 1000 mm, con el objetivo de acoplar los resultados del análisis CFD con el análisis estructural.

De manera representativa se muestra el análisis de la sección estructural térmicamente más desfavorable en el SC1. La distribución del campo de temperaturas para un tiempo de 1800 s (30 min) y 7200 s (120 min) es la que se puede observar en la figura 8.

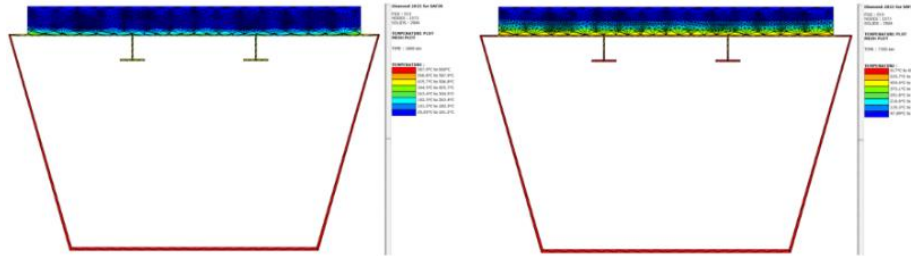


Figura 8: Distribución de temperaturas en el elemento estructural

Del campo de temperaturas no lineal en el interior de la sección transversal en el dominio del tiempo se puede indicar lo siguiente:

- En las caras laterales de la sección en cajón, para un tiempo aproximado de 1800 s (30 min), la temperatura de estas es del entorno de los 630 °C, superando los 550 °C.
- En la cara inferior se alcanzan los 695 °C para un instante de 7200 s (120 min); no obstante, a los 1800 s (30 min) la temperatura alcanzada está en el entorno de los 670 °C, superior a los 550°C.
- En la chapa superior, para un tiempo aproximado de 1800 s (30 min), la temperatura de estas es del entorno de los 350 °C. Para los 7200 s (120 min) la temperatura alcanzada se encuentra en el entorno de los 575 °C.
- En los perfiles de refuerzo del ala superior, para un tiempo aproximado de 1800 s (30 min), la temperatura de estas es del entorno de los 515 °C, Para un tiempo de 7200 s (120 min) la temperatura alcanzada es del orden de los 630 °C.
- En los conectores se alcanzan temperaturas del orden de los 195 °C y 230°C respectivamente, por lo que no se ven afectados por la severidad del incendio.

Una vez analizadas la totalidad de las secciones de los tres escenarios, se observa que para los escenarios 1 y 2, las temperaturas alcanzadas para cada uno de los elementos estructurales supera la temperatura de 550 °C (umbral de temperatura en vigas isostáticas donde el pandeo latero-torsional no es un potencial fenómeno de fallo de acuerdo con la referencia [14] en determinadas secciones transversales de las proximidades de la ubicación del incendio, mientras que para el escenario 3 las temperaturas máximas alcanzadas están en el orden de 300-350 °C.

Para los dos primeros escenarios, en las secciones transversales es esperable que aparezcan alabeos locales en las caras laterales y. como consecuencia de ellos que toda la sección en cajón sufra de distorsiones por alabeo tanto local como global, interactuando en el campo de desplazamientos del elemento estructural. Este efecto se prevé que sea menor en el escenario 3.

Paso 3. Resultados del análisis termo-mecánico acoplado

Se han realizado dos análisis termo-mecánicos acoplados diferentes. En primer lugar, un análisis 2D mediante elementos lineales, y en segundo lugar un análisis 3D mediante elementos tipo Shell, por medio del cual se pueden analizar los alabeos locales de la sección de acero. Ambos modelos estructurales se representan en la figura 9.

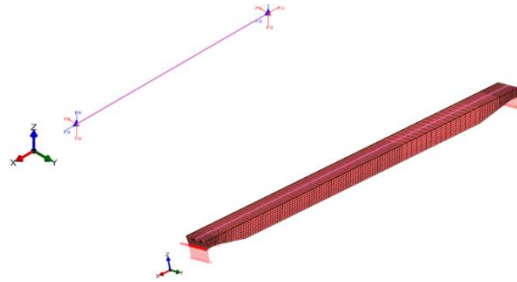


Figura 9: Modelo estructural analizado.

Para los tres escenarios se ha realizado un análisis del campo de tensiones y deformaciones para conocer la respuesta del sistema estructural en los tres escenarios de incendio estudiados. Se muestra a continuación unas imágenes extraídas del escenario 1, que resultó ser el más desfavorable; en la figura 10 se muestra los resultados obtenidos para cada uno de los modelos mecánicos de este escenario tanto a nivel local como global.

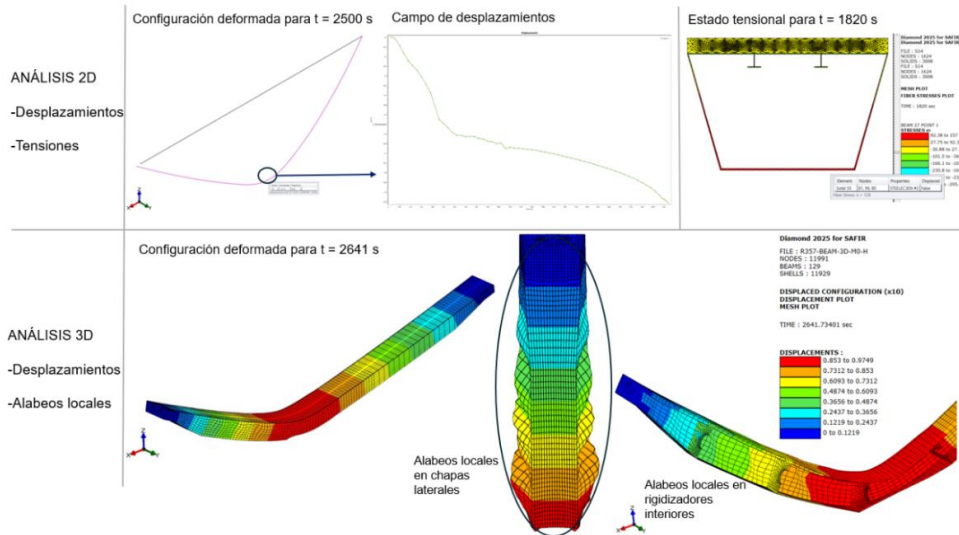


Figura 10: Modelo estructural analizado.

La tabla 1 presenta un resumen de los resultados obtenidos para cada uno de los escenarios de incendio:

Tabla 1: Resultados del análisis estructural

	Modelo estructural 2D			Modelo estructural 3D		
	SC1	SC2	SC3	SC1	SC2	SC3
t_{fallo}	2500 s (42 min)	N.A.	N.A.	2641 s (44 min)	N.A.	N.A.
$t_{\delta 3,max}$	2500 s (42 min)	7200 s (120 min)	10800 s (180 min)	2641 s (44 min)	7200 s (120 min)	10800 s (180 min)
$\delta_{3,max} (L/2) -$ mm	-955	-488	-236	-975	-465	-202
ratio $(L/\delta_{3,max})$	33.5	66.5	136	32.8	68	158
f.u. (σ_{max}/f_{yk})	0.5	0.82	0.86	N.A.	N.A.	N.A.
t_{satisf}	30 min	90 min	180 min	30 min	90 min	180 min

t_{fallo} se da cuando numéricamente el problema no encuentra convergencia (deformación unitaria plástica última, grandes desplazamientos, estado tensional por encima de la tensión plástica última, etc.)

$t_{\delta 3,max}$ hace referencia al tiempo en el cual se alcanzan los máximos desplazamientos

t_{satisf} hace referencia al tiempo durante el cual se satisfacen los desplazamientos del sistema estructural de acuerdo con los criterios de aceptabilidad (se remite al lector a la página 49, 50 y 51 (cláusula 6.1), de la referencia [13]).

Se muestra en la figura 11 los resultados obtenidos en cuanto a los alabeos en las chapas laterales de acero de la sección trapezoidal para los tres escenarios:

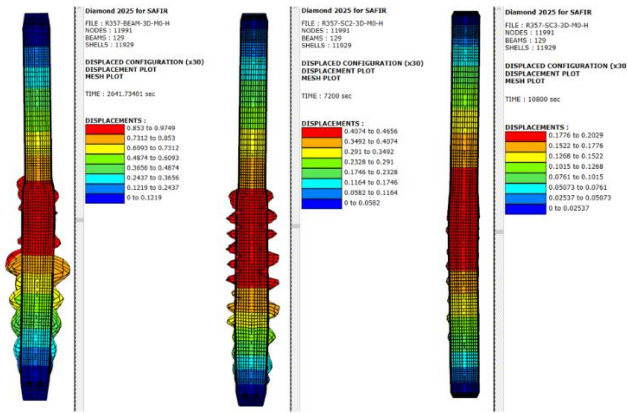


Figura 11: Alabeos locales en las secciones de acero.

Para los escenarios 1 y 2, cuyas temperaturas alcanzadas superan los 500°C, los alabeos locales en las chapas de acero y rigidizadores interiores son pronunciados en más de un 50% de la viga, mientras que para el escenario 3, cuyas temperaturas son inferiores a los 350°C, los alabeos no son relevantes.

CONCLUSIONES

De los resultados de los diferentes escenarios de incendio se ha detectado la necesidad de tener que proteger de forma pasiva el sistema estructural, más concretamente la sección en cajón que conforma la viga mixta para poder alcanzar un criterio R superior a R90 en el escenario N°1, con incendio ubicado a mitad de la luz.

Adicionalmente, se recomendaron medidas adicionales para los apoyos elastoméricos de neopreno de la viga mixta ubicados sobre los muros de hormigón armado. La solución propuesta fue colocar una barrera localizada a nivel de apoyo para limitar la llegada del campo de temperaturas al apoyo de neopreno, bien mediante una pared/cerramiento local que envuelva a todo el apoyo con placas de pladur o fábrica de bloques de hormigón o ladrillo con un guarnecido y enlucido que sea capaz de proporcionar el criterio EI90 como mínimo, establecido por el cliente.

El caso de estudio del túnel Ortega Prado permite obtener soluciones allí dónde la aplicación de criterios prescriptivos no es capaz de dar respuesta. El análisis computacional avanzado permitió definir la protección pasiva necesaria para el incendio máximo previsible, obteniéndose un comportamiento aceptable para el escenario crítico más probable, además de mantener la continuidad de la operación del túnel mientras se ejecutaban los trabajos de protección pasiva. La buena concepción estructural del proyecto original facilitó una respuesta adecuada frente a la acción accidental del incendio.

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SEGURIDAD CONTRA INCENDIOS EN TERMINALES AEROPORTUARIAS - LA NECESIDAD DE UNA VISIÓN HOLÍSTICA



Gabriele Vigne*
Director
JVVA
España



Jimmy Jönsson
Director
JVVA
España



**Manuel Juárez
Solano**
Responsable Dpto.
de Aeropuertos
Sacyr España

Palabras clave: Terminales aeroportuarias, Seguridad contra incendios, Evacuación, Ingeniería basada en prestaciones

ABSTRACT

Las terminales aeroportuarias constituyen uno de los entornos más complejos para la seguridad contra incendios, debido a la elevada ocupación, la coexistencia de usos comerciales y operativos y la necesidad de garantizar simultáneamente la seguridad de los pasajeros y la continuidad de las operaciones. La aplicación de normativas internacionales de prestigio, como NFPA 101, junto con referencias específicas como NFPA 415, el International Building Code (IBC) y los códigos nacionales, proporciona un marco de referencia sólido; no obstante, la mayoría de las normativas nacionales no están específicamente concebidas para aeropuertos, lo que limita su capacidad para abordar las particularidades de estas infraestructuras. Entre los principales retos destacan la adecuada estimación del aforo, que a menudo no refleja el diseño funcional del edificio, la ausencia de una sectorización efectiva en espacios abiertos y las grandes alturas interiores, que condicionan tanto la eficacia de los sistemas de extinción automática como el rendimiento del control de humos. A ello se suma la dificultad de cumplir los recorridos de evacuación normativos manteniendo la segregación entre lado tierra y lado aire, así como la complejidad introducida por atrios y conexiones verticales abiertas. En este contexto, las herramientas avanzadas de simulación, tanto de evacuación como de dinámica de fluidos computacional (CFD), se consolidan como elementos clave para verificar la relación entre RSET y ASET, minimizando interrupciones operativas. Este trabajo analiza estos retos desde una perspectiva normativa y técnica, subrayando la necesidad de un enfoque holístico que combine regulación, ingeniería basada en prestaciones y estrategias operativas, ilustrado mediante casos reales de aplicación a nivel internacional.

* Gabriele Vigne — JVVA Group, C/Velazquez 157, 28002 Madrid (Spain).

Telef.: +34 644298540, E-mail: gabriele.vigne@jvvafire.com

1. INTRODUCCION

Las terminales aeroportuarias se han consolidado en las últimas décadas como infraestructuras críticas dentro de los sistemas de transporte globales, caracterizadas por elevados niveles de ocupación, una notable diversidad de usuarios y una creciente complejidad arquitectónica y operativa. Además de su función principal como nodos de movilidad, estas instalaciones integran hoy en día amplias áreas comerciales, espacios de espera de gran escala y sistemas operativos altamente interconectados, lo que incrementa de forma significativa los retos asociados a la seguridad contra incendios. El diseño de la seguridad contra incendios en terminales aeroportuarias se enfrenta a condicionantes singulares que dificultan la aplicación directa de enfoques prescriptivos tradicionales. Entre ellos destacan la ausencia de sectorización efectiva en grandes espacios abiertos, la presencia de alturas considerables y grandes luces estructurales, la variabilidad temporal de la ocupación y la necesidad de mantener la segregación funcional entre zonas lado tierra y lado aire durante situaciones de emergencia. A estos factores se suma la exigencia de garantizar la continuidad operativa, dado que cualquier interrupción del servicio aeroportuario puede generar impactos económicos, operativos y de seguridad de gran magnitud. En este contexto, normativas internacionales de reconocido prestigio, como NFPA 101[1], NFPA 415[2] y el International Building Code (IBC)[3], proporcionan un marco regulatorio sólido para el diseño de la seguridad contra incendios. No obstante, la complejidad inherente a las terminales aeroportuarias hace que el cumplimiento estrictamente prescriptivo de dichos códigos resulte, en muchos casos, difícil o incluso incompatible con los objetivos arquitectónicos y operativos del proyecto. Esta situación ha impulsado de forma creciente la adopción de enfoques basados en prestaciones, que permiten evaluar el comportamiento real del edificio y de sus sistemas frente a escenarios de incendio representativos. Los modelos avanzados de evacuación y de dinámica de fluidos computacional (CFD) aplicados al análisis de incendios permiten estudiar de forma integrada la interacción entre el movimiento de los ocupantes, la propagación de humos, la eficacia de los sistemas de protección y la respuesta estructural al fuego, proporcionando una base objetiva para la toma de decisiones de diseño[9]. Este trabajo tiene como objetivo analizar los principales retos asociados a la seguridad contra incendios en terminales aeroportuarias modernas y las limitaciones que presentan los enfoques prescriptivos tradicionales cuando se aplican a este tipo de infraestructuras. El artículo pone de relieve la necesidad de adoptar una visión holística que integre requisitos normativos, ingeniería de seguridad basada en prestaciones y condicionantes operativos. Se presta especial atención a aspectos como las estrategias de evacuación, el control de humos en grandes espacios abiertos y el comportamiento estructural frente al fuego. Asimismo, se presentan casos reales de aplicación internacional que ilustran la implementación práctica de estas soluciones.

2. MARCO NORMATIVO Y ENFOQUE REGULATORIO

El diseño de la seguridad contra incendios en terminales aeroportuarias se apoya en un marco normativo amplio y heterogéneo, que combina códigos nacionales con estándares internacionales de reconocido prestigio. Dada la complejidad funcional y la relevancia estratégica de estas infraestructuras, en muchos proyectos se recurre a normativas internacionales, especialmente en contextos donde la regulación local no aborda de forma explícita las particularidades de los grandes espacios abiertos, las elevadas cargas de ocupación o los condicionantes operativos propios del entorno aeroportuario. En muchos países, las terminales

se han desarrollado —y en algunos casos continúan operando— en ausencia de normativas específicas de seguridad contra incendios, lo que ha favorecido la adopción de enfoques basados en prestaciones. Entre las referencias internacionales más utilizadas destacan NFPA 101[1], NFPA 415 [2] y el International Building Code (IBC)[3]. NFPA 101 establece criterios fundamentales relacionados con la evacuación y la seguridad de los ocupantes, mientras que NFPA 415 aborda riesgos específicos asociados a edificios terminales y a las operaciones de combustible. El IBC proporciona un marco prescriptivo general en aspectos constructivos, resistencia al fuego, evacuación y control de humos, sirviendo habitualmente como base para soluciones de ingeniería más avanzadas. No obstante, la aplicación directa de estos códigos presenta limitaciones en terminales caracterizadas por grandes atrios, espacios diáfanos y alturas considerables. Los criterios prescriptivos de sectorización, recorridos máximos de evacuación y determinación del aforo, basados en factores por superficie, no siempre reflejan la realidad operativa del aeropuerto. A ello se suma la dificultad de compatibilizar los requisitos de evacuación con las exigencias operativas, en particular la segregación entre zonas lado tierra y lado aire, lo que puede hacer operativamente inaceptable una evacuación total del edificio. Estas limitaciones han impulsado la adopción de enfoques basados en prestaciones, que permiten evaluar el comportamiento real del edificio y de sus sistemas frente a escenarios de incendio representativos, ofreciendo mayor flexibilidad para abordar situaciones complejas. En este contexto, el ingeniero de seguridad contra incendios desempeña un papel clave en la definición de los criterios de diseño, la selección de escenarios y la justificación técnica de las soluciones ante las autoridades competentes, siendo la estrategia de seguridad contra incendios una herramienta esencial para garantizar niveles de seguridad consistentes a lo largo de la vida útil de la terminal.

4. RETOS PRINCIPALES DE LA SEGURIDAD CONTRA INCENDIOS EN TERMINALES AEROPORTUARIAS

4.1 Ocupación elevada y variabilidad temporal

Las terminales aeroportuarias se caracterizan por concentrar grandes volúmenes de personas con perfiles muy heterogéneos, que incluyen pasajeros, acompañantes, personal aeroportuario y trabajadores de actividades comerciales. El propio diseño aeroportuario pone de manifiesto las limitaciones de los métodos tradicionales de cálculo del aforo basados exclusivamente en factores de carga por superficie. Tal y como se indica en la literatura especializada [9], el método convencional de *area-based occupant load factors* puede conducir rápidamente a valores poco realistas de ocupación (véase Figura 1), o a una representación inadecuada de los usos reales de determinadas áreas dentro de una terminal aeroportuaria [4].

En estos casos, se reconoce la necesidad de adoptar enfoques alternativos basados en el diseño funcional y el modelo operativo del aeropuerto, utilizando información procedente de la planificación aeroportuaria, como los programas de vuelos, la capacidad de proceso de las distintas áreas y la evaluación de escenarios desfavorables, incluyendo retrasos y acumulaciones de pasajeros. Este planteamiento permite definir un aforo de diseño más representativo de la demanda real y proporciona una base más sólida para la evaluación de la evacuación y el dimensionamiento de los medios de salida, en coherencia con una estrategia de seguridad contra incendios orientada a minimizar las interrupciones operativas. Además, las

terminales aeroportuarias integran múltiples usos y flujos superpuestos, que incluyen áreas públicas, zonas restringidas, espacios comerciales y áreas operativas. Esta complejidad funcional se ve acentuada por la necesidad de mantener la segregación entre zonas lado tierra y lado aire, así como entre pasajeros nacionales e internacionales. Durante una emergencia, el cruce de estas fronteras funcionales puede tener consecuencias operativas significativas. Por ello, las estrategias de evacuación deben diseñarse teniendo en cuenta no solo los requisitos normativos, sino también las implicaciones operativas y de seguridad asociadas a la gestión de flujos.

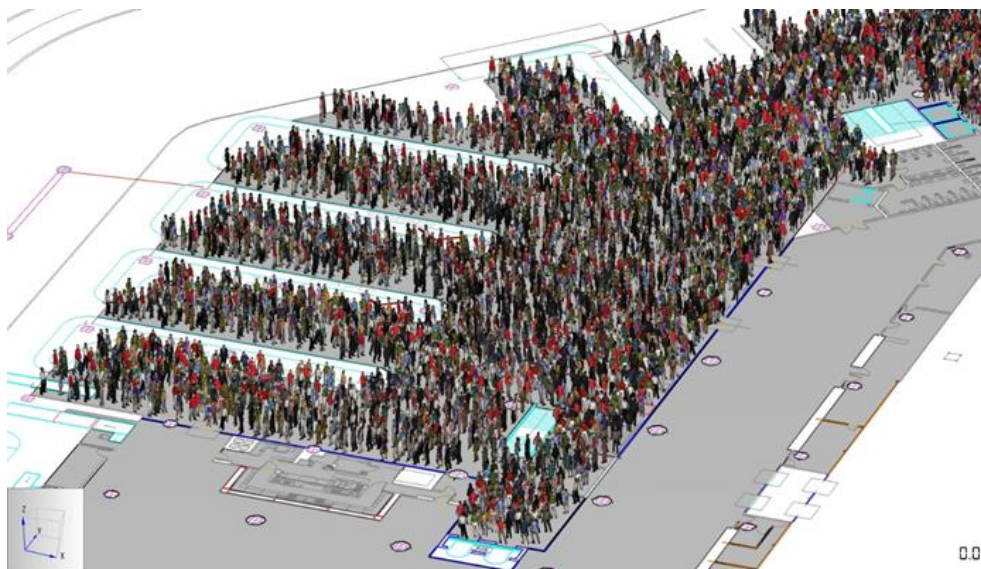


Figura 1 – Ejemplo de ocupación de una sala de recogida de equipaje según normativa

4.2 Evacuación y recorridos de evacuación

La evacuación de terminales aeroportuarias constituye uno de los principales retos de la seguridad contra incendios debido a la combinación de altas cargas de ocupación, usuarios no familiarizados con el edificio y configuraciones espaciales de gran escala. El cumplimiento de los recorridos máximos de evacuación establecidos por los códigos prescriptivos resulta especialmente complejo en edificios caracterizados por plantas extensas, grandes atrios y recorridos condicionados por requisitos funcionales y de seguridad. Un aspecto crítico es la necesidad de garantizar la demarcación entre zonas lado tierra y lado aire durante una emergencia. El cruce de esta frontera funcional puede implicar consecuencias operativas significativas. En este contexto, las estrategias de evacuación por zonas o fases se presentan como una alternativa viable a la evacuación total, permitiendo el desplazamiento de los ocupantes hacia zonas seguras adyacentes dentro del edificio. No obstante, la implementación de este tipo de soluciones requiere una cuidadosa coordinación entre compartimentación, sistemas de detección, control de humos y procedimientos operativos.

4.3 Arquitectura abierta y ausencia de sectorización efectiva

Desde el punto de vista arquitectónico, las terminales aeroportuarias modernas tienden a configurarse como grandes espacios abiertos, con atrios de múltiples niveles, amplias salas de facturación y extensas zonas de espera y embarque. En este contexto, la ausencia de una sectorización efectiva se convierte en una característica recurrente, dificultando la contención del incendio y de los productos de la combustión. La compartimentación tradicional, habitual en otros tipos de edificios, resulta en muchos casos incompatible con los requisitos funcionales del aeropuerto, tales como la fluidez de los flujos de pasajeros, la visibilidad de los espacios y la integración de usos comerciales. Como consecuencia, la seguridad contra incendios depende en mayor medida de sistemas activos y de estrategias avanzadas de control de humos.

4.4 Sistemas de extinción automática en grandes espacios

Los sistemas de extinción automática, en particular los sistemas de rociadores automáticos constituyen un elemento fundamental de la protección contra incendios en terminales aeroportuarias. Sin embargo, su eficacia puede verse significativamente condicionada por las grandes alturas interiores y las amplias luces estructurales características de estos edificios. En espacios de gran altura, los tiempos de activación de los rociadores pueden aumentar debido al retraso en la llegada del calor al elemento sensible, mientras que la dispersión del chorro de agua puede reducir la eficacia de la extinción en el foco del incendio. Estas limitaciones obligan a evaluar cuidadosamente la adecuación de los sistemas prescriptivos convencionales y, en determinados casos, a considerar soluciones alternativas o complementarias. La interacción entre los sistemas de extinción y otras medidas de protección resulta clave para garantizar un comportamiento global coherente frente a escenarios de incendio realistas.

4.5 Control de humos y condiciones de sostenibilidad

4.5.1 Control de humos de los atrios y espacios de gran altura

El control de humos representa uno de los aspectos más críticos en la seguridad contra incendios de terminales aeroportuarias, especialmente en edificios con grandes espacios abiertos y múltiples niveles interconectados. Las estratificaciones térmicas y gradientes de temperatura pueden retrasar el descenso de la capa de humos, pero al mismo tiempo dificultan su extracción eficaz, comprometiendo la capacidad de los sistemas de control para mantener condiciones de sostenibilidad adecuadas en las zonas ocupadas. La eficacia de los sistemas de extracción mecánica o natural debe evaluarse considerando escenarios de incendio representativos, así como la interacción con los sistemas de detección y extinción. La ubicación geográfica de la terminal, y el consiguiente gradiente térmico entre el ambiente interior y exterior, constituye un factor de gran relevancia en el diseño de las estrategias de control de humos. Este aspecto resulta especialmente crítico en soluciones basadas en ventilación natural, donde diferencias térmicas desfavorables pueden inducir fenómenos como el reverse stack effect [5], comprometiendo la eficacia del sistema y el control del movimiento de los humos durante un incendio. Si bien los grandes volúmenes característicos de muchas terminales aeroportuarias pueden permitir, desde el punto de vista de la evacuación, mantener condiciones de sostenibilidad aceptables incluso sin la implementación de sistemas activos de control de humos

—especialmente en espacios amplios y diáfanos—, dichos sistemas resultan imprescindibles desde la perspectiva de la continuidad operativa del aeropuerto, al permitir la gestión de incidentes localizados, la limitación de las áreas afectadas y la reducción de los tiempos de recuperación tras un evento de incendio.

4.5.2 Control de humos en tiendas y espacios de baja altura

En el caso de tiendas y/o espacios de baja altura, una de las soluciones utilizada es la denominada “cabin concept” [7]. Este modelo permite gestionar incidentes localizados sin comprometer la operatividad global de la terminal, reduciendo la necesidad de evacuaciones extensivas o cierres prolongados. El “cabin concept” se basa en tratar cada local comercial como un recinto funcionalmente autónomo en términos de control de humos, sin depender de una sectorización tradicional entre locales ni respecto a los espacios adyacentes. Para ello, se combinan medidas pasivas y activas, tales como elementos de contención pasiva, sistemas de extracción mecánica localizada y sectorización funcional de los sistemas de extracción. Mediante esta estrategia, el humo generado puede ser confinado y evacuado de forma eficaz, preservando las condiciones de sostenibilidad en los espacios colindantes y facilitando la gestión operativa del aeropuerto durante y después del incidente. El enfoque “cabin concept” se presenta así como una solución coherente con una visión holística de la seguridad contra incendios, en la que el control de humos contribuye no solo a la evacuación segura, sino también a la resiliencia y continuidad operativa de la infraestructura aeroportuaria.

4.6 Continuidad operativa y gestión de emergencias

La continuidad operativa constituye un factor determinante en la definición de las estrategias de seguridad contra incendios en terminales aeroportuarias. No obstante, al no ser un criterio directamente asociado a la seguridad de la vida, este aspecto se ve con frecuencia relegado a un segundo plano en los enfoques de diseño basados exclusivamente en el cumplimiento normativo. A diferencia de otros edificios de pública concurrencia, una evacuación total o una interrupción prolongada de la actividad puede generar impactos económicos y operativos de gran magnitud, además de implicaciones en términos de seguridad aeroportuaria. Por este motivo, los operadores suelen priorizar estrategias que permitan la gestión de incidentes localizados, evitando evacuaciones innecesarias siempre que se garantice la seguridad de los ocupantes. Esto requiere una estrecha integración entre el diseño del edificio, los sistemas de protección contra incendios y los procedimientos operativos, incluyendo la formación del personal y la coordinación con los servicios de emergencia. La seguridad contra incendios en terminales aeroportuarias debe entenderse, por tanto, como un sistema integral en el que las decisiones técnicas y operativas están estrechamente interrelacionadas. Además de los retos técnicos tradicionales, la resiliencia operacional frente a incendios y fallos de infraestructura ha sido objeto de investigación reciente. Zhu et al. [6] proponen un marco para evaluar y mejorar la resiliencia de los sistemas de respuesta contra incendios en aeropuertos, abordando aspectos de estabilidad, resistencia, recuperación y adaptación que son esenciales para la operación continua de infraestructuras de alta complejidad. Incidentes ocurridos en los últimos años en grandes aeropuertos internacionales —como el incendio del Aeropuerto de Roma-Fiumicino (2015), así como otros eventos registrados en JFK (2017), Frankfurt (2018) y Heathrow (2025)— han puesto de manifiesto que incendios localizados pueden generar interrupciones operativas

significativas, con cierres parciales o totales de terminales y tiempos de recuperación prolongados.

5. HERRAMIENTAS AVANZADAS DE SIMULACIÓN Y ANÁLISIS

La complejidad geométrica, funcional y operativa de las terminales aeroportuarias limita la eficacia de los enfoques prescriptivos tradicionales para evaluar la seguridad contra incendios. En este contexto, las herramientas avanzadas de simulación se han consolidado como instrumentos esenciales para el desarrollo de estrategias basadas en prestaciones, permitiendo analizar de forma integrada la evacuación, el comportamiento del humo y la respuesta estructural frente a escenarios de incendio representativos. Las herramientas y metodologías descritas a continuación permiten abordar de forma directa los retos identificados en la sección anterior, proporcionando un marco de análisis que facilita la evaluación cuantitativa de estrategias de evacuación, control de humos y comportamiento estructural frente al fuego en terminales aeroportuarias.

5.1 Modelos de evacuación y análisis del RSET

Los modelos de evacuación permiten simular el movimiento de los ocupantes desde las zonas de origen hasta los espacios seguros, considerando factores como la densidad de ocupación, la geometría del edificio, la capacidad de las salidas y el comportamiento humano. En terminales aeroportuarias, estas herramientas resultan especialmente útiles para evaluar configuraciones complejas con múltiples niveles, grandes espacios abiertos y recorridos condicionados por requisitos funcionales y de seguridad. El principal resultado de estos modelos es la estimación del tiempo requerido para la evacuación (RSET), que incluye las fases de detección, pre-movimiento y desplazamiento. La variabilidad de la ocupación y la heterogeneidad de los usuarios hacen necesario analizar diferentes escenarios, incluyendo situaciones de máxima demanda y condiciones operativas desfavorables.

5.2 CFD aplicado al análisis de incendios y control de humos y análisis del ASET

La dinámica de fluidos computacional (CFD) aplicada a incendios permite analizar la propagación del humo, la evolución térmica y la interacción con los sistemas de control de humos en geometrías complejas. En terminales aeroportuarias, donde predominan los grandes espacios abiertos y las alturas considerables, el CFD resulta fundamental para evaluar fenómenos como la estratificación térmica, los gradientes de temperatura y la eficacia real de los sistemas de extracción. El análisis CFD proporciona información detallada sobre variables clave para la sostenibilidad, como la visibilidad, la temperatura y la concentración de gases en las zonas ocupadas. Estos resultados permiten estimar el tiempo disponible para la evacuación (ASET) bajo escenarios de incendio representativos, teniendo en cuenta la activación de los sistemas de protección y las condiciones operativas del edificio.

5.3 Integración RSET–ASET como criterio de diseño

El enfoque basado en prestaciones se fundamenta en la comparación entre el RSET obtenido mediante modelos de evacuación y el ASET determinado a partir del análisis CFD. Esta

comparación permite verificar que las condiciones de sostenibilidad se mantienen durante el tiempo necesario para que los ocupantes alcancen zonas seguras. En terminales aeroportuarias, esta integración resulta especialmente relevante debido a la ausencia de sectorización efectiva, las grandes distancias de evacuación y la necesidad de mantener la continuidad operativa. La evaluación conjunta de ASET y RSET permite identificar cuellos de botella, optimizar la ubicación y capacidad de los sistemas de control de humos y justificar soluciones alternativas frente a las autoridades competentes. Cabe señalar que un enfoque holístico basado en prestaciones puede conducir a soluciones de diseño que difieren de los criterios prescriptivos tradicionales de códigos como NFPA 101[1], por ejemplo, en relación con los márgenes de seguridad sugeridos (NFPA 101[1] establece que el análisis ha de realizarse para un periodo equivalente a 1.5 veces el tiempo requerido para la evacuación o 20 minutos, el que resulte mayor – independientemente del tipo de recinto, ocupación, etc.), siempre que se demuestre mediante análisis cuantitativo que el nivel de seguridad alcanzado es equivalente o superior.

5.4 Análisis estructural al fuego

Las herramientas de simulación térmica y estructural permiten evaluar la respuesta de los sistemas estructurales frente al fuego considerando escenarios realistas, en lugar de curvas normalizadas simplificadas. En terminales aeroportuarias, este tipo de análisis es especialmente relevante para cubiertas de grandes luces y estructuras expuestas, donde la aplicación de protección pasiva convencional puede resultar compleja o incompatible con el diseño arquitectónico. El análisis estructural al fuego permite verificar que la estabilidad del sistema se mantiene durante el tiempo requerido para la evacuación y la intervención de los servicios de emergencia, alineando los objetivos de seguridad estructural con los criterios de sostenibilidad y evacuación definidos en la estrategia global.

5.5 Ventajas y limitaciones del enfoque basado en simulaciones computacionales avanzadas

El uso de herramientas avanzadas de simulación ofrece ventajas significativas frente a los enfoques prescriptivos tradicionales, entre las que destacan una mayor comprensión del comportamiento real del edificio, la posibilidad de optimizar soluciones de diseño y la justificación técnica de estrategias complejas como la evacuación por zonas o por fases o la reducción de compartimentación. No obstante, estos enfoques también presentan limitaciones, como la dependencia de hipótesis de partida, la sensibilidad a los parámetros de entrada y la necesidad de una adecuada validación y experiencia por parte del equipo de ingeniería [14]. Por ello, los resultados de las simulaciones deben interpretarse dentro de un marco coherente de diseño y siempre en combinación con criterios normativos y operativos.

6. CASOS REALES DE APLICACIÓN INTERNACIONAL

La aplicación práctica de enfoques de seguridad contra incendios basados en prestaciones en terminales aeroportuarias permite evaluar de forma realista la eficacia de las estrategias adoptadas frente a los retos descritos en los capítulos anteriores. A continuación, se presentan varios casos reales de aplicación a nivel internacional, seleccionados por su representatividad y

por ilustrar diferentes problemáticas recurrentes en el diseño y operación de terminales aeroportuarias modernas.

6.1 Aeropuerto de Denver (Colorado, USA)

El Aeropuerto Internacional de Denver es el 18º aeropuerto más concurrido del mundo y el sexto aeropuerto más ocupado de los Estados Unidos. Con 58,3 millones de pasajeros viajando por el aeropuerto cada año, el Aeropuerto de Denver (DEN) es uno de los centros de aerolíneas más concurridos en el mercado de aviación más grande del mundo. Gracias a un análisis ASET/RSET a través del uso de herramientas de simulación CFD [13] y simulación de evacuación [12] en el Great Hall del Aeropuerto Internacional de Denver, se evaluó satisfactoriamente si el edificio podía considerarse seguro para los ocupantes durante un evento de incendio.

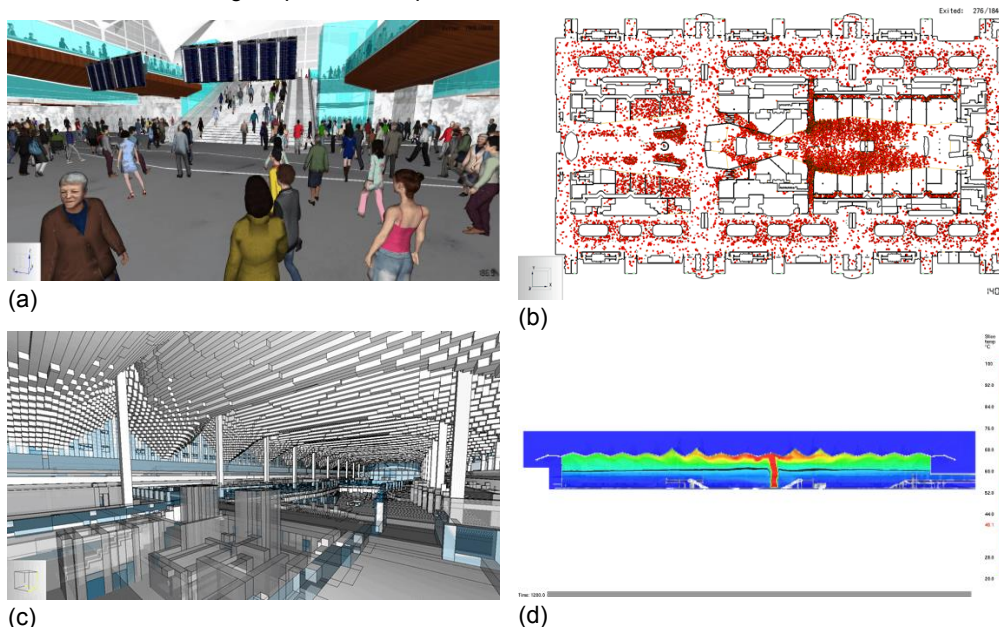


Figura 2 – (a) Visualización 3D de la simulación de evacuación (b) Visualización de los flujos peatonales durante la evacuación de la simulación (c) Visualización del modelo CFD utilizado para la modelización de humos e incendio (d) Corte transversal de visibilidad del modelo CFD

6.2 Aeropuerto Adolfo Suarez Madrid-Barajas (Madrid, España)

El Aeropuerto Adolfo Suárez Madrid-Barajas es el principal aeropuerto internacional que sirve Madrid en España. En el momento del diseño e inauguración de las grandes terminales aeroportuarias T4 y la T4S de Madrid-Barajas, el Código Técnico de la Edificación (CTE) [10] aún no estaba en vigor, aplicándose en su lugar una normativa básica de protección contra incendios (NBE-CPI/96) que no había sido concebida para infraestructuras aeroportuarias ni para edificios de gran complejidad y escala. Esta situación hizo necesario recurrir a criterios complementarios y a estándares internacionales para garantizar niveles adecuados de seguridad. En una terminal aeroportuaria de gran escala como la T4 y la T4S, caracterizada por

amplias salas de facturación y zonas de embarque configuradas como espacios abiertos de gran altura, el principal reto estuvo asociado a la ausencia de sectorización efectiva y al cumplimiento de los recorridos máximos de evacuación exigidos por la normativa de referencia. Se desarrolló una estrategia basada en prestaciones que combinó modelos de evacuación [12] para la estimación del RSET y simulaciones CFD[13] para evaluar la propagación de humos y la sostenibilidad de los espacios durante escenarios de incendio representativos. Los resultados permitieron justificar la evacuación de la terminal, apoyada por un sistema de control de humos diseñado en parte según el “cabin concept”.

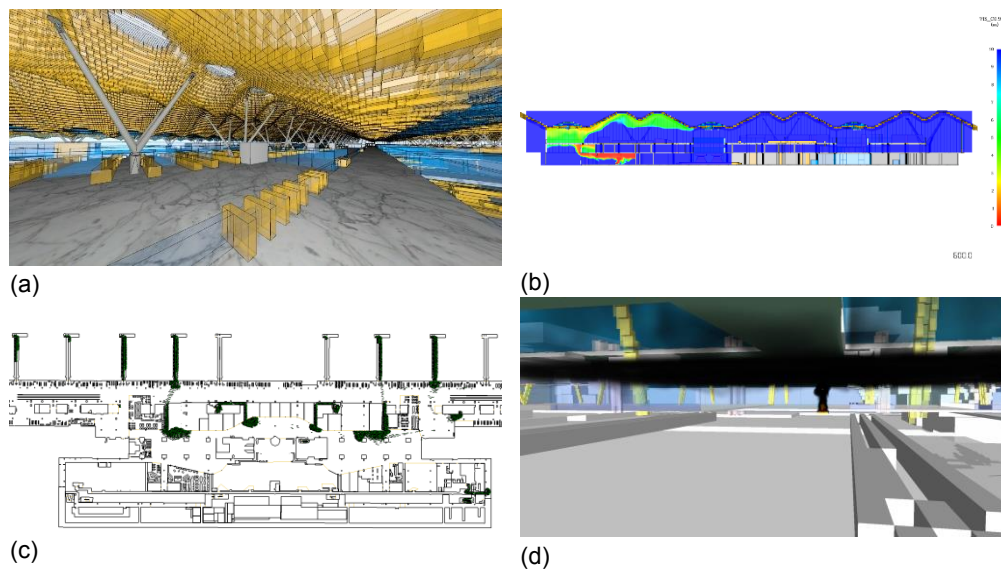


Figura 3 – (a) Visualización del modelo CFD utilizado para la modelización de humos e incendio (b) Visualización de la propagación del humo mediante cortes de visibilidad (c) Visualización de los flujos peatonales durante la evacuación de la simulación (d) Visualización de la propagación del humo en el análisis CFD

6.2 Aeropuerto Internacional Jorge Chávez (Lima, Perú)

El nuevo terminal del Aeropuerto Internacional Jorge Chávez (Lima) ha sido diseñado para una capacidad inicial cercana a 30 millones de pasajeros anuales, incorporando grandes espacios abiertos y una elevada complejidad operativa, lo que plantea retos relevantes en seguridad contra incendios y continuidad operativa. En este proyecto, desarrollado con referencia al marco normativo de la NFPA 101, fue necesario justificar recorridos de evacuación superiores a los límites prescriptivos establecidos por la norma, mediante un enfoque basado en prestaciones. Asimismo, se diseñaron y validaron estrategias específicas de control de humos, orientadas tanto a la seguridad de los ocupantes como a la continuidad operativa. De manera complementaria, se evaluó la necesidad de protección frente al fuego de los elementos estructurales expuestos, considerando escenarios de incendio representativos y su interacción con los sistemas de protección activa. En este contexto, un enfoque puramente normativo no resultó suficiente para dar respuesta a la complejidad del edificio y a los requisitos operativos del aeropuerto, siendo

necesario complementar los criterios prescriptivos con soluciones de ingeniería basadas en prestaciones que permitieran demostrar niveles de seguridad equivalentes o superiores a los exigidos por la normativa.

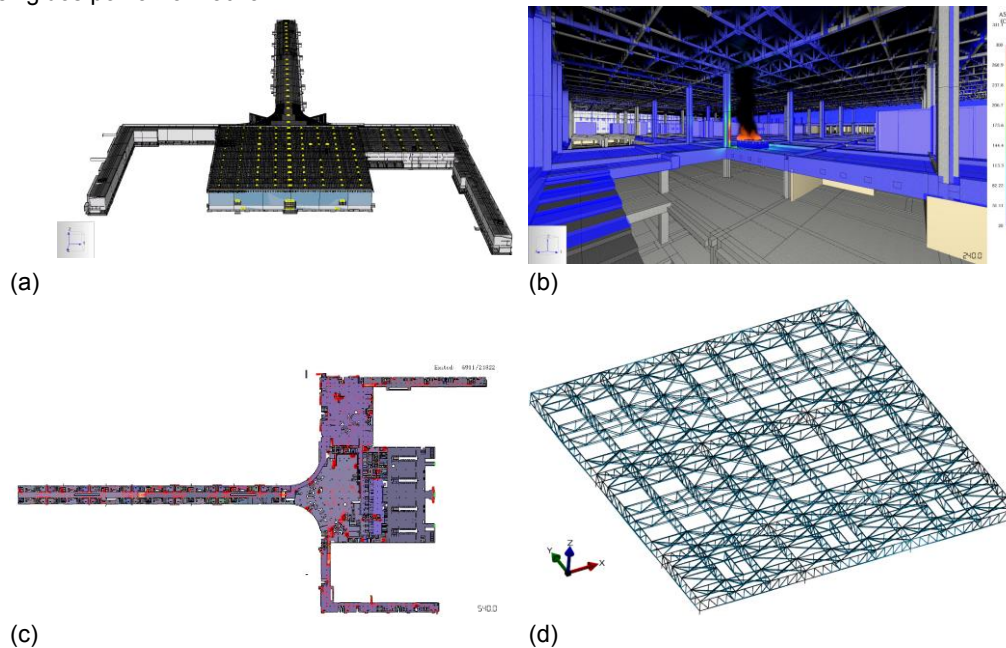


Figura 4 – (a) Visualización del modelo CFD [13] utilizado para la modelización de humos e incendio. (b) Visualización de la propagación del humo y temperatura adiabáticas registradas en los elementos estructurales. (c) Visualización de los flujos peatonales durante la evacuación de la simulación de evacuación[12]. (d) Deformación de los elementos estructurales obtenido en el cálculo estructural al fuego[15].

8. CONCLUSIONES

Las terminales aeroportuarias representan uno de los entornos más exigentes para el diseño de la seguridad contra incendios, debido a la combinación de elevadas y variables cargas de ocupación, arquitecturas abiertas de gran escala, restricciones operativas y la necesidad de garantizar la continuidad del servicio. El análisis del marco normativo y de las particularidades propias de las terminales aeroportuarias evidencia la necesidad de complementar los requisitos prescriptivos con enfoques basados en prestaciones, que permitan evaluar el comportamiento real del edificio y de sus sistemas frente a escenarios de incendio representativos. Aspectos como la evacuación, la eficacia limitada de los sistemas de extinción en grandes alturas y el control de humos en espacios no sectorizados requieren una evaluación integrada y específica para cada proyecto. Las herramientas avanzadas de simulación, incluyendo modelos de evacuación, análisis CFD y FEM, se han consolidado como instrumentos fundamentales para apoyar este enfoque. La integración de estos análisis facilita la justificación técnica de soluciones complejas y mejora el proceso de toma de decisiones tanto en fase de diseño como de operación. Los casos reales de aplicación internacional presentados demuestran que la adopción de estrategias de seguridad contra incendios basadas en prestaciones permite alcanzar niveles de

seguridad equivalentes o superiores a los exigidos por la normativa, al tiempo que se preservan los objetivos arquitectónicos y operativos de las terminales. Por eso resulta fundamental que la seguridad contra incendios en terminales aeroportuarias se aborde desde una visión holística, en la que normativa, ingeniería, arquitectura y operación se integren en una estrategia coherente y documentada. Desde una perspectiva práctica, el análisis realizado permite extraer varias recomendaciones relevantes para el diseño de terminales aeroportuarias:

- Las estrategias de seguridad contra incendios deben definirse desde las fases iniciales de diseño mediante un enfoque holístico que integre arquitectura, operación aeroportuaria e ingeniería de seguridad contra incendios.
- Los métodos basados en prestaciones resultan con frecuencia necesarios para abordar las limitaciones de los códigos prescriptivos en edificios caracterizados por grandes espacios abiertos y condiciones complejas de evacuación.
- Las estrategias de control de humos deben considerar no solo la seguridad de los ocupantes, sino también la continuidad operativa de la infraestructura.
- La colaboración entre diseñadores, ingenieros de seguridad contra incendios y operadores aeroportuarios es esencial para garantizar que las soluciones adoptadas sean compatibles con los requisitos operativos de la terminal.

8. TRABAJOS FUTUROS

Como línea de trabajo futuro, se considera necesario avanzar hacia marcos normativos más flexibles capaces de abordar las particularidades de las terminales aeroportuarias. La creciente complejidad de estas infraestructuras exige normas que integren enfoques basados en prestaciones y que contemplen tanto la seguridad de vida como la continuidad operativa.

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PERFORMANCE BASED DESIGN OF WATER BASED FIRE PROTECTION SYSTEMS IN MINING CONVEYOR BELTS USING CFD



Patricio Valdés¹

Asociado
MAPA Fire
Chile



Miguel Perez

Asociado
MAPA Fire
Chile

Palabras clave: Mining, conveyor belt, CFD, PBD, Fire

BACKGROUND AND MOTIVATION

Conveyor belts in mining are typically protected with sprinkler systems designed according to prescriptive codes. While these systems are effective, they discharge large volumes of water that can pose environmental risks, especially in offshore installations such as copper concentrate conveyor belts at docks. The discharge of contaminated water necessitates costly drainage and containment systems to prevent marine pollution. This problem motivates the exploration of alternative fire protection methods with a lower environmental impact.

¹ Autor correspondiente – MAPA Fire Engineering, BEAUCHEFF 1325 Depto. 1109 - Santiago (Chile). Telef.: +56 9 7325 9995, E-mail: patricio.valdes@mapafire.com

1. INTRODUCTION

Chilean mining company requires the installation of an active fire protection system in the mineral transport system, specifically in the conveyor belts over a pier that transport copper concentrate from the mining process to the transportation ships. The mining company desires to fulfil the fire protection goals of; life safety, operational continuity and minimize the environmental impact of water protection system discharged, due to the conveyors belts are transporting copper concentrate over the water (sea). Thus, an eventually discharge from the fire protection system would contaminate the sea water. To avoid sea water contamination, the company needs to contain the eventual water discharge from the fire protection system. The performance base analysis is developed to minimize the water drainage system and the potential contamination of the sea water.

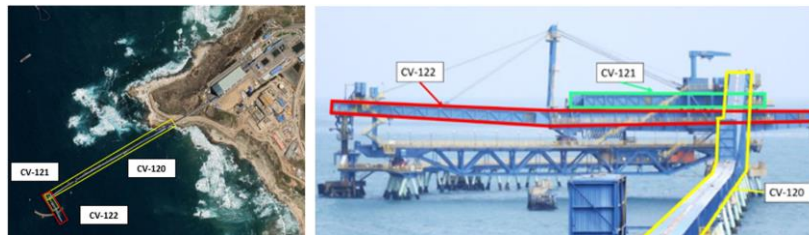


Figure 1: Left - Aerial view of the facilities/Right – POV facilities, starting at first conveyor belt

2. METHODOLOGY

The general methodology to assess the present study corresponds to the General methodology for PBD according SFPE Handbook [1]

2.1 Scope

The scope of the study corresponds to the conveyor belts indicated in the Figure 1.

2.2 Goals

The goals correspond to:

- Provide an environment reasonably safe from fire for occupants that's are not closely related to the initial development of the fire and improve the survival capacity of the occupants closely related to the initial development of the fire.
- Provide an environment for the protection of property and operational continuity in the event of a fire, considering the environmental protection requirements.

2.3 Objectives

- Protection of the occupants: evaluate a fire protection system that protects the occupants who are not familiar with the initial development of the fire during the time necessary to

evacuate. Allow occupants who are closely related to the fire to evacuate in sustainable conditions for life safety.

- Operational continuity: Evaluate a fire protection system that minimizes the impact of fire in the facilities, considering the fire propagation, heat released rate, among others.
- Minimize the water discharge: evaluate a fire protection system that allows compliance with objectives 1 and 2 before mentioned and that also fulfils the environmental requirements of minimize the water containment.

2.4 Performance Criteria

The main goal of this study is to analyze the performance of several configurations of water-based fire suppression systems for conveyor belts. Tenability limits for life safety and operational continuity are considered satisfied when the system can suppress the fire at an early stage. Therefore, the volume of water discharged is used as the key variable to compare the performance of the different trial designs, since all systems are expected to control and extinguish the fire while meeting the remaining performance criteria.

2.5 Fire Scenarios

The fire scenario analyzed considers that the fire starts in the area where the belt presents a greater slope, considering an average angle of 10° of inclination and 130m length (Figure 2). The scenario also considers that the belt stops due to the activation of detection system and the auxiliary systems also stop when the detection system operates.

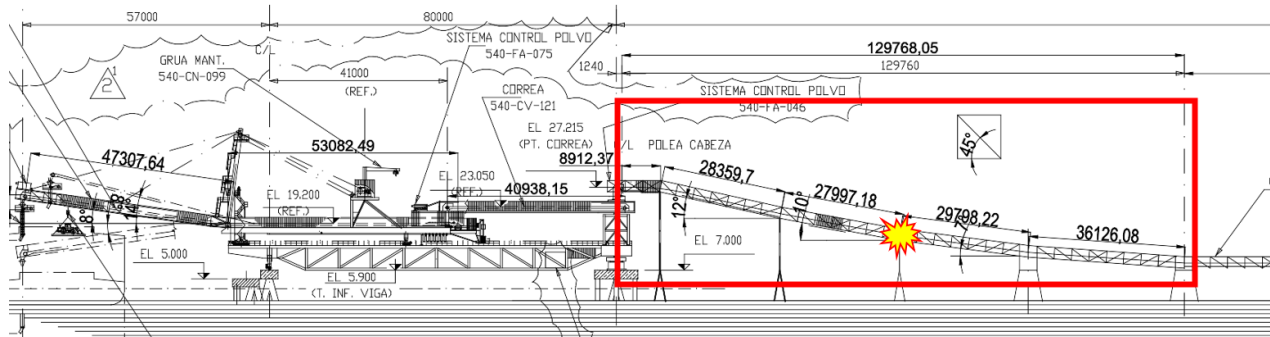


Figure 2: Fire localization

3. PERFORMANCE CRITERIA

The performance of the water-based test designs will be analyzed regarding the fire protection requirements by Factory Mutual in the Datasheet 7-11 Art. 2.3.3 (**Error! No se encuentra el origen de la referencia.**). Therefore, the water-based fire protection trial designs will be analyzed against Factory mutual design and therefore, against the expected operation.

4.1.4 Fire Location and Geometry

Due to the length of the conveyor belt system covered by the scope of the investigation, the analysis has been implemented in a section of the conveyor belt, allowing to obtain precise and useful results without increasing the computational cost of the model. Thus, the fire location is considered in the area where the conveyor belt presents the greatest slope, considering a total inclination of 10° over a 130m section (Figure 3). The fire location presents the worst-case scenario in terms of heat release rate, fire propagation and smoke production due to the sloped condition.

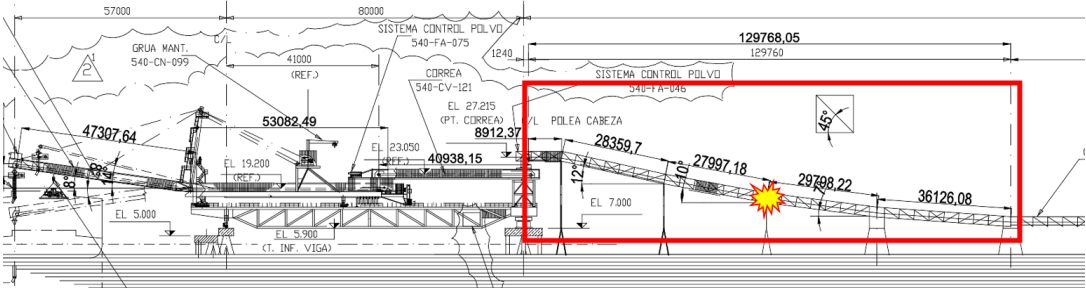


Figure 3: Fire Location

The geometry of the conveyor belt and the location is presented in the Figure 4, where is considered a belt with 1200mm width and 10mm thick. The enclosure is considered as a metal sheet with the properties specified in the Figure 4. Inside of the passageway where the conveyor is located, there is no airflow while the equipment is stopped, while is considered that every ventilation and equipment working will halt in case a fire is detected in the conveyor belt.

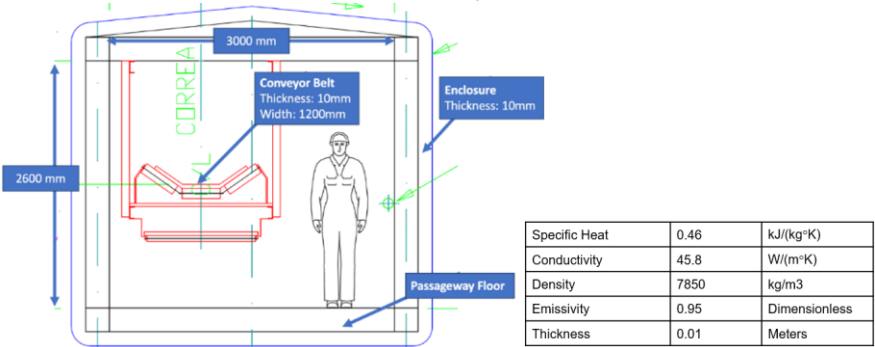


Figure 4: Conveyor Belt Geometry & Enclosure material's properties

4.2 Fire Scenarios 02 - Conveyor Belt Active Fire Protection

The current fire scenario considers the entire scenario described in the title “4.1 Fire Scenario 01 - Conveyor Belt Fire” and is complemented with the active fire protection systems considered in the title “TRIAL DESIGNS” of the current study.

4.2.1 Considerations for Fire Scenario 02 – 05-A, 05-B, 05-C

Sprinklers System – Number of Droplets

According to test and analysis assessed by the WPI [5], it is concluded that run FDS with more particles than the default (5000), will not improve the prediction of the water bucket test for a sprinkler K=5.6. Therefore, it is considered 5000 droplets.

Sprinklers System – Droplets Size Estimation

According to David Sheppard's investigation [6], several sprinkles with similar features than the sprinklers considered in the current study has been tested, presenting droplets sizes Dv_{50} between 700 to 1000 μm . There is a mathematical correlation to estimate the sprinkler droplet size [7] and is described following.

$$\frac{Dv_{50}}{D_n} = C W_e^{-1/3} \quad \text{Equation 1}$$

Where Dv_{50} correspond to the mean value of droplets discharged by the sprinkler, D_n correspond to the sprinkler diameter, C is a constant sprinkler dependent with values between 1.74 - 3.21, and W_e correspond to the Weber number, which one is calculated as following.

$$W_e = \frac{\rho_l * U_j^2 * D_n}{\sigma} \quad \text{Equation 2}$$

Where ρ_l corresponds to the density of water, σ corresponds to the surface tension, U corresponds to the velocity of the discharged water by the sprinkler. Therefore, the droplet size (Dv_{50}) will be estimated for the sprinklers to be used in the computer simulations.

Sprinklers System – Droplet Initial Velocity

The droplet initial velocity can be computed based on mean flow velocity, which depends on the injection pressure and the discharge coefficient, according to the following equation.

$$V_0 = C * \sqrt{\frac{\Delta P}{\rho}} \quad \text{Equation 3}$$

Where V_0 is the initial velocity in m/s, ρ is the density of water in kg/m^3 and ΔP is the relative pressure at the nozzle in Pascals. The parameter C is a factor used to take into account friction losses in the nozzle. It has not been determined experimentally and typically, the value of C varies between 0.5 and 1, which corresponds to initial velocity values between 22 and 45 m/s [8].

Sprinklers System – Discharge Coefficient

The discharge coefficient (K) relates the physical and geometrical features of the nozzle and the operation pressure of the device. Besides, the K factor considers the behavior of the vena contracta of the flow and the flow that is discharging through the nozzle. The K factor can be computed according to the following equation.

$$K = \frac{Q}{\sqrt{P}} \quad \text{Equation 4}$$

Where the flow Q is measured in liter per minute, the relative pressure P at the nozzle is in Bar or MPa and the discharge coefficient K is in L/m/bar^{1/2}.

4.2.2 Considerations for Fire Scenario 02 – 05-D

Water Mist System – Number of Droplets

The default number of particles per second used in sprinkler modeling in the FDS package corresponds to 5000. Most research and studies in simulations were achieved with 1.0, 1.5 and 2, 0 x 10⁵ particles per second for watermist discharge nozzles [9]. Counting small particles caused numerical instability when the particles hit the hot surface and the higher flows aggravated the phenomenon. Therefore, the number of particles that has been chosen to simulate the watermist nozzle will correspond to 100,000, according to the results obtained in sensitivity analysis [10].

Water Mist System – Droplets Size

There are different quantities to characterize the size of the droplets in the sprinkler discharge. In fact, sprinkler discharge consists of millions of droplets with a certain size distribution. One quantity is the volume median diameter D_{v50}, which is the diameter defined such that half the volume of the water is contained in droplets with a diameter less than D_{v50} (and therefore half the water is contained in droplets with a diameter greater than D_{v50}). According to what is indicated by the average manufacturers of water mist systems, a droplet size of 120 µm is considered [11].

Water Mist System – Technical Nozzle Specification

The watermist nozzles correspond to the manufacturer RG Systems for local application with activation bulb at 66°C and RTI=50.

4.3 Mesh and Cell Size

For the initial grid resolution, the expression stated in the FDS User Guide has been considered. For simulations involving buoyant plumes, a measure of how well the flow field is resolved is given by the non-dimensional expression $\frac{D^*}{\delta x}$, where D* is a characteristic fire diameter and δx is the nominal size of a mesh cell.

$$D^* = \left(\frac{Q}{\rho C T \sqrt{g}} \right)^{\frac{2}{5}} \quad \text{Equation 5}$$

Where $\dot{Q}$ is heat release rate of the fire is, ρ is the air density at ambient temperature, C correspond to the air specific heat, T is the ambient temperature and g is the acceleration due to gravity. In a sensitivity analysis (Hill et al., 2007), sponsored by the U.S. Nuclear Regulatory Commission, the $D^* / \Delta x$ value ranges between 4 and 16. As a cell size criterion, the following relationship of numerical intervals will be used, where 4 will correspond to a poor resolution without affecting the values of the results and 16 will correspond to the greatest resolution without demanding a high cost of computational resources.

$$4 < \frac{D^*}{\delta x} < 16 \quad \text{Equation 6}$$

Thus, by applying the before mentioned criteria and considering the values of Ambient Temperature 1.2 kg/m³, Cp Ambient Air 1 kJ/kg °K, Ambient Temperature 293°K and Gravity Acceleration 9.81 m/s² it is possible to obtain the flow resolution quality indicator values for the combustion zone, and the plume zone of the hot gases produced by the fire in the conveyor belt. The mesh geometry will be built considering cubic cells with a symmetrical configuration. The entire computational domain will be divided into different meshes with different cell sizes, allowing them to cover the computational domain without overusing cells. The meshing technique consists of where the conveyor belt zone contains the smallest cell in the domain and then the fire plume contains cells with a middle size. The biggest cell size is used in the lower part of the domain, where the fresh air inlet for the fire is located. The sensitivity analysis for the cell according to the to the Equation 5 and Equation 6 is indicated in the Table 2. The value of 2 MW used in the Table 2 correspond to a value obtained in a previous research [12] where a similar conveyor belt was burned in a real scale test and a HRR of 2 MW was obtained in the early stage of the fire. Therefore, the value of 2 MW has been used just to assess the sensitivity analysis prior to the simulations and avoid the process of try-error to choose the correct mesh cell size.

Table 2: Cellsize Combustion Zone

Zone	HRR		D*	Cellsize (m)	D*/Cellsize
Combustion Zone	2000	kW	0.8041	0.05	16
Smoke Plume Zone	2000	kW	0.8041	0.1	8

5. TRIAL DESIGNS

The following trial designs contemplate the fire protection strategy that is intended to fulfill the goals and objectives of the study. To be considered acceptable, the trials designs must achieve the performance criteria indicated earlier. The following described trial designs are grouped in the following categories,

- Ignition and spreading of fire, due to the methods are used to reduce the probability of ignition and/or reduce the heat release rate of a fire.
- Fire suppression, including automatic and/or manual fire protection systems.

The trial designs are evaluated in the fire scenario 01 described earlier in the current document.

5.1 Scenario 05-A

The current scenario presents the following considerations.

- Sprinkler selected K factor of 8.0 (115) and a temperature rating of 165°F (74°C).
- Operating pressure = 15 PSI , RTI = 50 m^{1/2}*s^{1/2} (quick response sprinkler).
- The separation distance between sprinklers corresponds to 3.5m.
- The installation distance from the roof of the passageway corresponds to 0.2m.
- According to the sprinkler's manufacturer [13], the discharge pattern for the operating pressure (15 PSI) corresponds to an angle of 55°.
- The droplets size estimation Dv50 according title 4.2.1 corresponds to 2274.8 μm.

5.2 Scenario 05-B

The current scenario presents the following considerations.

- Sprinkler selected K factor = 5.6 (80.6) and temperature rating of 165°F (74°C).
- Operating pressure = 15 PSI, RTI = 50 m^{1/2}*s^{1/2} (quick response sprinkler).
- The separation distance between sprinklers corresponds to 3.5m.
- The installation distance from the roof of the passageway corresponds to 0.2m.
- According to the sprinkler's manufacturer [14], the discharge pattern for the operating pressure (15 PSI) corresponds to an angle of 56°.
- The droplets size estimation Dv50 according title 4.2.1 corresponds to 1623.12 μm.

5.3 Scenario 05-C

The current scenario presents the following considerations.

- Sprinklers selected with a K factor of 5.6 (80.6) and a temperature rating of 165°F (74°C).
- Operating pressure = 15 PSI, RTI = 100 m^{1/2}*s^{1/2} (standard response sprinkler).
- The separation distance between sprinklers corresponds to 3.5m.
- The installation distance from the roof of the passageway corresponds to 0.2m.
- According to the sprinkler's manufacturer [15], the discharge pattern for the operating pressure (15 PSI) corresponds to an angle of 56°.
- The droplets size estimation Dv50 according title 4.2.1 corresponds to 1623.12 μm.

5.4 Scenario 05-D

The current scenario presents the following considerations.

- The system considered corresponds to local application, machinery space.
- The maximum working pressure must be 200 Bar and the test pressure must be 600 Bar.
- The montage will be pendent at 0.2m under the roof.
- The discharge coefficient K=2.04 lpm/bar^{1/2}.
- Maximum spacing according to the manufacturer corresponds to 4m.
- Operating pressure corresponds to 100 Bar, RTI=50, Temperature rating of 66°C

6. EVALUATION OF TRIAL DESIGNS

The Figure 5 contains the activation sequence of the trial designs, where it is possible to observe that every configuration proposed and analyzed was able to control and extinguish the fire. As every design is capable of control and extinguish the fire, the differences between the designs correspond to the water discharged, as is presented in the Table 3. Therefore, the trial designs fulfill the tenability limits for life safety and operational continuity due to each design suppressed the fire at an early stage, avoiding the people or facility affectation.

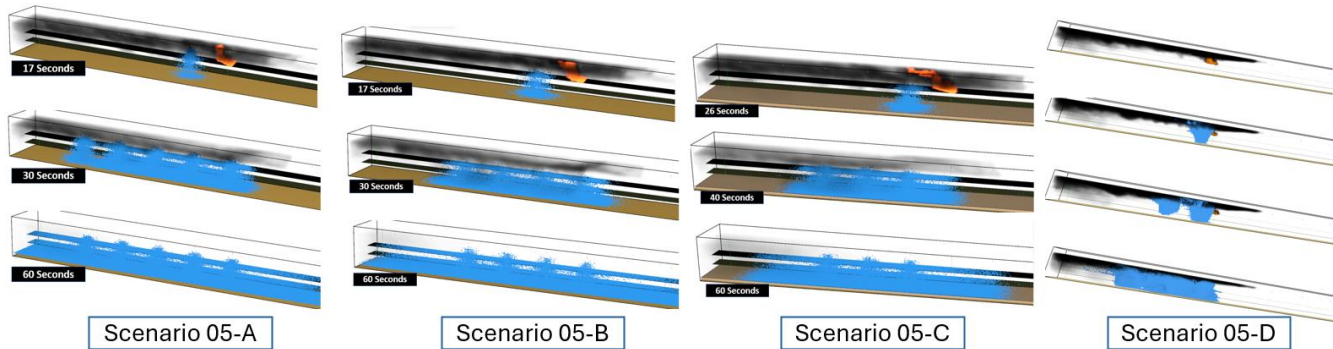


Figure 5: Extinction by Trial Designs

Table 3: Summary of water discharged

	Scenario 05-A		Scenario 05-B		Scenario 05-C		Scenario 05-D	
Opened Sprinklers	5	Un	4	Un	3	Un	3	Un
Total Flow	155	gpm	86.8	gpm	65.1	gpm	16.17	gpm
	586	lpm	328	lpm	246	lpm	61	lpm
Average Activation Time	22.3	sec	20.6	sec	28.3	sec	25.5	sec

7. RESULTS AND DISCUSSION

The numerical simulations performed for the four trial designs demonstrate that all water-based systems—both conventional sprinklers and water mist—are capable of controlling and extinguishing the conveyor belt fire under the defined scenario. However, the systems exhibit significant differences in activation time, heat release rate (HRR) reduction, and total water discharged, which directly influence environmental impact and operational continuity.

Figure 6 shows that the activation time is strongly influenced by the RTI and K-factor of the sprinklers. As expected, the quick-response sprinklers (Scenarios 05-A and 05-B) activate earlier, resulting in faster HRR reduction but also in higher total water discharge. Scenario 05-C, which uses standard-response sprinklers, activates later and therefore allows the fire to grow slightly larger before suppression begins. Despite this, the system still achieves full extinguishment within acceptable performance limits.

The water mist system (Scenario 05-D) exhibits a distinct behavior. Due to its smaller droplet size, higher momentum, and superior cooling efficiency, the system suppresses the fire with a significantly lower water flow rate. Although its activation time is comparable to the sprinkler systems, the HRR curves indicate that water mist achieves a similar level of fire control with only 10% of the water volume used by the FM Global reference design. This is consistent with previous research showing that water mist systems can provide effective suppression in confined or semi-confined conveyor belt environments due to enhanced heat extraction and surface cooling.

Table 3 highlights the operational implications of these differences. While all systems meet the performance criteria for life safety and operational continuity, the environmental impact varies substantially. The conventional sprinkler system with the fastest activation (Scenario 05-A) discharges the largest water volume, which would require a more robust drainage and containment system to prevent contamination of seawater with copper concentrate. Conversely, the water mist system minimizes water discharge, reducing the required containment capacity and lowering the environmental footprint of the fire protection strategy.

Overall, the results confirm that activation time alone is not the determining factor for environmental performance. Instead, the combination of droplet characteristics, discharge density, and suppression efficiency determines the total water volume required to extinguish the fire. This reinforces the value of performance-based design when environmental constraints are critical.

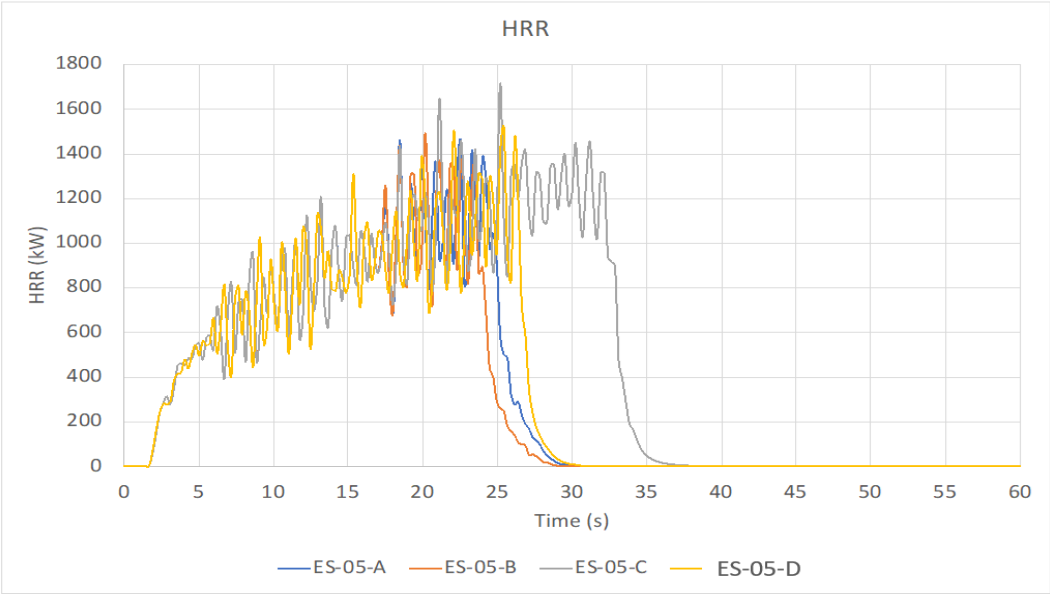


Figure 6: HRR Comparison

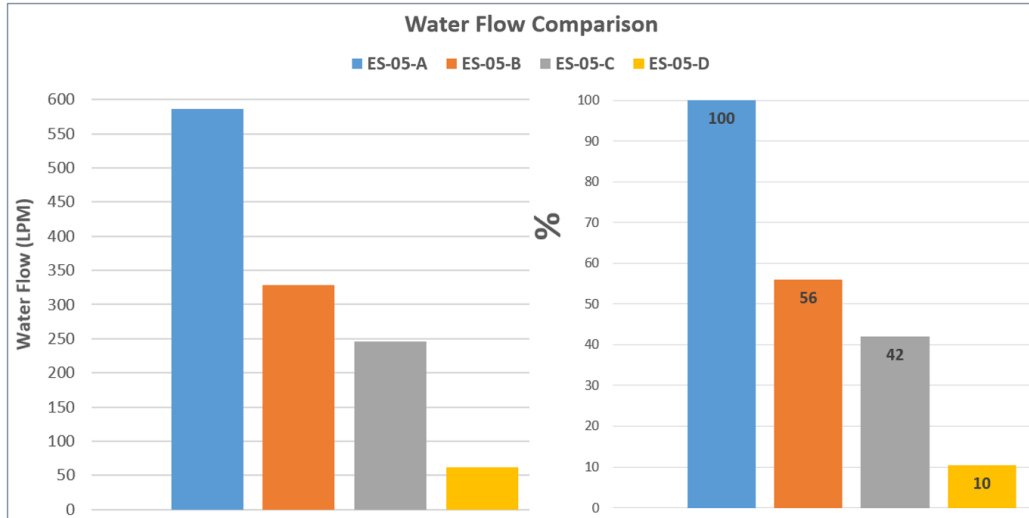


Figure 7: Water Flow Comparison

8. CONCLUSIONS

The performance based analysis conducted in this study leads to the following conclusions:

- All evaluated fire protection configurations—conventional sprinklers, modified sprinklers, and water mist—successfully controlled and extinguished the conveyor belt fire, meeting the performance criteria for life safety and operational continuity.
- Sprinkler systems with faster activation times discharge significantly more water, which reduces the fire growth period but increases the environmental impact due to larger containment requirements.
- Modified sprinkler configurations (lower K factor or higher RTI) still achieve effective suppression while reducing water discharge compared to the FM Global prescriptive design. These configurations remain viable alternatives when environmental constraints are relevant.
- The water mist system demonstrated the highest efficiency, achieving full extinguishment with approximately 10% of the water volume expected from the FM Global reference sprinkler design. This reduction is attributed to the enhanced cooling and heat extraction capacity of fine droplets.
- The reduced water discharge of the water mist system directly minimizes the size of the drainage and containment infrastructure required to prevent seawater contamination with copper concentrate. This represents a significant operational and environmental advantage for conveyor belts installed over marine environments.
- Based on the results, water mist systems represent a technically robust and environmentally superior solution for conveyor belt fire protection in mining applications where water discharge must be minimized.

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- ⁷ Spray Characteristics of Fire Sprinklers - David Thomas Sheppard, Northwestern University
- ⁸ Numerical analysis of a water mist spray: The importance of various numerical and physical parameters, including the drag force, Yuanjun Liu, Tarek Beji, Martin Thielens, Zhi Tang, Zheng Fang, Bart Merci
- ⁹ Lehtimäki, M. (2017). Simulation of Water Cooling in Fires. Aalto, Finland. School of Engineering Aalto University.
- ¹⁰ CFD Study on the Interaction between Water Sprays and Longitudinal Ventilation in Tunnel Fires. Patricio Valdés – University of Ghent
- ¹¹ APPROXIMATE TRAVELLING DISTANCES OF WATER MIST DROPLETS IN TUNNELS - Richard Crosfield, Angelo Cavallo, Francesco Colella, Ricky Carvel, José L. Torero & Guillermo Rein BRE Centre for Fire Safety Engineering, University of Edinburgh, UK
- ¹² Numerical and experimental study on flame spread over conveyor belts in a large-scale tunnel -Liming Yuan*, Richard J. Mainiero, James H. Rowland, Richard A. Thomas, Alex C. Smith - Journal of Loss Prevention in the Process Industries
- ¹³ VIKING Technical data - VK3521 quick response technical data pendant sprinkler (k8.0)
- ¹⁴ VIKING Technical data - VK3021 quick response technical data pendant sprinkler (k5.6)
- ¹⁵ VIKING Technical data – VK1021 quick response technical data pendant sprinkler (k5.6)

Session 7

Sesión 7

Sessão 7

FORENSIC EVALUATION OF WILDLAND FIRE SPOT IGNITION BY STEEL SPARKS FROM HOT WORK: A CASE STUDY

James L. Urban^a, Jose Rivera^b and Carlos Fernandez-Pello^{b,c,*}

^a Department of Fire Protection Engineering, Worcester Polytechnic Institute (WPI),
Worcester, MA 01609, USA

^b Department of Mechanical Engineering, University of California Berkeley,
Berkeley, CA, 94720, USA

^c Reax Engineering. Berkeley, CA 94704

ABSTRACT

Wildland and Wildland Urban Interface (WUI) fires are a problem in many areas of the world, and may have major consequences in terms of safety, air quality, and damage to buildings, infrastructure, and the ecosystem. It is expected that with climate change the wildland fire and WUI fire problem will only intensify. The spot fire ignition of a wildland fire by hot metal particles/sparks is an important fire ignition pathway by which wildfires, WUI fires, are started, and may propagate. There are numerous cases reported of wildland fires started by hot metal particles from clashing power-lines, or generated by machines, or hot work. Here we will report a case study where hot metal particles (sparks) generated during cutting rebar with a saw blade (grinding) or during electrical welding of steel components of a bridge under construction may have caused a wildland fire. The specific bridge is the Taylor bridge in the State of Washington, US, and the wildland fire is the Taylor Bridge Fire that was initiated near the bridge on August 13, 2012 [1]. The fire eventually consumed in excess of 23,000 acres and destroyed approximately 60 homes and in excess of 200 outbuildings [1]. The steel particles could have been generated at high temperature, both from grinding or welding, propelled by the tool which produced them, carried by the wind, and fall to the ground at different distances from the generation source and at different temperatures, depending on the ejection velocity and direction, initial particle size, and wind velocity and direction. Some of these particles could have had sufficient energy and temperature to ignite the vegetation in the area of fire origin and initiate this fire. The determination if some of these particles could land near the location where the fire started and had the capabilities to ignite the fire is the primary objective of this work.

* Corresponding author — Department of Mechanical Engineering, University of California Berkeley, Berkeley, CA, 94720, (USA).

E-mail: ferpello@me.berkeley.edu

1. INTRODUCTION

The forensic analysis of the spot ignition of wildland fires by metal particles can be separated in several individual processes: the generation and ejection of the particles and their thermochemical state; their flight by wind drag; the particle thermo-chemical change during the flight; the onset of ignition (smolder or flaming) of the fuel bed after the particle landing, the sustained ignition of the combustible material, transition to a flaming fire and its potential spread. A schematic of the methodology used to analyze this problem is given in Fig. 1.

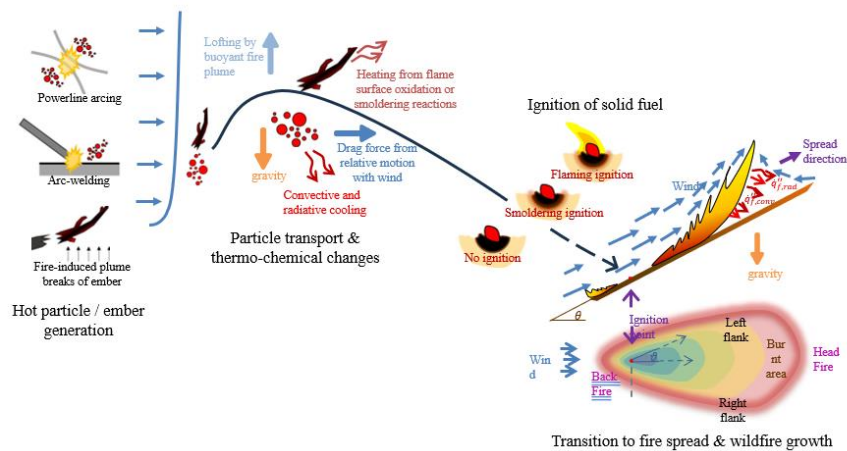


Figure 1: Schematic of the development of spot wildland fires.

This methodology is applied in the present study to determine if hot particles generated during the hot work at the Taylor bridge could ignite the 2012 Taylor Bridge wildland fire. At the time the fire was ignited, two types of hot work were being performed on the bridge: arc welding of the underside of the bridge and abrasive metal cutting of rebar on the top of the bridge. The particle characteristics at ejection are obtained from abrasive metal cutting experiments reported in [3] and welding experiments conducted by the authors and in [4]. The model used to calculate the trajectory and temperature history is that of [5], which is basically a ballistic trajectory simulation with a hot spherical body cooling to the ambient air. In the model application, the ejected particles are characterized by their generation location, initial size, ejection velocity, and initial temperature. Once the particles are ejected by the saw blade or the welder, the particles experience both drag and gravitational forces during their flight. The resulting particle trajectory is roughly parabolic (with deviations caused by drag forces), and the landing location depends on the particle size, ejection velocity (magnitude and direction), and the wind velocity (magnitude and direction). During the trajectory the metal particles cool down reaching the ground at a temperature that depends on the particle initial characteristics and ambient conditions. After landing the particles may have the potential to ignite (smolder or flaming) a bed of vegetation depending on their size and temperature at landing and the characteristics of the fuel bed [2, 6]. The issue in the present study is whether some of the particles generated during the grinding or welding could fall in the alleged area of fire origin [1] and could have the thermal characteristics necessary for igniting the thin vegetation (duff, grass) at the landing location.

2. ANALYSIS

The following photographs document the progression of the Taylor Bridge Fire near Cle Elum in Kittitas County, Washington. In August 2012, a small ignition linked to hot-work activity on a bridge project (sparks/slag from welding and/or cutting) escaped into receptive, dry vegetation and quickly transitioned into a large wildland–urban interface fire. The incident ultimately destroyed 61 homes and burned roughly 23,000–23,500 acres (≈9323 hectares).



Figure 2: Photo Sequence — Taylor Bridge Fire (WA, 2012).

2.1 Scenario 1: Rebar Cutting (grinding) on the Top of the Bridge.

During the rebar cutting (grinding) a shower of hot steel particles is generated by the grinding blade of the cutting tool (Fig. 3). The particles would have different sizes and would be ejected in the direction of rotation of the blade at velocities that depend on the blade rotation speed and characteristics. In the experiments reported by Liu et al [3], 95% of the sparks generated in the tests were between 0.005 mm and 0.067.5 mm, with a maximum size of 0.93 mm measured. The ejection velocity was reported to have an average of 5 m/s for low blade tip speed of 16.8 m/s, and 15 m/s for a high tip speed of 50 m/s. The particle temperature at ejection would depend on the blade speed and force applied by the blade on the steel during cutting, although given that the sparks are incandescent, the temperature would have to be higher than 600 °C [7]. In the experiments of Ref. [3] temperatures as high as 1550 °C were measured.

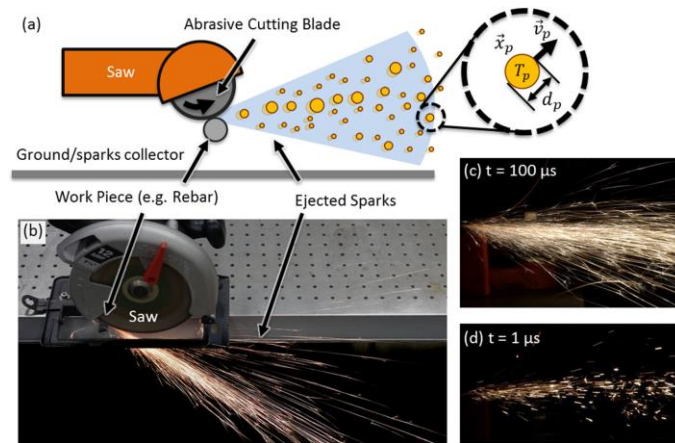


Figure 3: Example of steel sparks generated from grinding/cutting by an abrasive saw blade [3].

The ejected particles would be carried by their inertia in the ejection direction although affected by the wind in its prevailing direction. The particles would fall to the ground at distances from the rebar cutting location that depended on the wind velocity, and particle ejection velocity and size. The issue is whether some of these particles could fall in the alleged area of fire origin [1] and could have the thermal characteristics necessary for igniting the thin vegetation (duff, grass) at the landing location [6]. As mentioned above there is an established methodology to calculate the trajectories that the particle would follow [5] for a given set of conditions, that has been applied here to calculate the trajectories that particles generated by the rebar cutting would follow.

The parameters used for the calculations are as follows: particle diameters for the ejecta from the abrasive cutting (grinding), between 1.0 mm and 2.5 mm. The particles greater than 1 mm in diameter are being considered to simulate the potential accumulation of particles in dense ejection sprays, although dense sprays are not evident in grinding as seen in Fig. 3; the ejection height, approximately 12 m [1], and the wind speed of 11 m/s is based on information from [1]; an initial particle temperature of 1310 °C is selected as above average between the Draper point and the melting temperature of steel; and two ejection velocities of 4.65 m/s and 11 m/s are obtained from [3].

An example of the calculated particle trajectories is given in Fig. 4 for particles with different diameters and two different ejection speeds. Also indicated in the figure is the approximate region (section of radial distance from the location of rebar cutting) for the origins of the fire identified in the DNR Fire Investigation Report [1]. It is seen that the particles with ejection velocities larger than 11 m/s would land in the area of fire origin and beyond.

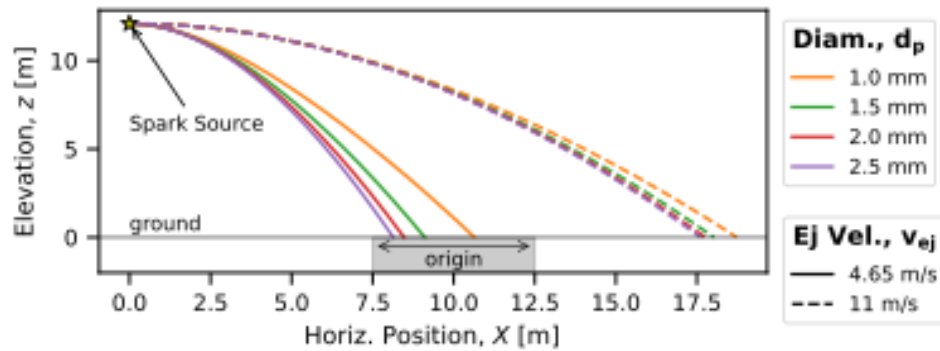


Figure 4: Trajectories of rebar cutting particles for different diameters, two ejection velocities and a wind of 11 m/s. Boundaries of approximate fire origin are also indicated.

The distribution of the landing locations of the particles in relation to the bridge and the origin of the sparks are shown in Fig. 5 for several particle diameters, ejection velocities, and wind speed. The landing locations of the sparks are colored according to the size of the generated particles. The sparks land in different locations depending on the ejection velocity (speed and direction) and the wind velocity (speed and direction). The fire origins denoted determined by the DNR report are shown with white circles [1].

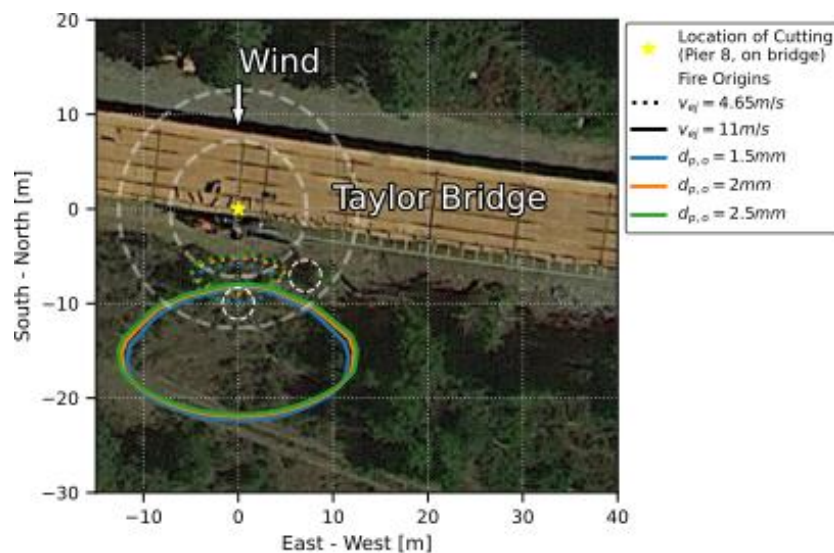


Figure 5: Landing locations of particles generated by the rebar cutting in a southern wind of 11 m/s. Map image obtained using Google Earth.

The ability of these particles to ignite a fire after landing on the ground depends on their size and temperature at landing as well as the type of fuel they land on. To evaluate the ignition capability of these particles we can compare the ignition conditions to the ignition boundaries determined through controlled experiments [6].

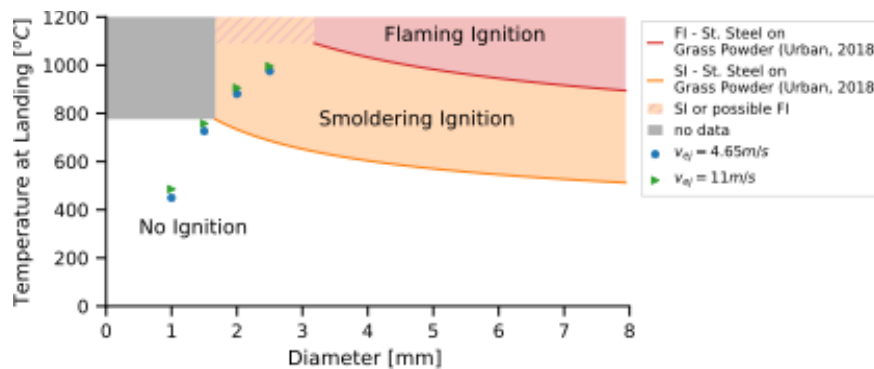


Figure 6: Landing conditions of particles generated by rebar cutting compared to ignition boundaries for a grass blend powder by hot steel particles.

The calculated conditions (temperature and diameter) of the grinding sparks at the time of landing are shown in Fig. 6, together with ignition boundaries (flaming and smoldering ignition) for a powdered grass fuel bed by hot steel particles [6]. The ignition boundaries were determined through experiments dropping steel particles of known size and temperature onto a well characterized fuel bed. It is seen that individual particles in a sparse spray with sizes of less than 1.5 mm were not capable of igniting the fire. Particles in a dense spray that accumulated to an equivalent particle of sizes larger than 2 mm in diameter could initiate a smolder fire upon landing on fine vegetation.

2.2 Scenario 2: Welding Beneath the Bridge

During the process of welding of the bottom structure of the bridge a shower of hot/molten steel particles would be generated by arcing of the welding rod and steel structure. These particles would have different diameters and be ejected in different directions and would be carried by the prevailing wind falling to the ground at distances from the particle origin depending on the wind velocity and particle size. An example of the welding trajectories is shown in Fig. 7 for experiments conducted welding a steel sheet to a steel beam [9]. The welding tests were conducted with a constant current electric welder (Lincoln AC 225) at 230 V and currents of 120 A and 150A. The welding was conducted at 2 m high and the ejected steel particles were collected in a pan with water placed on the ground. The diameter of the particle collected varied between 0.1 and 2.0 mm, and had ejection velocities between 0.8 m/s and 2.6 m/s. The welding event was video recorded with a SONY RX10M3 camera. As in the case of the rebar cutting, the trajectories of these particles are calculated with the methodology of [5]; the welding spatter is assumed to be generated at a height of 10 m above the ground at the base of the piers, corresponding the underside of the bridge [1]; the spatter initial temperature is assumed to have a maximum value

of 2862 °C, the boiling point of steel; the wind speed is 11 m/s; and ejection velocities of 2, 3, 4, 5 m/s are selected from [4].

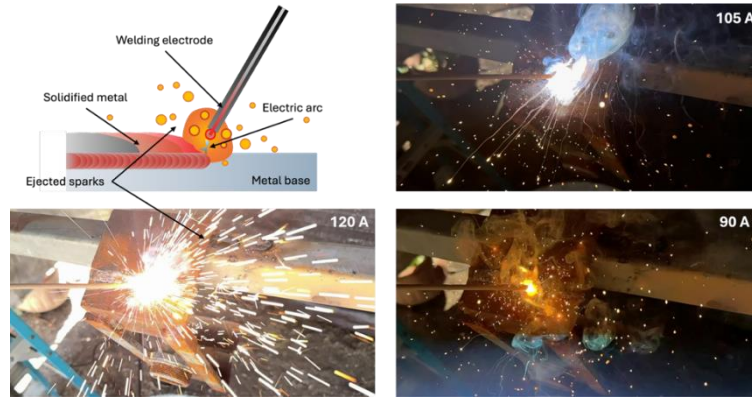


Figure 7: Example of steel sparks generated during constant current welding of two steel structural components. [9]

An example of the calculated particle trajectories is given in Fig. 8a for particles of several diameters and an ejection velocity of 4.5 m/s, and in Fig. 8b the calculated particle trajectories of 2 mm in diameter and several ejection velocities.

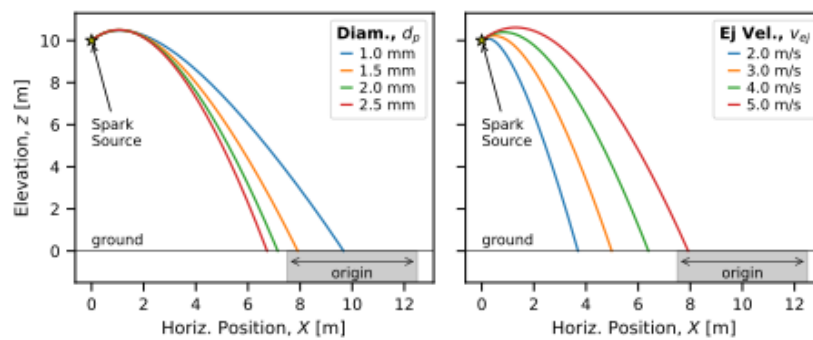


Figure 8: Trajectories of welding particles for: a) several diameters and an ejection velocity of 5 m/s. b) particle 2 mm diameter and several ejection velocities. Boundaries of approximate fire origin are also indicated.

The calculated landing locations of particles generated by the welding beneath the bridge superimposed over image obtained using Google Earth are presented in Fig. 9 for different particle diameters. It should be noted that the particles would have landed under the bridge, not on top of it. The figure shows that particles of sizes up to 1.5 mm could have landed on the norther region in the fire origin area.

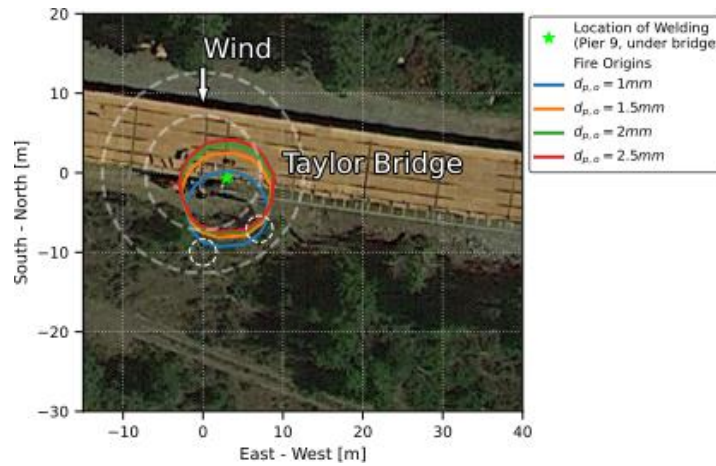


Figure 9: Landing locations of particles generated by welding support beams underneath the bridge.

The calculated conditions (temperature and diameter) of the welding particles at the time of landing are shown in Fig. 10. plotted with ignition boundaries (flaming and smoldering ignition) for a powdered grass fuel bed by hot steel particles [6]. It is seen that particles with sizes smaller than 1.0 mm in diameter would not be able to initiate a smolder fire upon landing on fine vegetation. Larger particles would have a higher probability of igniting a fire but would barely land in the identified location of fire initiation (origin).

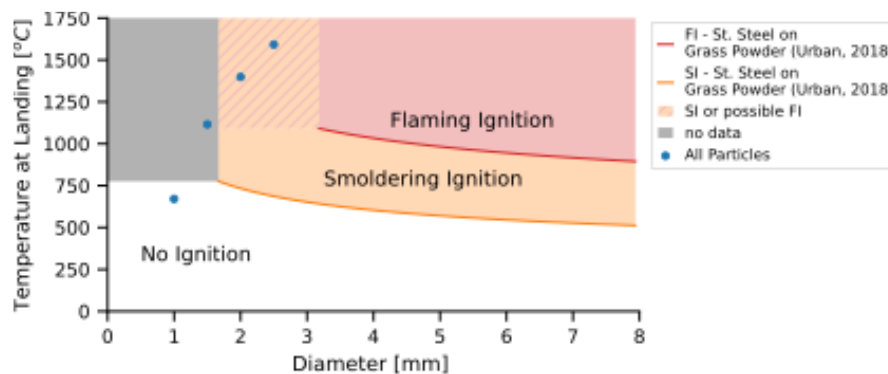


Figure 10: Landing conditions of particles generated by welding. The particle diameters and temperature are compared to ignition boundaries for a grass blend powder by hot steel particles. [6]

3. CONCLUSIONS

The present analysis indicates that although both the hot particles generated by rebar cutting, or welding of the bridge structures, had the potential to ignite a wildland fire, there are differences in their landing location and ignition characteristics that show different probabilities of ignition. The grinding steel particles would have landed at longer distances from the bridge, at and beyond the area of fire origin, than the welding particles. However, the grinding particles would land with smaller sizes and temperatures, and consequently less potential for igniting the fire. Although the welding generated particles were hotter and bigger at landing, and consequently with more potential for ignition, their landing locations were somewhat shorter than the alleged location of fire origin, although that location of the ignition area is only approximate.

It should be noted, however, that the results presented above are for single particles. In the case of rebar cutting with a grinding disc a shower of particles would have been generated. This may cause the accumulation of multiple particles at the landing location with the result of having an equivalent larger particle with a higher capability of igniting the vegetation. At the same time, the determination of the area of fire origin is somewhat empirical and it is possible that the fire origin was closer to the bridge than alleged. However, although there is not a clear conclusion of what hot-work caused the fire, it is more likely that it was the welding than the grinding, because the welding sparks would have a higher capability of igniting the vegetation and a higher probability of landing on a finer and easier to ignite fuel.

4. ACKNOWLEDGEMENTS

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PROPOSITION OF A SIMPLE RELATION TO DESCRIBE TRANSIENT GROWTH OF SOLVENT POOL FIRE



Gildas AUGUIN* (PhD)
Technical Director
Efectis
France



Manon FLEUROTTE, (PhD)
Fire safety Engineer
Efectis
France

SUMMARY

Hydrocarbon pool fires are widely used as reference scenarios in fire safety engineering due to their penalizing thermal effects and rapid development after ignition. While a lot empirical and semi-empirical models exist to predict steady-state burning rate, fewer approaches accurately describe the transient fire growth phase. This study presents an experimental and analytical investigation of the temporal fire development phase of the hexahydrotoluene (methylcyclohexane) solvent pool fires. A series of medium-scale fire tests was conducted under a semi-open calorimetric hood for surfaces ranging from 0.25 m² to 1.88 m². Complementary experiments using n-heptane were performed to provide a reference comparison. Experimental results show rapid ignition and flame spread, followed by a growth phase, before reaching a quasi-steady state. The peak of heat release rate (HRR) increases significantly with pool surface area. Solvent exhibits combustion behaviour comparable to n-heptane, with slightly lower burning rates and maximum HRR values for equivalent geometries. For surfaces below approximately 1 m², classical semi-empirical burning rate correlations provide satisfactory agreement with experiments. For larger pools, deviations are observed due to wind effects and enhanced radiative feedback. Then, a simple algebraic relation is proposed to describe the full transient evolution of the HRR, including the fire growth phase and the quasi-steady regime. The model relies on a limited number of physically meaningful parameters, as maximum HRR, total energy content, and time to peak HRR, and is shown to reproduce both the experimental results and independent literature data for different fuels. This approach offers a practical alternative to conventional t-square fire growth models for hydrocarbon pool fire design.

Keywords: pool fire, heptane, hexahydrotoluene, heat release rate, fire growth, fire test, algebraic relation.

* Corresponding author – Efectis France, Espace Technologique Bâtiment Explorer, Route de l'Orme des Merisiers, 91190 Saint-Aubin (France).

Tel.: +33 676 226 562, E-mail: gildas.auguin@efectis.com

1 INTRODUCTION

Hydrocarbon pool fires are reference scenarios in fire safety engineering in industrial facilities due to their high level hazard and their penalizing thermal effects. After ignition, the heat release rate (HRR) rises rapidly due to radiative and convective feedback from the flame heating the fuel surface. Depending on the fuel and ambient conditions, a quasi-steady plateau may be reached within 3 to 10 minutes.

Hydrocarbon pool fire characteristics are strongly dependent on the type of fuel, the pool diameter and the fuel depth. The original works of Babrauskas [1] provided empirical correlations linking the HRR to the pool diameter, burning rate and heat of combustion of the implied fuel, showing an asymptotic trend for large surface areas. More recent studies [2][3][4][5] have developed global models based on the energy balance of the fuel surface and flame radiative feedback. These approaches were mainly developed to describe steady-state regime, and are less dedicated in reproducing transient dynamics of fire growth development and heat release. The growth of fire development during the first minutes after ignition could be of particular importance in the case of a based-performance approach using computational fluid dynamics, for, by example, the determination of steel structure heating, or optimization of automatic sprinkler systems,.

In this context, an experimental study has been initiated to characterize the kinetic development of pool fires of the solvent hexahydrotoluene (also so-called methylcyclohexane), over pool surfaces ranging from 0.25 m² to 1.88 m² in a semi-opened large calorimetric hood. Since the experimental results, the combustion characteristics of hexahydrotoluene pool combustion are determined in comparison with the n-heptane fuel. Then a simple and robust algebraic model able to reproduce both the growth phase and the quasi-steady regime of fire development is developed. The so-defined algebraic evolution of HRR are compared to the actual experiments and also data from literature.

2. FIRE TESTS

2.1 Tests program

The tests consisted of carrying out fire experiments with trays of varying sizes and shapes filled with hexahydrotoluene, in order to generate representative HRR versus time curves. The hexahydrotoluene is an organic compound with the molecular formula CH₃C₆H₁₁, classified as saturated hydrocarbon and used as solvent. A tests comparison was also made with pool fires of n-heptane (C₇H₁₆), a similar and well-known hydrocarbon. The characteristics of each tests conditions are detailed in the following Table 1.

Table 1: Tests program of pool fire

Test #	Pool surface (m ²)	Geometry of tray (-)	Dimension of tray (m)	Fuel
1a	0.25	circular	0.55	hexahydrotoluene
1b*	0.25	circular	0.55	n-heptane
2	0.38	square	0.62 x 0.62	hexahydrotoluene

Test #	Pool surface (m ²)	Geometry of tray (-)	Dimension of tray (m)	Fuel
3	0.49	square	0.7 x 0.7	hexahydrotoluene
4	0.98	rectangular	1.4 x 0.7	hexahydrotoluene
5a	1.88	rectangular	1.14 x 1.65	hexahydrotoluene
5b*	1.88	rectangular	1.14 x 1.65	n-heptane

The involved trays are made of 1.5 mm thickness carbon steel, and designed according shape and dimensions indicated in Table 1. For each test, the corresponding tray is filled with a water height of 10 mm. Then the fuel is added to raise a free-board level of 50 mm. The ignition is operated by a small gas burner flame.

2.2 Testing facility and apparatus

The tests were carried out in the calorimetric hood of Efectis France laboratory site of Saint-Yan. It is a semi- open enclosure, with a floor area of 7 m x 5 m, topped by a hood and a central chimney (see Figure 1). Aerated concrete walls and insulated steel panels fallouts and non-combustible curtains are present around the South, West and North hood sides to limit loss of smoke and fire effluents, and adverse external effects such as wind. The West and East sides are partially open to permit video recording, fire ventilation and safety intervention if necessary. West side door is closed by a curtain during the tests. The smoke produced is naturally evacuated through the 3.5 m high central chimney, which is a square metal insulated duct of side 1.2 m. The under surface of the roof is protected by alkaline earth silicate wool layers.



Figure 1: Large calorimetric hood of Efectis France in Saint-Yan. West side (left), South side (center), East side (right)

The chimney is fitted with a gas sampling probe, thermocouples and a velocity probe. The gas probe is linked to a gas analyser equipped with cells by infrared absorption for measuring CO and CO₂ concentrations, and galvanic probes for measuring O₂ concentration. The gas cells range are 0 to 25% for O₂, 0 to 25%, for CO₂ and CO: 0 to 10,000 ppm The velocity is measured from a bidirectional McCaffrey velocity probe [6], derived from the principle of the Pitot tube, and connected to a differential micro pressure sensor with a ± 250 Pa gauge range (accuracy 0.5 Pa). The temperature of flue is measured by a type K-thermocouple at the same location. The probes are located in the center of the section. The velocity and temperature profiles in the chimney have been characterized during calibration tests of hood to determine the adapted correction factor to

extrapolate the flow rate from one center measurement point. Concerning the gas profile, a well-mixed flow is generally observed in the duct, promoting the use of one centre location. A 1Hz sampling resolution is used during the tests for all devices.

The heat release rate Q (in kW) is determined thanks to the concentration gas measurement following the oxygen consumption calorimetry proposed by Janssens [7] :

$$Q = \alpha_{O_2} \left[\frac{X_{O_2}^0 - X_{O_2}^A}{1 - X_{O_2}^A} \right] \dot{m}_a \frac{M_{O_2}}{M_a} (1 - X_{H_2O}^0 - X_{CO_2}^0) \quad (1)$$

where X_G represents the molar fraction of gas G , $\dot{m}_a$ is the mass flow rate of the smoke, M_{O_2} and M_a are the molar mass of dioxygen and air respectively. α_{O_2} is the heat release per mass unit of consumed oxygen (≈ 13.1 kJ/kg). The subscript 0 and A correspond to the incoming air and the exhaust duct conditions respectively.

The volume flow of the smoke in the chimney is calculated from the flue velocity measurement multiplied by cross section surface and considering a correction factor to taking account the flow profile. Measuring temperature at the same location allows to determine the density of the smoke using the ideal gas law, and to convert the volume flow rate into mass flow rate.

2.3 Results

All tests exhibited an instant ignition of the fuel upon approaching the gas burner flame, rapid fire spread across the entire surface of the tray, an increase in fire intensity within minutes, a more or less long plateau and a swift extinguishment. In spite of closing curtains and walls, external wind influenced the flame shape and combustion rate with pulsation and undulating flames, coupling with an increase of fire intensity. Time-varying fluctuations of flame turbulence are well observed. This turbulence also increases in turn because of the combination of the increasing HRR and the soot formation [4]. In addition a significant free-board could initiate turbulence at the pool edge that would intensify the convective heat transfer [8].

The flame shape during the plateau, i.e. just before extinction of combustion, are illustrated in the figures 2 and 3 below.

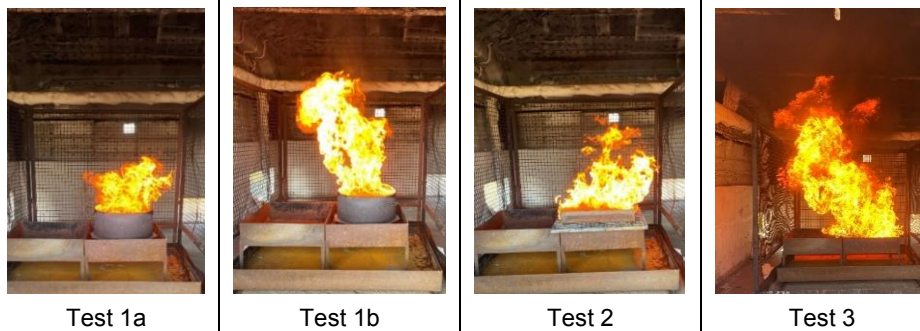


Figure 2: Flames observations of pool fire with tray surface under $0.5m^2$



Figure 3: Flames observations of pool fire with tray surface above 0.9m^2

The time evolutions of heat release rate for each test are described in Figure 4 for small trays (surface under 0.5m^2) and for large trays (surface above 0.9m^2). The fire development kinetics, or time evolution of fire growth, is notably observable with an increase of heat release rate during 60 s for small trays and almost 120 s for large ones. Then a steady state of heat release is more or less settled. The maximum value of heat release rate obtained during this steady state increases with pool surface. Depending the initial amount of fuel, the plateau can be short.

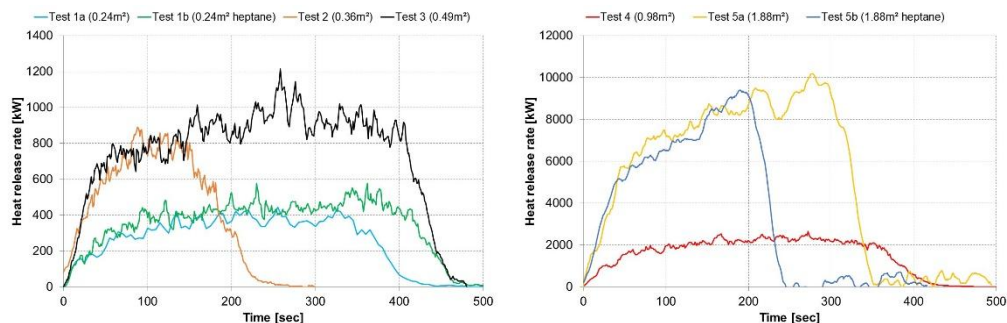


Figure 4: Evolution of HRR during pool fire tests with surface tray under 0.5 m^2 (left), and with surface tray above 0.9 m^2 (right)

Fluctuations, due to turbulence and convective currents, but also from velocity fluctuations in the chimney, are observed on HHR evolution curves. The heat release rate determination can be considered by the mass flow times O_2 concentration depletion, and the main contributor of fluctuation is the flow rate, meaning velocity in chimney, which exhibits higher fluctuation, especially at low regime of ventilation. Indeed, a $\pm 1\text{Pa}$ dynamic pressure fluctuation is measured during all the tests at the McCaffrey probe, representing 9% of the mean value at low regime, and only 1.8% at high regime.

The wind conditions with gust, impact also the maximum value of heat release rate to retain. An uncertainty of $\pm 10\%$ can be adopted in general. For the tests with a surface of 1.88 m^2 , the heat release rate increases by stepping, with several levels. It is partly due to wind, but also to the

growth of fuel heating by flames radiation on the fuel surface. In these conditions, different values of burning rate, and consequently heat release rate, can be assumed. The proposed maximum heat release rate values are reported in Table 2. For all tests, the phase of combustion extinction is faster than increase phase. It appears more abrupt for large pool fire of 1.88 m² for both fuel. There is also slight difference between solvent pool fire and n-heptane pool fire, with a higher heat release rate with n-heptane.

Table 2: maximum heat release rate of pool fire tests

Test #	surface (m ²)	solvent (kW)	n-heptane (kW)
1a	0.25	390	-
1b	0.25		485
2	0.38	670	-
3	0.49	945	-
4	0.98	2560	-
5a	1.88	7100 / 8100 / 9300	-
5b	1.88	-	7000 /9000

2.4 Analysis of solvent pool fire characteristics

The burning rate m'' (in kg/m.s²) of large pool fire, i.e. diameter above 50 cm, and considered as fully turbulent and governed by radiation, can be represented by the following empirical expression [1] [9]:

$$m'' = m''_{\infty} (1 - e^{-k\beta D}) \quad (2)$$

where m''_{∞} is the maximum asymptotic burning rate of a hypothetical infinite pool fire (in kg/m².s), κ is the extinction coefficient (in m⁻¹), D is the hydraulic diameter of the pool (in m) and β is the mean beam length corrector (-). The evaluation of these parameters requires the availability of experimental data.

So considering the tests data previously described and the physical properties of fuels [10][11] in terms of density and heat of combustion, the intrinsic parameters of the empirical law of burning rate for solvent can be determined. The figure 5 shows the so-obtained burning rate evolution in function of pool geometrical characteristics, expressed in terms of regression rate (in mm/min), or equivalently as heat release rate per unit area (in kW/m²). In the case of square or rectangular tray, the hydraulic diameter is determined as the ratio of 4 times its surface on perimeter. The set of parameters for solvent determined to fit the experiments results is indicated in Table 3. The parameters of the empirical law for n-heptane come from Brabauskas [1].

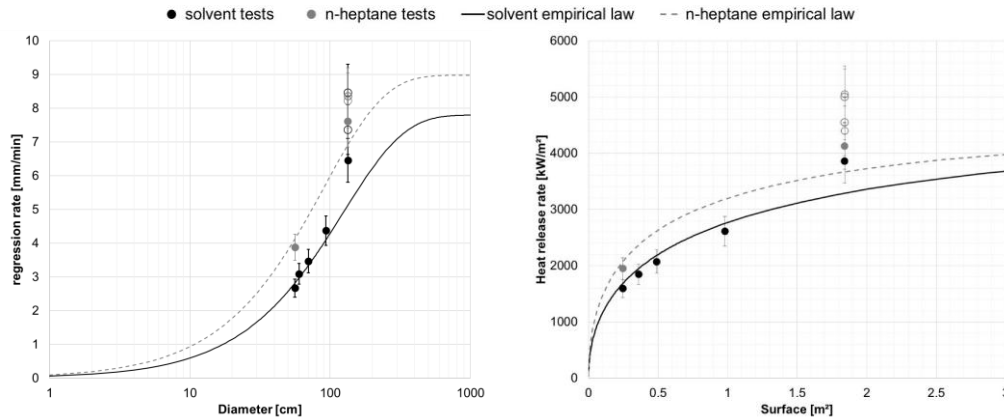


Figure 5: Evolution of regression rate and heat release rate according pool diameter (left), and pool surface (right)

Table 3: burning rate parameters of semi-empirical law

Fuel	$\dot{m}_{\infty}''$ [kg/m².s]	$k\beta$ [m⁻¹]	ΔH_c [kJ/kg]	ρ [kg/m³]
n-heptane [1]	0.101	1.1	44600	675
hexahydrofluorene	0.095	0.8	46580	769

The chosen parameters permit to obtain a quite consistent correlation for surface under 1 m². For higher surface, the turbulence and wind impact increasing the fuel evaporation, and promoting a more important feedback radiative heat transfer, increase the combustion rate. In these conditions, the empirical law, established for still-wind conditions, is not quite adapted. This situation concerns both fuel, meaning that it is only due to testing conditions. An increase of the tray geometrical diameter to an actual "combustion" diameter, of 15 to 20% order of magnitude, permits to artificially obtain the experiments values with the empirical law and parameters set.

3. DEVELOPMENT OF A SIMPLE RELATION TO DESCRIBE FIRE KINETICS

3.1 Fire growth relation

Generally in fire safety engineering approach requiring hydrocarbon pool fire design, the time-dependant fire development of heat release rate is simply described by the well-known t-square fire growth, which is based on extensive experimental data. It consists of fire development kinetics of ultrafast, fast, medium and slow in terms of growth coefficient according to the time to reach 1 MW. In case of pool fire, an Ultra-Fast factor of 75s is often chosen.

Nevertheless, mostly of experimental and numerical studies [3] [4] [12] [13][14][15] highlight that analytical approaches often relying on power-law calibrated from experimental campaigns, not quite adapted to catch the actual increasing phase and time to reach the maximum HRR. Moreover these approaches remain limited in their applicability due to a lack of systematic validation for others length scales and fuels. It exhibits the need of a simple, robust, and

parametric kinetic models able to predict the heat release rate evolution as a function of pool size and fuel properties.

Based on the works of Numajiri and Furukawa [16] on mathematical expressions describing a complete fire development and improved by Ingason [17] for fuel controlled fires in tunnel, a simple exponential in function of time is defined as follows:

$$Q(t) = Q_{max} \cdot n \cdot r \cdot (1 - e^{(-kt)})^{(n-1)} e^{(-kt)} \quad (3)$$

where Q_{max} is the maximum heat release rate (in kW), t the time (in seconds), r the amplitude coefficient, k the time width coefficient and n the retard index.

The following additional relations are then necessary:

$$r = \left(1 - \frac{1}{n}\right)^{(1-n)} \quad (3)$$

$$k = \ln(n)/t_{max} \quad (4)$$

$$t_{max} = 3/4 \frac{E_{tot}}{Q_{max}} \quad (5)$$

The key parameters in the model are consequently the maximum heat release rate, the time to reach maximum heat release rate t_{max} (in seconds) and the total energy content E_{tot} (in kJ). n is an arbitrary parameter with no physical meaning. So the original value fixed to 1.8 and proposed by Ingason [18], and Numajiri and Furukawa [16], is chosen.

The decrease/extinguishment phase is considered when 95% of the total energy content has been released. At this time instant, the decline of fire is reproduced by a simple function as the form $Q(t) = Q_{0.95} e^{-\lambda(t-t_{0.95})}$, where $Q_{0.95}$ and $t_{0.95}$ represent the heat release rate and time obtained at 95% respectively. λ is an arbitrary parameter chosen to fulfil with experiments results, and consequently tuned to $\ln(0.95)$. This decrease phase of heat release rate evolution time is no more detailed and discussed in this article, needing further investigations and argumentations.

3.2 Application on solvent and heptane pool fire tests

The Figure 6 below show the evolution time of heat release rate for each tests characteristics by application of Eq. 3 and considering the Eq. 2 to determine the maximum heat release rate with parameters from Table 2. The key parameters of the empirical relation is listed in Table 4.

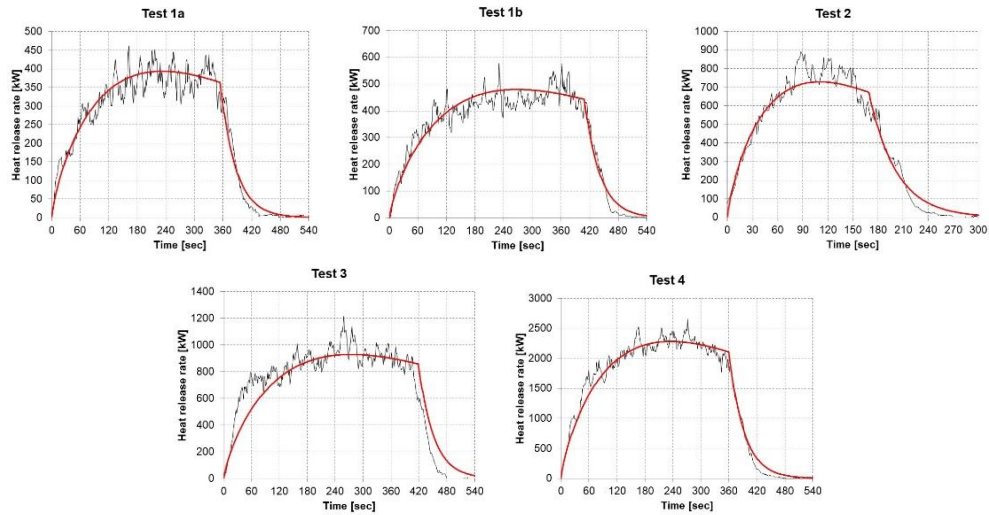


Figure 6: Comparison of HRR evolution (pool surface < 1m²) (algebraic relation: red line, experimental: black line)

Table 4: key parameters of HRR growth relation

Test #	Q _{max} (kW)	E _{tot} (MJ)	t _{max} (s)
1a	34	122	232
1b	510	172	25
2	729	107	110
3	1015	340	251
4	2250	734	241
5a	5900 (8100*)	2042	273 (199)
5b	6550 (7100*)	1372	157 (145)

(*: measured HRR)

The key parameters and the linked relations (Eq. 3 to 5) permit to obtain a consistent evolution of heat release for the tests where the wind does not influence the burning rate. So, for Test1 to Test4, the proposed algebraic relation permit to reproduce the right kinetics of fire development and the time to reach the maximum of heat release rate.

For Test5a and Test5b (see Figure 7), where the wind, turbulence and fire conditions have impact on burning rate increases, the use of the actual measured heat release rate during tests permits to find a more consistent evolution curve and maximum time. It confirms the functionality of the relation, but exhibits its limits in case of large pool under wind or strong turbulence conditions, where the expected HRR maximum values from Eq. 2. Is not followed.

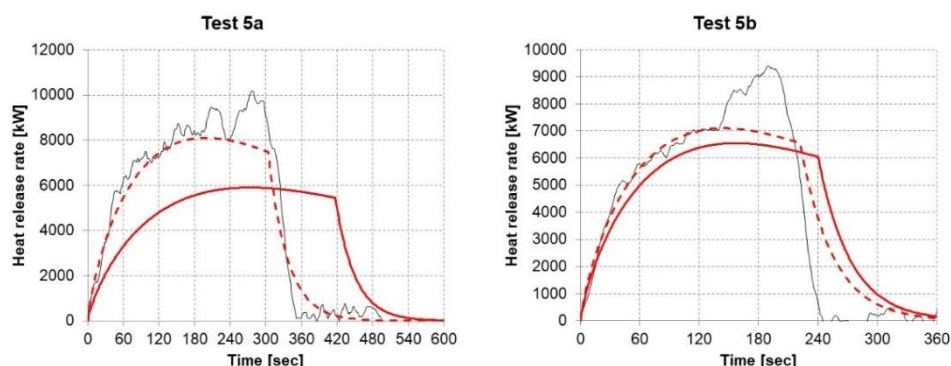


Figure 7: Comparison of HRR evolution (pool surface of 1.88m^2)
(algebraic relation: red continuous and dotted line, experimental: black line)

The application of the relation with the experiment conditions concerning the fire development of a 0.57m^2 ethanol pool [19] permits to verify the ability of this equation using the simple key parameters (see Figure 8) with another fuel and surface.

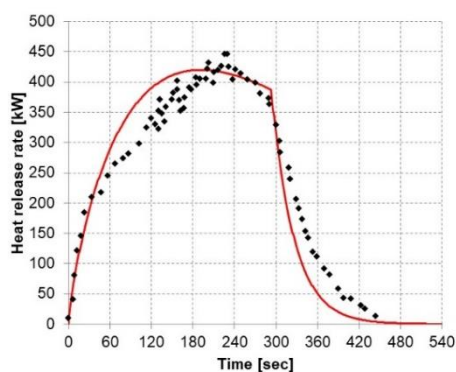


Figure 8: Comparison of HRR evolution (algebraic relation: red line – black diamond: Thomas et al (2007) 0.57m^2 ethanol [19])

4. CONCLUSION

This study presents an experimental and analytical investigation of the transient growth phase of hydrocarbon pool fires, with a specific focus on hexahydrotoluene as a representative solvent fuel, and with n-heptane used as a reference. A series of medium- and large-scale pool fire experiments were conducted under controlled calorimetric conditions for surfaces ranging from 0.25m^2 to 1.88m^2 . These experiments provided the heat release rate time evolution, enabling both the characterization of fuel burning behaviour and the assessment of fire growth during the critical early stages following ignition.

The experimental results confirmed that hexahydrotoluene exhibits combustion characteristics approximately comparable to those of n-heptane, with slightly lower burning rates and peak of

heat release rate values for equivalent pool geometries. For surfaces up to approximately 1 m², the observed burning rates were well described by the classical semi-empirical correlations. For larger surfaces, deviations were observed, primarily attributed to wind effects, turbulence and enhanced flame–fuel interactions, highlighting the limitations of steady-state models when applied to semi-open experimental configurations.

The main contribution of this work is the development and verification of a simple and robust algebraic relation able to reproduce the full transient evolution of the heat release rate, including the growth phase and the quasi-steady plateau. The proposed formulation relies on a limited number of physically meaningful parameters, as the maximum heat release rate, the total energy content (volume of fuel) and the time to reach peak of HRR, which can be derived from basic fuel properties and pool geometry. Comparisons with experimental data show that this relation provides a consistent and robust representation of fire development for both fuels, as well as for independent data from the literature involving a different fuel.

From a fire safety engineering perspective, the proposed approach offers a practical alternative to conventional t-square fire curves design, which often fails to capture the actual growth of pool fire. By better representing the transient HRR evolution during the first minutes after ignition, the model helps bridge the gap between experimental fire behaviour and engineering applications such as sprinkler system design, structural fire resistance assessment, and CFD-based performance analyses. Further work is nevertheless required to refine the description of the decay phase and to extend the validation to a wider range of fuels and ambient conditions.

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Evaluation and thermal characterization of boundary conditions in the EN 50399 cable fire test apparatus for digital twin development

Alain Alonso¹

UC - Santander
España

Erwin Opazo

Prysmian Cables
Spain S.A.U.
España

Mariano Lázaro

Profesor
UC - Santander
España

Neus Generó

Prysmian Cables
Spain S.A.U.
España

Elena Pérez

Prysmian Cables
Spain S.A.U.
España

Daniel Alvear

Catedrático
UC - Santander
España

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ABSTRACT

The Construction Products Regulation (CPR 305/2011) [1] establishes harmonised standards to ensure the safety and performance of construction materials within the European Union. In this framework, electrical cables are assessed for reaction-to-fire performance using the EN 50399 large-scale test [2]. Nonetheless, these tests are costly and time-consuming, which has increased interest in complementary numerical approaches. Digital twins—virtual replicas of physical systems—offer a promising route to reproduce standard fire test conditions in a controlled digital environment, but their accuracy depends strongly on how boundary conditions are defined. Although EN 50399 specifies the cabinet geometry, sample positioning, and burner configuration, the available information is often insufficient for high-fidelity CFD modelling. This study provides an experimental characterisation of key boundary conditions in the EN 50399 setup, focusing on the ignition source. Results show that small variations in burner flow can significantly affect the thermal environment.

1. INTRODUCTION

Construction products placed on the European market are regulated under the Construction Products Regulation (CPR 305/2011) [1], which establishes mandatory requirements through harmonised standards, including fire safety. Within this framework, electrical cables are classified as construction products and must be assessed for reaction-to-fire performance, as they may contribute to flame spread, heat release, and smoke production in buildings. Due to their extensive installation in building compartments, and openings through walls, shafts, cables can act as preferential pathways for the propagation of fire, heat, and smoke. This issue is particularly

¹ Autor correspondiente — GIDAI Group, University of Cantabria. Ave. Los Castros s/n, 39005 Santander (Spain).

Telef.: +34 942 201826, Fax: +34 942 202276, E-mail: lazarom@unican.es

critical in facilities such as hospitals, data centres, and transport hubs, where cable failure during a fire can compromise essential services and hinder safe evacuation.

Compliance with the CPR for electrical cables is demonstrated through large-scale fire testing according to EN 50399 [2], with the resulting data used for classification under EN 13501-6 [3]. While these tests are essential for regulatory purposes, they are costly, time-consuming, and logistically demanding. As a result, increasing attention has been directed towards complementary experimental and numerical approaches aimed at improving the understanding of cable fire behaviour while reducing experimental complexity.

Existing research in this field can be broadly classified into three main categories. The first includes small- and bench-scale tests, such as cone calorimeter and Fire Propagation Apparatus-FPA experiments, which aim to characterise material fire behaviour and establish correlations with large-scale performance [4-9]. The second category comprises intermediate- and large-scale experimental campaigns, including projects such as CHRISTIFIRE [10] and PRISME [11], which investigate flame spread and fire development under more representative configurations. The third category consists of modelling approaches, ranging from simplified and semi-empirical models to high-fidelity numerical simulations.

Among simplified approaches, the FLASH-CAT model [12] predicts flame spread over cable trays based on the theoretical framework developed by Quintiere [13] using source terms derived from bench-scale data. Similarly, the THIEF (Thermally-Induced Electrical Failure) model, developed within the CAROLFIRE project [14], focuses on predicting cable functional failure under thermal exposure. While these models offer computational efficiency, they are limited in their ability to reproduce complex flow-flame-structure interactions. In contrast, Computational Fluid Dynamics (CFD) approaches, most commonly implemented using the Fire Dynamics Simulator (FDS) [15], allow for a more detailed representation of the physical phenomena governing cable fires. Several studies have demonstrated the capability of FDS-based models to reproduce cable fire behaviour when supported by appropriate experimental data [16, 17].

More recently, the concept of digital twins has been applied to standardised fire tests, including EN 50399, highlighting the critical role of accurately defined boundary conditions. In particular, Girardin et al. [18] demonstrated the strong sensitivity of EN 50399 simulations to burner boundary conditions when using FDS. Building on this work, and supported by recent experimental studies that underline the sensitivity of flame spread and cable fire behaviour to burner flame shape [19, 20], the present study extends the analysis through a dedicated experimental campaign. A detailed characterisation of the EN 50399 boundary conditions is performed, with a specific focus on controlled physical variations of the burner and their influence on the thermal environment. These boundary conditions are directly related to the flame development and combustion behaviour of two different cable specimens.

The focus of this work is the characterisation of the burner action zone within the test cabinet. An experimental campaign was conducted in which key boundary conditions related to burner operation were systematically modified. The resulting measurements were then used to inform and validate an FDS-based numerical model. The overall objective is to improve the definition of realistic boundary conditions for digital-twin simulations of the EN 50399 cable fire test.

2 EXPERIMENTAL SETUP

2.1 EN 50399 test apparatus and reference configuration

The EN 50399 cabinet consists of a vertical non-combustible enclosure equipped with a rear-mounted cable ladder, a bottom air inlet, and a mechanically driven exhaust system at the top for combustion product collection and heat release rate determination. Air is supplied through the inlet box at a nominal flow rate of 8000 ± 400 L/min, while combustion gases are extracted at approximately 1000 L/s. Ignition source is provided by a horizontally mounted propane burner located at the base of the cable ladder. For standard reaction-to-fire classifications, the burner operates at a nominal heat release rate of 20,5 kW, corresponding to propane and air mass flow rates of approximately 442 mg/s and 1550 mg/s, respectively. These conditions define the reference configuration against which modified boundary conditions were evaluated.

According to EN 50399, the burner is required to produce a prescribed flame shape to ensure test reproducibility. To characterise the resulting thermal environment and to evaluate the influence of cable specimens as physical obstacles capable of altering this flame structure, two experimental configurations were considered: tests conducted without cables and tests conducted with cables installed on the ladder.

In total, fourteen tests were performed. Eight tests were conducted without cable specimens in order to characterise the burner-induced thermal environment and to isolate the influence of burner operating conditions on the gas-phase temperature field. In these tests, the burner operating parameters and air inlet flow rate were systematically varied. Six additional tests were carried out with cable specimens installed on the ladder, using two different cable types, to evaluate how the presence of combustible materials modifies the flame structure and the resulting temperature distribution. In all cases, gas-phase temperatures were measured in the lower region of the ladder, which is the most relevant zone for flame spread and cable classification under EN 50399. An overview of all tests conducted and their corresponding boundary conditions is provided in Table 1.

Table 1: Tests conducted for measuring the gas temperatures.

Test	Air inlet flow (L/s)	Extraction flow (L/s)	Propane mass flow (mg/s)	Air mass flow (mg/s)	Specimen in the ladder
1 & 2	8000	1000	442	1550	No
3 & 4	8000		433	1500	No
5 & 6	7800		433	1500	No
7 & 8	8200		433	1500	No
9,10 &11	8200		433	1500	Yes ^a
12, 13 &14	8200		433	1500	Yes ^b

(a) AFUMEX CLASS 750V H07Z1-K (AS) 1x50mm² Cca s1b d1 a1

(b) AFUMEX CLASS 750V H07Z1-K (AS) 1X16mm² Cca s1b d1 a1

2.2 Temperature measurement layout

Gas-phase temperatures were measured in the region where the burner flame impinges on the cable ladder and along the lower part of the ladder, covering the first metre of the specimen. This region is particularly relevant for the EN 50399 test results and, consequently, for cable reaction-to-fire classification under the CPR. Temperatures were measured using Type K thermocouples connected to a data acquisition system, with an estimated measurement uncertainty of approximately $\pm 1\text{--}2\text{ }^{\circ}\text{C}$ associated with the instrumentation. In addition, bare thermocouples in fire environments may experience radiative heat losses from the junction to the surroundings, which can lead to a slight underestimation of the true gas temperature, particularly in the hottest regions near the burner. Local flame intermittency and occasional flame contact with the thermocouple junction may also increase the dispersion of instantaneous measurements.

Taking the burner height as the reference level, thermocouples were installed at vertical distances of 50, 150, 250, 350, 450, 550, 650, and 750 mm above the burner. At each height, five thermocouples were installed across the width of the cabinet: one located on the symmetry axis (array A3), two positioned on the left side (arrays A1 and A2), and two on the right side (arrays A4 and A5), as shown in Figure 1. This configuration allows the assessment of both vertical and lateral temperature gradients within the ladder region.

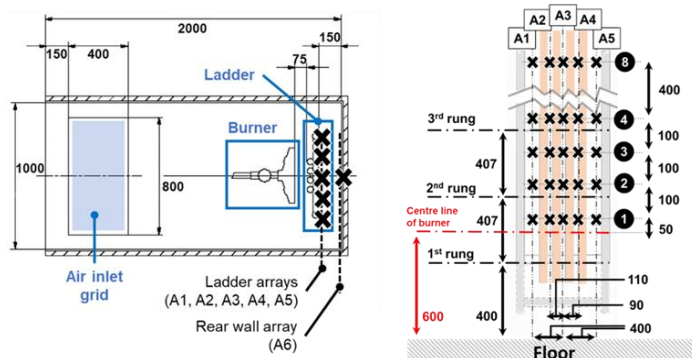


Figure 1: Location of thermocouple arrays within the EN 50399 test cabinet: (left) top view and (right) front view. Distances are in millimetres.

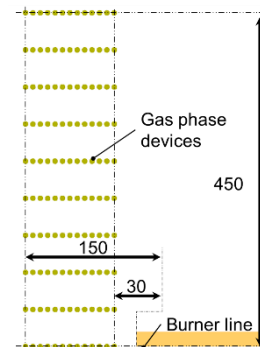


Figure 2: Location of gas phase in the model. Distances are in millimetres.

In addition, an extra vertical array of thermocouples (array A6) was installed near the rear wall, at a distance of 10 mm from the surface and aligned with the symmetry axis. This array consisted of eight thermocouples located at the same vertical heights as those used in the ladder arrays. The purpose of this additional array was to quantify the thermal exposure of the rear wall and to assess flame deflection effects in tests performed without cable specimens. The thermocouple locations implemented the experimental tests illustrated in Figures 1.

3 SIMULATION SET-UP

The numerical simulations were designed to reproduce the experimental conditions of the EN 50399 test cabinet as closely as possible and to analyse the influence of boundary conditions on the thermal environment in the region of the cable ladder, particularly within the burner influence zone.

All internal surfaces of the cabinet and ladder were modelled as non-combustible materials, consistent with the experimental setup. Boundary conditions corresponding to the EN 50399 reference configuration were implemented as a baseline. Specifically, the model was configured according to standard conditions: an inlet airflow of 8000 L/min, an exhaust flow rate of 1000 L/s, and a burner power of 20.5 kW, corresponding to propane and air mass flow rates of approximately 442 mg/s and 1550 mg/s, respectively. Selected modifications were introduced to reflect the experimental variations applied during the test campaign. A sensitivity analysis was conducted to evaluate the influence of mesh resolution on temperature predictions, considering cell sizes of 1 cm, 2 cm, and 4 cm. While no significant differences in temperature results were observed, a cell size of 2 cm was selected as it offered an optimal balance between computational efficiency and result accuracy. The simulations were performed using the Fire Dynamics Simulator (FDS) [15].

To enable comparison between experimental and numerical results, gas-phase temperature measurement devices were implemented in the numerical model along the symmetry axis of the cabinet, at locations corresponding to the thermocouple positions of array A3 described in Section 2 and shown in Figure 1. These devices allow the extraction of time-averaged temperatures at positions that are representative of the experimental measurements while avoiding lateral asymmetry effects.

In addition, the numerical model was instrumented with a denser set of gas-phase temperature devices to characterise the thermal field in the vicinity of the burner outlet. These devices were placed on a vertical plane located on the cabinet symmetry axis and perpendicular to the burner outlet. Measurement points were distributed at distances ranging from 30 to 150 mm from the burner exit with a spacing of 10 mm, and at vertical positions extending from the burner level up to 450 mm with a spacing of 50 mm, as illustrated in Figure 2. This extended instrumentation, which cannot be implemented experimentally with the same spatial resolution, was used to analyse the flame structure and temperature distribution resulting from different burner boundary condition configurations.

The numerical results were post-processed under steady-state conditions by time-averaging the gas-phase temperatures over selected intervals once transient effects had decayed. This approach ensured consistency with the experimental data processing and provided a reliable basis for comparison between simulations and measurements.

4. RESULTS

4.1 Experimental results

The experimental campaign included two groups of tests: tests conducted without cable specimens installed on the ladder (T1–T8), and tests conducted with cable specimens (T9–T14).

In the tests without cables, gas-phase temperatures were recorded for a minimum duration of 5 minutes after steady-state conditions were reached. In the tests with cable specimens, temperature measurements were recorded after flame extinction of the cables and continued for at least 3 minutes in order to minimise the contribution of additional heat release from the cable sheaths. For each test, time-averaged gas-phase temperatures were calculated for all thermocouple locations. The results obtained for tests without cable specimens (T1–T8) are shown in Figure 3, while the results for tests with cable specimens (T9–T14) are presented in Figure 4.

In the absence of cable specimens, temperature measurements at identical thermocouple locations remain within a narrow and comparable range, considering both variations in burner mixture conditions and the turbulent nature of the flame. Under these conditions, the flame extends towards the rear wall (array A6), where the highest temperatures are measured. Significant heating is observed at heights of 250 mm (367 °C), 350 mm (429 °C), and 450 mm (394 °C). In the ladder region, the highest temperatures are recorded in arrays A2–A4, particularly at heights of 50 mm (319–598 °C) and 150 mm (102–330 °C). At a height of 250 mm, a marked decrease in temperature is observed, with a maximum value of 148 °C.

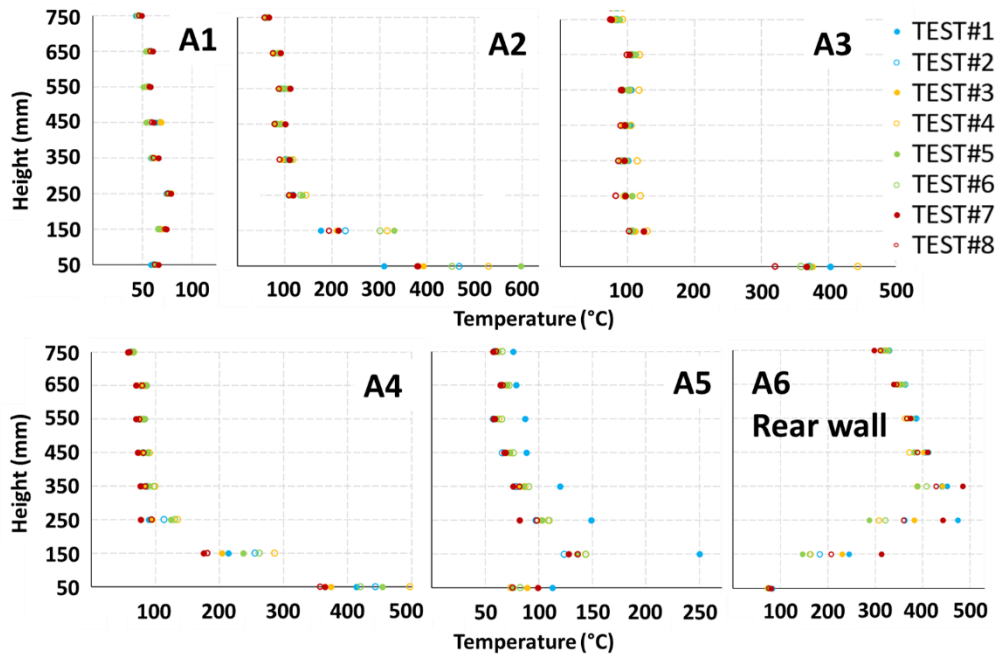


Figure 3. Time-averaged gas-phase temperatures measured in tests without specimens.

When cable specimens are installed on the ladder, the temperature distribution changes significantly. The region of highest temperatures shifts from the rear wall to the ladder zone, and the maximum temperatures measured near the rear wall decrease substantially. For example, at a height of 350 mm, the maximum temperature near the rear wall decreases from 429 °C in tests without cables to approximately 206 °C when cables are present. In contrast, the highest temperatures are observed within the ladder arrays, particularly in arrays A2, A3, and A4.

The temperature profiles indicate that the hottest region is located between 50 and 250 mm above the burner, with temperatures decreasing progressively at higher elevations. Measured temperatures in these arrays range from 221 °C to 967 °C at 50 mm, from 475 °C to 975 °C at 150 mm, and from 343 °C to 841 °C at 350 mm.

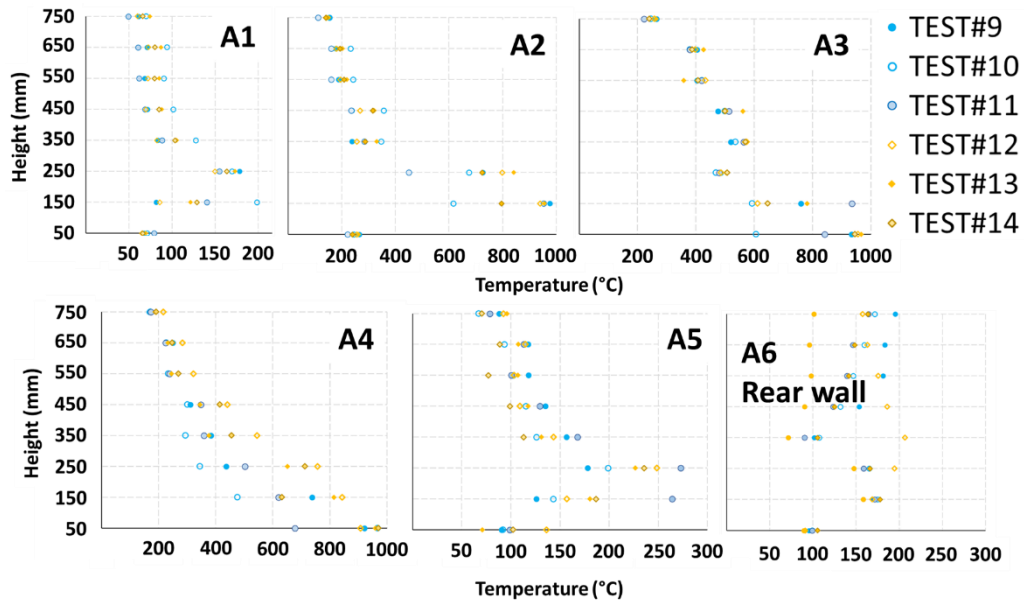


Figure 4. Time-averaged gas-phase temperatures measured in tests with specimens.

With cable specimens installed on the ladder, the temperature distribution shifts, relocating the zone of highest temperatures from the rear wall to the ladder region. For example, the maximum temperature measured near the rear wall at a height of 350 mm decreases from 429 °C in the absence of cables to approximately 206 °C at the same level. In contrast, the highest temperatures are observed in the ladder arrays, particularly in A2, A3, and A4. The temperature profiles of these arrays indicate that the hottest region is located between 50 and 250 mm, above which temperatures progressively decrease with height. Measured temperatures in these arrays range from 221 °C to 967 °C at 50 mm, from 475 °C to 975 °C at 150 mm, and from 343 °C to 841 °C at 350 mm. Although this spread represents a relatively wide temperature range, it reflects the fully turbulent nature of the flame and its interaction with the cable bundle, which makes it difficult to obtain a narrow temperature range or a single representative value. Nevertheless, the observed temperature patterns, including their spatial distribution and the locations of maximum temperatures, provide valuable reference information for validating the FDS model.

4.2 Simulation results

Although gas-phase temperatures were monitored at multiple locations in the numerical model (Figure 2), the evaluation of the simulations focused on a plane located between 70 and 75 mm from the burner outlet. This plane corresponds to the nominal distance between the burner outlet

and the cable bundle defined in EN 50399 (75 ± 5 mm), and therefore represents the most relevant region for comparison with experimental conditions.

Using burner dimensions consistent with the standard and adapted to the computational grid (220 mm wide $\times$ 20 mm high), a series of numerical cases was simulated to assess how different modelling strategies for the burner and its surrounding boundary conditions influence the resulting thermal field. All cases were defined to deliver a nominal heat release rate of 20.5 kW. The modification strategies were selected to reproduce the flame trajectory observed experimentally, in which the burner flame impinges on the cable bundle rather than developing freely toward the rear wall or remaining confined near the burner outlet. Three main approaches were considered: (i) geometric modifications of the burner outlet, including the addition of top and lateral plates; (ii) variations in the surrounding airflow through the introduction of air vents generating forced horizontal flow; and (iii) the application of prescribed velocity patches to modify flame deflection. The simulated cases and their corresponding configurations are summarised in Table 2.

For each case, time-averaged gas-phase temperatures were extracted under steady-state conditions on the selected measurement plane. The resulting temperature distributions are presented in Figure 5. Among all configurations, cases q3 and q7 yield the highest temperature levels, although they are obtained through different modification strategies. Case q3 produces the highest peak temperature, reaching values of approximately 1480 °C, with very high temperatures (>1000 °C) concentrated within the first 150 mm above the burner. In contrast, case q7 results in slightly lower peak temperatures (up to 1202 °C), but exhibits elevated temperatures over a broader region, with temperatures above 1000 °C extending up to approximately 300 mm.

Overall, the results indicate that similar peak temperature values can be achieved using different burner modelling strategies; however, the resulting thermal fields differ substantially in their spatial distribution. Geometry-based modifications (cases q1–q3) concentrate high temperatures in narrow regions close to the burner, while velocity-based approaches (cases q7–q9) yield more spatially distributed thermal fields despite comparable maximum temperatures. In contrast, cases involving air vents near the burner (cases q4–q6) do not reach comparable temperature levels.

Table 2: List of cases simulated.

Case	Modification
q1	No modifications, base case
q2	Top plate added in the burner
q3	Top and lateral plates added in the burner
q4	Propane/air mixture proportions in accordance with the standard.
q5	Top vent added to create 0,9 m/s horizontal flow.
q6	Vent added in the middle of the burner to create 0,3 m/s horizontal flow.
q7	Velocity patch of 0,4 m/s
q8	Velocity patch of 1,2 m/s
q9	Velocity patch of 2,0 m/s

Height	Geometry			Air vent			Velocity patch		
450 mm	460	529	186	74	293	490	643	232	98
400 mm	493	580	212	77	327	535	740	261	109
350 mm	543	660	268	83	395	611	914	328	132
300 mm	585	738	363	88	490	696	1066	433	166
250 mm	598	784	473	88	569	744	1134	531	193
200 mm	587	807	640	85	653	770	1169	651	234
150 mm	481	747	1016	77	756	715	1191	873	360
100 mm	347	592	1287	89	768	566	1202	1037	485
50 mm	135	223	1546	24	559	235	1076	1199	709
0 mm	51	69	1480	10	170	63	153	1034	1096
	q1	q2	q3	q4	q5	q6	q7	q8	q9

Figure 5. Time-averaged temperatures in steady-state.

5. DISCUSSION AND CONCLUSIONS

5.1 Experimental tests

The experimental results highlight the strong influence of physical obstructions on the thermal environment within the EN 50399 test cabinet. In tests performed without cable specimens, the flame develops freely from the burner and is primarily governed by burner momentum and buoyancy effects. Under these conditions, the flame is consistently deflected toward the rear wall, leading to elevated temperatures in array A6 and comparatively lower temperatures within the ladder region. Despite variations in burner mixture conditions, the overall spatial distribution of temperatures remains similar, indicating that the burner-induced flow structure is relatively stable in the absence of obstacles, even when considering the turbulent nature of the flame. When cable specimens are introduced, the thermal field changes substantially. The cable bundle acts as a physical obstruction that alters the flame trajectory and redistributes the heat release toward the ladder region. As a result, the highest temperatures shift from the rear wall to the ladder arrays, particularly arrays A2–A4, and the hottest region is consistently located within the first 250 mm above the burner. This behaviour confirms the critical role of the cable bundle in shaping the flame structure and determining the thermal exposure of the cables. These differences are illustrated in Figure 6, where the impact of cable presence on the temperature distribution along the ladder can be clearly observed.

Although the measured temperatures in the ladder region span a relatively wide range, this variability reflects the fully turbulent nature of the burner flame and its interaction with the cable bundle. In this case, the obstacles introduced by the cables play a major role in increasing flame variability. Furthermore, the use of two different cable types results in different gaps between cables, introducing an additional source of variability in flame behaviour. As a consequence, pronounced local fluctuations in flame position and heat release make it difficult to define a narrow temperature range or a single representative value at a given location.

Nevertheless, the experimental results exhibit consistent spatial trends across repeated tests, particularly with respect to the vertical extent of the hot zone and the locations of maximum temperatures. These spatial patterns were therefore used as the primary reference for the computational modelling. In this context, an FDS model that reproduces similar temperature

ranges and, more importantly, a comparable spatial distribution of the thermal field can be considered representative of the thermal action induced by the EN 50399 burner within the test cabinet.

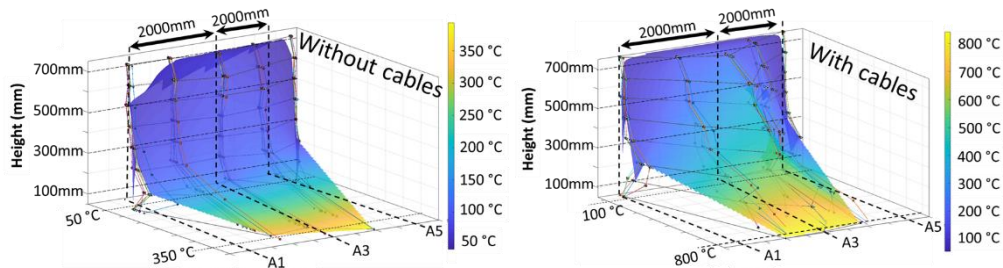


Figure 6: Three-dimensional distribution of time-averaged gas-phase temperatures measured in tests without cable specimens (left) and with cable specimens (right).

5.2 Experimental - numerical comparison

The numerical results confirm that reproducing the thermal environment of the EN 50399 test requires more than matching the nominal heat release rate of the burner. Although all simulated cases were defined to deliver a constant power of 20,5 kW, the experimental results show that the spatial distribution of temperatures and the flame impingement region are the key factors governing the thermal exposure of the cable ladder. Consequently, the numerical models were assessed primarily based on their ability to reproduce these experimentally observed spatial patterns.

Among the simulated cases, configurations q3 and q7 produce peak temperature levels comparable to those measured experimentally in the ladder region. However, the simulations tend to slightly overestimate temperatures in the lower zones. In numerical models despite using suitable cell size to represent the dimensions of the chamber, burner, ladder and cables, it seems to be difficult to model the cable bundle effect over the flame shape. Case q3, which relies on geometric confinement of the burner outlet, generates highly localised regions of very high temperature close to the burner, with steep thermal gradients. This behaviour differs from the experimental observations, where the hot zone extends over a broader region and the temperature field shows smoother spatial variations due to flame–obstacle interactions. Case q7, based on the introduction of a prescribed velocity field near the burner, produces a more distributed thermal footprint that better matches the experimental temperature patterns observed in the presence of cable specimens. However, the profile of temperatures is higher than the observed in the tests in larger heights up to 450 mm.

The comparison between experiments and simulations demonstrates that agreement in peak temperature values alone is insufficient for validating a numerical representation of the EN 50399 burner. Instead, the spatial distribution of the thermal field and the location of flame impingement zones must be considered as primary validation criteria. From this perspective, both models q3 and q7 tend to overestimate temperatures relative to the experimental measurements; however, they differ markedly in how this overheating is distributed along the cable ladder.

In the case of model q7, elevated temperatures extend over a large vertical region, from 50 mm up to 450 mm, resulting in a broader and more intense thermal exposure of the cable specimens. By contrast, model q3 concentrates the overestimation primarily in the lower region, around 50 mm above the burner, while showing a closer agreement with the experimental temperature range between 150 mm and 250 mm, and slightly lower temperatures between 250 mm and 450 mm. This behaviour is more consistent with the experimentally observed temperature profiles along the ladder. These results indicate that, although both q3 and q7 reproduce the nominal burner power of 20,5 kW, the resulting temperature maps over the cable specimens differ significantly. When the spatial distribution of temperatures is taken into account, model q3 provides a closer representation of the experimental thermal exposure than model q7.

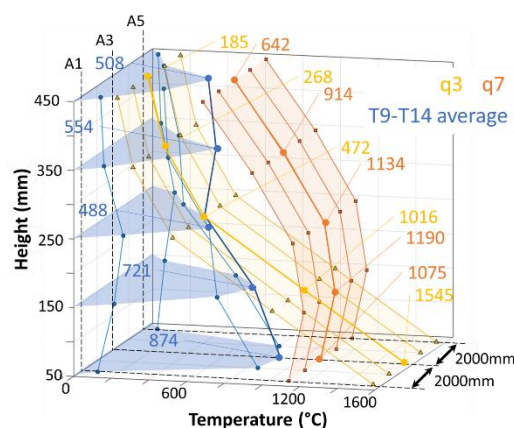


Figure 7: Three-dimensional distribution of time-averaged gas-phase temperatures measured in tests with cable specimens (blue) and predicted by numerical models q3 (yellow) and q7 (orange). Numerical values indicate time-averaged gas-phase temperatures measured along array A3.

Although this study was conducted using a specific EN 50399 apparatus, the main findings are expected to be applicable to other laboratories operating under the same standard configuration. Since the EN 50399 test prescribes cabinet geometry, burner power, and ventilation conditions, the observed influence of burner boundary conditions on flame trajectory and spatial temperature distribution should be generally representative.

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**ARGAMASSAS MISTAS COM SUBSTITUIÇÃO DA CAL HIDRATADA POR
ESCÓRIA DE FORNO PANELA SUBMETIDAS A TEMPERATURAS
ELEVADAS: PROPRIEDADES MECÂNICAS RESIDUAIS**

Tayná Silva

Doutoranda
UNICAMP -
Campinas
Brasil

Everton Souza

Doutorando
UNICAMP -
Campinas
Brasil

Eduardo Mariano

Doutorando
UNICAMP -
Campinas
Brasil

Gisleiva Ferreira*

Professor
UNICAMP -
Campinas
Brasil

Armando Moreno Jr.

Professor
UNICAMP -
Campinas
Brasil

Mylene Castro

Graduanda
UNICAMP -
Campinas
Brasil

Marcele Soares

Engenheira Civil
UNICAMP -
Campinas
Brasil

Palavras-chave: Resistência à compressão, módulo de elasticidade, resíduo industrial.

* Autor correspondente — MATS, Faculdade de Engenharia Civil, Arquitetura e Urbanismo, Universidade Estadual de Campinas, 13083-889 Campinas, Brazil,
E-mail: gisleiva@unicamp.br

1. INTRODUÇÃO

A construção civil é um dos principais setores econômicos e, consequentemente, exerce influência significativa tanto na economia quanto na sociedade. No entanto, também está associada a impactos ambientais relevantes com o consumo de recursos naturais e geração de altos volumes de resíduos [1]. Em escala global, o setor pode ser responsável por cerca de 40% das emissões de gases de efeito estufa (GEE) e por 30% dos fluxos de resíduos gerados [2,3]. Nesse contexto, a busca pela economia circular na construção civil assume papel central na sociedade contemporânea, visando mitigar os impactos ambientais, sociais e econômicos relacionados ao ambiente construído [1].

Nesse cenário, uma alternativa para reduzir os impactos ambientais é incentivar o uso de resíduos provenientes da própria construção civil ou de outros setores produtivos [4]. Inserido na mesma problemática está o setor siderúrgico, também buscando alternativas de uso dos resíduos sólidos gerados em suas atividades fim (produção de ligas metálicas) [5]. Dentre os resíduos gerados por esse setor, destaca-se a Escória de Forno Panela (EFP), cuja produção mundial é estimada em cerca de 30 milhões de toneladas por ano [6]. A EFP tem origem nos fornos de aciaria, utilizados no processo secundário de refino do aço [6,7]. De modo geral, a EFP é composta principalmente por óxidos de cálcio (CaO) e hidróxidos de cálcio (Ca(OH)_2), apresentando ainda teores menores de óxidos de alumínio, silício e ferro. Essa composição evidencia o potencial da EFP como material cimentício suplementar (MCS), a depender da proporção desses óxidos, além da finura e reatividade química de cada lote [8–10].

Diversos estudos têm investigado a incorporação da EFP em concretos e argamassas [11–13]. Em relação ao uso da EFP como MCS em argamassas cimentícias, houve um aumento significativo dos estudos, motivado pela elevada demanda global por esse tipo de material, aliada à escassez e baixa qualidade de algumas matérias-primas convencionais. Além das argamassas cimentícias, tem-se também as argamassas mistas, compostas por cimento Portland (CP) e cal hidratada (CH), em que adiciona-se a CH para melhorar a fluidez e retenção de água no estado fresco e reduzir o módulo de elasticidade e a retração no estado endurecido [14]. Neste sentido, alinhar o uso da EFP em substituição à CH na produção de argamassas mostra-se uma alternativa tecnicamente promissora e ambientalmente favorável e também apresenta a vantagem de geralmente não desempenhar funções estruturais nas edificações, o que evita eventuais problemas com a redução das propriedades mecânicas.

Entretanto, apesar dos resultados promissores em relação às propriedades no estado fresco e endurecido, há a necessidade de obter parâmetros de desempenho e durabilidade destas argamassas com EFP. Em relação ao desempenho, destaca-se a segurança estrutural, por exemplo, em situações de incêndio, considerando que as argamassas exercem funções de estanqueidade e proteção de elementos estruturais de uma edificação [15]. Neste contexto, é importante realizar estudos para a caracterização mecânica das argamassas com EFP, cujos resultados poderão ser utilizados nas fases de projeto, execução e recuperação de uma edificação exposta às condições de incêndio, que tenham sido concebidas com esse tipo de argamassa.

Diante desta lacuna de conhecimento, o objetivo desse estudo foi determinar as propriedades mecânicas residuais de argamassas mistas com substituição total da CH por EFP, conforme exposição a altas temperaturas. Adicionalmente, tem-se o objetivo secundário de obter o comportamento mecânico destas argamassas com adição de uma pozolana (metacaulim - MK), haja vista a necessidade de combinações terciárias de aglomerantes (CP+EFP+MK). Isso se faz necessário devido à baixa reatividade de lotes de EFP que foram gerados com resfriamento lento [16]. Essa abordagem é promissora devido ao elevado teor de CaO e Ca(OH)_2 presente na EFP, que, em interação com pozolanas ricas em óxidos de silício e alumínio, favorece a formação de silicatos de cálcio hidratado (C-S-H), melhorando o desempenho da argamassa [17,18]. As propriedades mecânicas investigadas foram a resistência à tração na flexão (R_t), resistência à compressão (R_c) e módulo de elasticidade dinâmico (E_d).

2. MATERIAS E MÉTODOS

Os materiais utilizados nesta pesquisa foram: Cimento Portland (CP), Cal Hidratada (CH), Metacaulim (MK), Escória de Forno Panela (EFP), Areia Quartzosa (AQ) e Água. A amostra de EFP foi fornecida por empresa do setor siderúrgico, obtida pelo método de resfriamento lento, o que resulta em baixa reatividade. O material bruto foi submetido a um pré-processamento, que consistiu em secagem em estufa a 105°C por 24 h, peneiramento prévio para separação de restos de metais (peneira com abertura 0,6 mm) e moagem em moinho de bolas com ciclo de 10 min e velocidade de 200 RPM. Os valores de massas específicas dos materiais utilizados nas argamassas foram: CP: 3,01g/cm³, CH: 2,50g/cm³, MK: 2,73g/cm³, EFP: 2,75g/cm³ e AQ: 2,65g/cm³. As curvas granulométricas dos aglomerantes estão representadas na Figura 1.

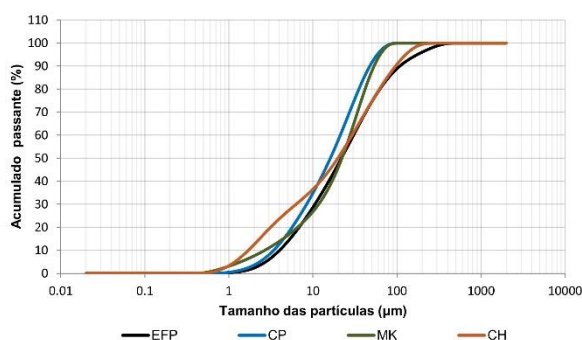


Figura 1: Curvas granulométricas dos aglomerantes utilizados nas argamassas

Para caracterização química dos materiais, realizou-se os ensaios de Fluorescência de Raios X (FRX) e Perda ao Fogo (PF), cujos resultados estão apresentados na Tabela 1. Já a Figura 2 apresenta o difratograma da amostra de EFP, obtido a partir da análise de Difração de Raios X (DRX).

Tabela 1: Composição química dos aglomerantes utilizados nas argamassas

Material	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	MnO	PF (%)
EFP	9.78	0.80	7.59	54.60	5.79	0.60	7.29	12.0
CP	15.30	3.62	2.32	57.5	4.28	2.65	<0.10	12.5
CH	1.01	0.15	0.25	38.7	27.3	0.04	0.03	32.4
MK	69.2	24.1	2.02	<0.10	0.23	<0.10	<0.10	1.18

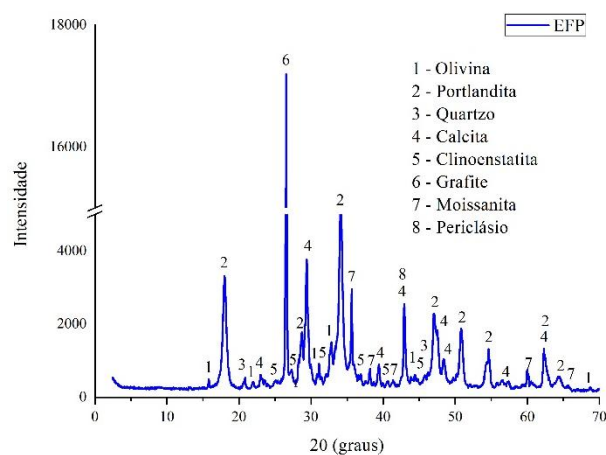


Figura 2: Difratograma da amostra de EFP

A Tabela 2 descreve as proporções dos materiais utilizados nas 4 argamassas desse estudo, sendo 1:0.5:3 (CP:CH:AQ). As argamassas EFP e EFP-MK foram compostas por EFP em substituição à 100% da CH. Já as argamassas REF-MK e EFP-MK receberam o MK em substituição à 10% do CP. A relação água/aglomerante foi definida conforme NBR 13276 [19], para uma trabalhabilidade de 260 ± 5 mm.

Tabela 2: Composição dos traços de argamassas, em volume

Identificação	Aglomerante				AQ	Água/aglomerante
	CP	EFP	CH	MK		
REF	1	0	0.5	0	3	0.78
REF-MK	0.9	0	0.5	0.1	3	0.78
EFP	1	0.5	0	0	3	0.75
EFP-MK	0.9	0.5	0	0.1	3	0.75

Os ensaios foram realizados em corpos de prova prismáticos (40 mm x 40 mm x 160 mm), conforme NBR 13279 [20]. Após um período de cura mínimo de 90 dias, os corpos de prova foram expostos às temperaturas de 200°C, 400°C e 600°C, nas quais foram mantidos durante 60 min, para promover o aquecimento de forma homogêneo nos corpos de prova. Foi utilizada uma taxa de aquecimento e resfriamento de 4°C/min, com um forno elétrico instalado no Laboratório de Estruturas da FECFAU (UNICAMP, Brasil). Foram moldados e ensaiados 96 corpos de prova, sendo 6 repetições para cada temperatura.

Antes dos ensaios destrutivos (resistência à tração na flexão (R_t) e resistência à compressão (R_c), conforme NBR 13279 [20], realizou-se os ensaios de ultrassom para determinar o módulo de elasticidade dinâmico (E_d), conforme NBR 15630 [21], utilizando transdutores de faces planas de 45 kHz de frequência. Para obter os valores residuais (relativos) das propriedades mecânicas, também realizou-se os mesmos ensaios em corpos de prova de argamassa em temperatura ambiente ($\pm 20^\circ\text{C}$).

3. RESULTADOS E DISCUSSÕES

3.1 Resistência à tração

A Figura 3 ilustra as resistências à tração nominal e residual das argamassas em temperaturas elevadas de 200°C , 400°C e 600°C , juntamente com a resistência à tração obtida à temperatura ambiente ($\pm 20^\circ\text{C}$). Ao analisar os resultados em temperatura ambiente, aos 90 dias de cura, as argamassas apresentaram valores entre 1.50 a 2.70MPa, sendo que as misturas com EFP, apresentaram valores abaixo que os do traço referência, e isto pode ser atribuído à coesão entre os materiais, que podem ter influenciado à zona de transição entre a pasta e o agregado.

Aos 200°C , a argamassa REF apresentou perda de R_t , enquanto as demais misturas apresentaram ganho de tal propriedade, o que pode ser atribuído à liberação da água livre no corpo de prova da argamassa e a desidratação e endurecimento do gel C-S-H, que aumentaram a R_t das argamassas [22]. Além de que o MK proporcionou à formação de novos produtos de hidratação em razão das reações pozolânicas entre os materiais [23]. Já aos 400°C a argamassa EFP-MK foi a única que apresentou ganho de R_t , evidenciando que as reações de hidratação entre a EFP e MK foram mais estáveis em elevadas temperaturas, preservando a estrutura dos produtos hidratados [23]. Por fim, aos 600°C todas as argamassas apresentaram redução significativa da R_t .

A Figura 3b, apresentam os valores residuais da R_t . O comportamento da argamassa EFP foi similar à REF, sendo possível afirmar que a substituição de EFP por CH, mantém esta propriedade a altas temperaturas. Entretanto, a mistura EFP-MK, foi superior a todas as misturas analisadas e manteve o comportamento similar a temperatura ambiente até os 400°C , o que pode ser justificado pela maior coesão da matriz e sua resistência à propagação de microfissuras sob tensão de flexão [24].

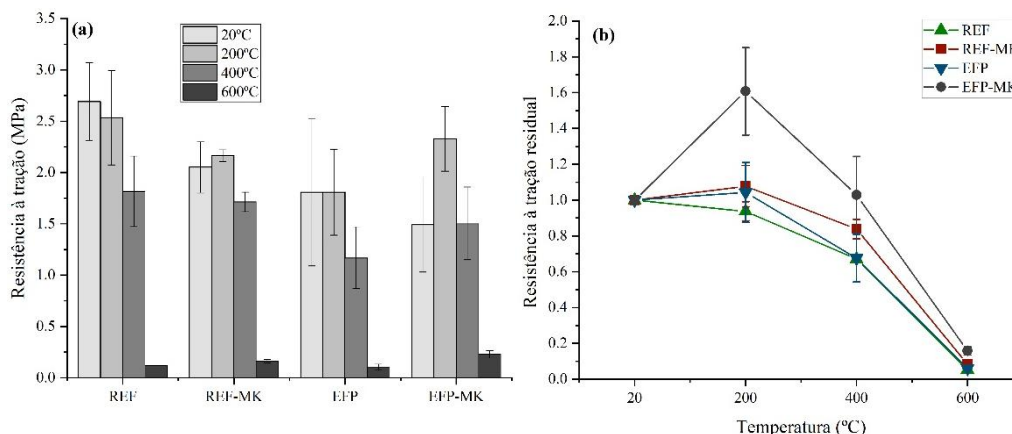


Figura 3: Resistência à tração das argamassas (a) nominal e (b) residual

3.2 Resistência à compressão

Os resultados de resistência à compressão e resistência à compressão residual estão apresentadas na Figura 4. Aos 20°C, as argamassas com EFP, apresentaram valores superiores as argamassas com CH, e isto pode ser atribuído ao maior teor de CaO, SiO₂, Al₂O₃ e Fe₂O₃ presentes na EFP, que proporcionaram formação adicional de C-S-H [25].

Em relação as temperaturas elevadas, todas as combinações de argamassas apresentaram perda de resistência à compressão a medida que as temperaturas aumentaram, em razão da desidratação dos produtos de hidratação, que ocorre devido à perda de umidade da pasta de cimento como resultado do aquecimento. Observa-se também que, com o aumento da temperatura, a variação na perda de Rc entre as misturas diminuiu: aos 200 °C essa variação foi de 21%, enquanto que aos 600 °C reduziu-se para apenas 7%.

As argamassas com EFP, apresentaram redução mais acentuada de Rc em relação à argamassa com CH, o que é atribuído a dissociação do Ca(OH)₂ em CaO, que é um dos principais produtos de hidratação [26], que causa retração na matriz. Após o resfriamento, o CaO é convertido novamente em Ca(OH)₂ e causa um aumento de volume. Essas repetidas mudanças de volume causam deterioração e fissuras na matriz de cimento, que contribuíram para a maior perda de Rc [27]. Porém, com a combinação da EFP+MK, a redução da Rc foi menor, em razão das reações pozolânicas responsáveis por diminuir o teor da portlandita (Ca(OH)₂), através da formação do C-S-H. Esta melhora no desempenho pode ser observado na Figura 4b, que apresenta os valores de Rc residuais das argamassas. A incorporação conjunta de EFP e MK resultou em um comportamento semelhante à mistura REF, nas misturas analisadas.

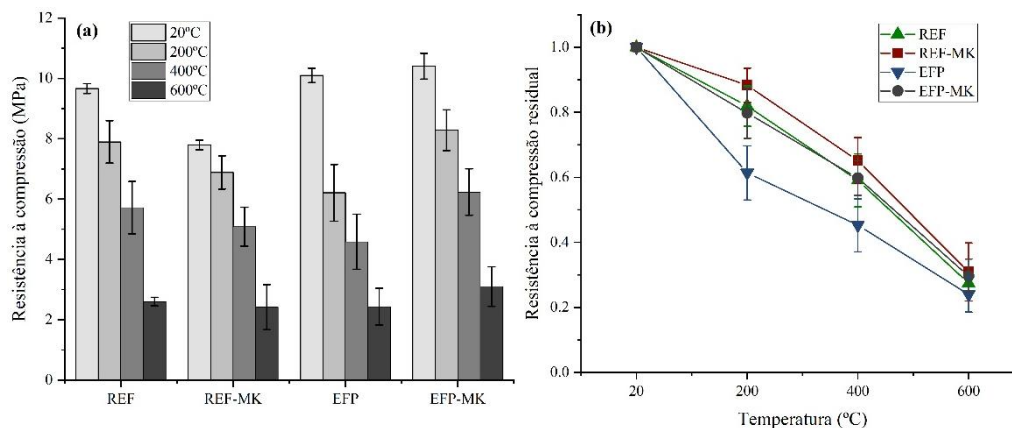


Figura 4: Resistência à compressão das argamassas (a) nominal e (b) residual.

3.3 Módulo de elasticidade dinâmico

A Figura 5 apresenta os resultados de módulo de elasticidade (E_d) nominal e residual das argamassas, aos 20°C, 200°C, 400°C e 600°C. Ao analisar os valores nominais de E_d , verifica-se que as argamassas apresentaram comportamentos similares, com redução proporcional ao aumento da temperatura. Vale destacar que a presença da EFP não prejudicou tal propriedade das argamassas com EFP, apresentando melhores resultados nas temperaturas mais críticas (400°C e 600°C), quando comparadas às argamassas com CH. Além disso, a presença do MK não melhorou o desempenho das argamassas em relação altas temperaturas.

Já em relação aos valores residuais de E_d , parâmetro mais importante para analisar as propriedades mecânicas de materiais cimentícios expostos a altas temperaturas, verifica-se que não foi possível diferenciar o comportamento das argamassas, considerando a presença ou não da EFP e MK. Isso pode ser atribuído à sensibilidade que o pulso ultrassônico apresenta ao percorrer material com microfissuração, proveniente tanto pela retração por secagem durante a cura como durante a evaporação da água livre (aumento dos poros abertos e microfissuras devido tensões internas) e alterações nos compostos químicos oriundos da hidratação dos aglomerantes [28,29]. Conforme conceitos relacionados às ondas ultrassônicas, a VPU é menor em materiais secos e não homogêneos [30]. Vale ressaltar que não são esperadas alterações químicas significativas na areia quartzosa presente nas argamassas até a temperatura de 600°C.

Assim, como na R_t e R_c a incorporação de EFP+MK possibilitou a maior preservação do E_d , indicando maior estabilidade térmica em relação às outras misturas. Os resultados da medição pela técnica de ultrassom, pode ser um indicador valioso de danos às argamassas induzidos pelas altas temperaturas e permitem obter dados sobre a elasticidade do material [31], especialmente quando não é possível obter pelo ensaio destrutivo.

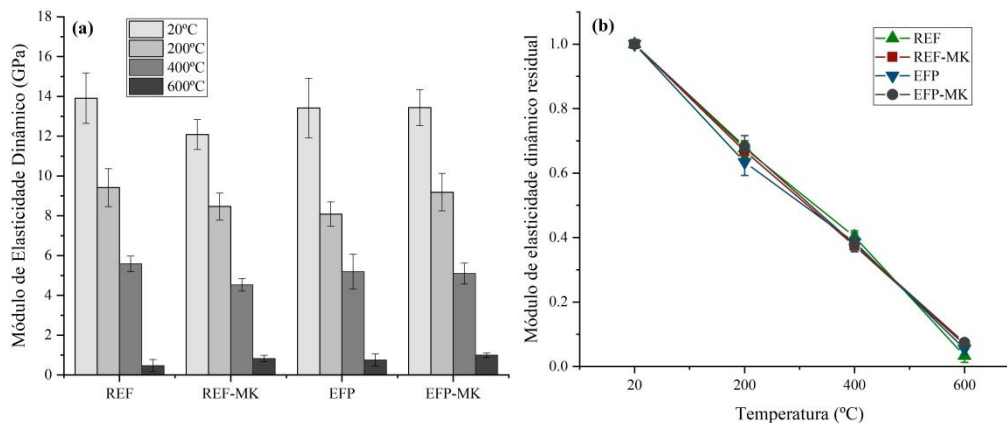


Figura 5: Módulo de elasticidade dinâmico das argamassas: (a) nominal e (b) residual.

5. CONCLUSÕES

Este estudo avaliou o desempenho de misturas de argamassas com substituição total (100%) da CH por EFP e substituição parcial do CP (10%) por MK, analisando suas propriedades mecânicas residuais expostas a elevadas temperaturas. Os principais resultados obtidos foram:

O uso de MK nas argamassas (CH ou EFP) melhoraram as propriedades mecânicas residuais em elevadas temperaturas, e isto é justificado, pela menor quantidade de Ca(OH)_2 nestas misturas em virtude das reações pozolânicas. A dissociação em CaO e conversão novamente em Ca(OH)_2 , causam variação volumétrica e, conseqüentemente, maior deterioração da matriz.

A incorporação de EFP proporcionou resultados semelhantes aos da mistura REF, para a Rt e Ed. No entanto, a Rc diminuiu, e isto foi atribuído ao maior teor de CaO da EFP em relação à CH, que contribuiu para a maior formação de Ca(OH)_2 ;

A combinação de EFP+MK obteve os melhores resultados entre as misturas analisadas, em elevadas temperaturas, sendo responsável pela maior preservação das propriedades mecânicas residuais (Rt, Rc e Ed) com o aumento das temperaturas. Isto pode ser explicado pela maior formação de C-S-H, além do efeito filler proporcionado pela presença da EFP.

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SCALING-UP VENTILATION CONDITIONS INFLUENCE ON POOL FIRE COMBUSTION

María González Alvear*		David Lázaro		Mariano Lázaro
CIF Cantabria -		Universidad de		Universidad de
Torrelavega		Cantabria -		Cantabria -
España		Santander		Santander
Eugenia Morgado		España		España
Consejo de		Miguel Ángel		Daniel Alvear
Seguridad Nuclear,		Jiménez		Universidad de
Spain.		Consejo de		Cantabria, Spain.
		Seguridad Nuclear,		
		Spain.		

Key words: Underventilated combustion, vitiated atmospheres, FPA, RCT.

ABSTRACT

This work presents an experimental study of heptane pool fires under different ventilation conditions to evaluate whether the Global Equivalence Ratio (GER) is a useful parameter to characterise the effect of ventilation on fire behaviour at different scales. Tests were carried out at three scales: bench scale using a Fire Propagation Apparatus (FPA), a medium-scale compartment, and a full-scale Room Corner Test (RCT). In the FPA, the influence of oxygen concentration and external heat flux was studied. In the compartment tests, ventilation was varied by changing the door opening height. The FPA results show that applying external heat flux increases the Mass Loss Rate (MLR), while reducing the oxygen concentration lowers the peak MLR and makes the fire last longer. Poor ventilation led to under-ventilated regimes and, in some cases, extinction, whereas better ventilation produced higher and more stable burning rates. Similar trends were observed at all scales. Although the results indicate that GER is a useful parameter to relate oxygen availability and combustion conditions in heptane pool fires, not a direct extrapolation was found between FPA campaign and compartments fires performed at medium and full-scale.

1. INTRODUCTION

Understanding of the combustion processes under vitiated atmospheres, where the oxygen available for combustion is significantly reduced due to limited ventilation, remains a key challenge in fire science. This difficulty comes from multiple phenomena coupling, including heat

* Autor correspondiente — CIF Cantabria, Clúster del Comportamiento e Investigación del Fuego de Cantabria. Ave. Del Niño nº 4, 39005 Santander (Spain).
Telef.: +34 942 201826, Fax: +34 942 202276, E-mail: maria.gonzalez@cifcantabria.com

transfer, pyrolysis, mass flow, turbulence and combustion processes, as well as the practical challenges of reproducing these conditions at a large scale [1]. Within this context, the calculation of the Global Equivalence Ratio (GER) may provide a quantitative metric for characterizing ventilation-controlled combustion [2] enabling systematic analysis of how oxygen limitation can affect fire behaviour and combustion efficiency.

The transition from fuel-controlled to ventilation-controlled regimes is driven by changes in local oxygen concentration, which affects heat release rate (HRR), flame temperature, soot generation, and radiant fraction [3]. Prior research has demonstrated that oxygen depletion reduces combustion completeness, increases incomplete combustion products (CO, soot), and decreases radiative power distribution while altering flame geometry. Critically, accurate determination of HRR in vitiated atmospheres requires careful accounting of soot generation, as incomplete combustion yields significant carbon conversion to particulate form rather than CO₂.

The fundamental mechanisms governing combustion under ventilation control have been extensively studied by Tewarson et al. [2], who demonstrated that the transition to ventilation-limited regimes exhibits consistent, predictable dependencies on stoichiometric balance. Using the Global Equivalence Ratio (GER) as the controlling parameter, Tewarson showed that combustion efficiency, flame characteristics, and mass loss rate follow systematic functions of oxygen availability across different polymer types (including cellulose, polystyrene, polyester, and polyurethane). Their seminal work established that mass loss rate in under-ventilated conditions scales with the ratio of available oxygen to stoichiometric requirement, enabling prediction of HRR reduction factors as oxygen concentration falls below ambient levels. Tewarson's methodology provides the theoretical framework for interpreting how GER governs not only the intensity of combustion but also the composition of effluents, including yields of CO, soot, and other incomplete combustion products, making GER a robust parameter for correlating combustion behavior across different material types and fire scales.

According to this framework, it is necessary to assess if GER retains its predictive capability across experimental scales and compartment geometries. In particular, it remains unclear whether the GER can consistently represent the relationship between oxygen availability and burning rate under vitiated conditions. This study presents a detailed experimental analysis of the combustion of a heptane pool fire under vitiated atmospheric conditions. The experimental tests were carried out using different scale tests, like Fire Propagation Apparatus (FPA), reduced-scale room configuration and Room Corner Test (RCT) [4] [5]. To address this, the study compares the evolution of the GER and the mass loss rate (MLR) obtained at each of the three experimental scales. This makes possible to evaluate whether GER behaves consistently as the scale increases. This supports the use of this parameter as a more robust metric for interpreting the influence of ventilation on fire behaviour in compartment scenarios.

2. METHODS

Heptane one of the most widely used fuels in fire safety research [6], was selected for the experimental campaign due to its well-characterized and reproducible behaviour.

In order to assess the scaling effect of the experimental test campaign in the fire behaviour of liquid combustibles, the experimental campaign was structured into three sub-campaigns, conducted at bench, medium and large scale. In all sub-campaign the influence of a vitiated environment on burning rates is investigated. The bench-scale tests were carried out in the FPA (Figure 1), the medium-scale (Figure 2) experiments were performed in a custom-built setup and the large-scale experiments in a RCT (Figure 3). Repeatability test have been performed in all scales.



Figure 1: Fire propagation apparatus.



Figure 2: Medium-scale apparatus.



Figure 3: Room corner test.

The first sub-campaign, performed in the FPA, aimed to analyse the influence of O_2 concentration and of the external heat flux in the combustion [7]. FPA is a bench-scale testing device designed to quantify fire behaviour of materials under well-controlled conditions, this apparatus consists of a sample holder placed below an electrically heated radiant panel that supplies a controlled heat flux, while the surrounding atmosphere can be conditioned in terms of oxygen concentration and flow rate. The FPA allows precise control of key parameters, such as the inlet gas flow rate (set at 200 L/min in this test), the O_2 and the measurement of the MLR, which are the three main parameters used to estimate the GER. During the experimental campaign in the FPA, the influence of oxygen concentration on the combustion of a heptane pool fire was studied. The FPA tests were conducted at concentrations of 21 %, 18 % and 15 % as is summarized in Table 1.

Table 1: FPA experimental tests.

Case	Atmosphere	Incident heat flux [IHF] (kW/m ²)
FPA_Hep-1	Aire	0
FPA_Hep-2	18 % O_2	0
FPA_Hep-3	15 % O_2	0
FPA_Hep-4	Aire	15
FPA_Hep-5	18 % O_2	15
FPA_Hep-6	15 % O_2	15

The second experimental campaign was conducted at medium scale, in a compartment with a volume of 0.125 m³, designed to reproduce more realistic fire conditions. These tests aimed to study the influence of a vitiated environment on a heptane pool fire of 0.01 m². To do this, the door openings were modified to consider three scenarios with different ventilation factor, with the

opening height of 0.05 m, 0.1 m and 0.25 m. For each configuration, the MLR was measured and the GER calculated.

Table 2: Medium scale compartment experimental tests.

Case	$\dot{Q}$ (kW)	A_0 (m ²)	H_0 (m)
ME_Hep-1	5.26	0.0075	0.05
ME_Hep-2	5.26	0.0150	0.10
ME_Hep-3	5.26	0.0375	0.25

Finally, it was conducted an experimental campaign in the RCT set up. The enclosure consists of a single compartment with dimensions of $3.6m \times 2.4m \times 2.4m$, and the door width is 0.8 m for all the cases. The walls are insulated using a multilayer system composed of a fire-resistant gypsum board, a layer of rock wool and an inner layer of promatec, in order to ensure adequate thermal insulation and structural protection during the experimental campaign [7]. As in the medium scale tests, the door opening height was modified. There were considered three different heights: 0.1 m for restricted ventilation, 0.8 m for moderate ventilation and 2 m for maximum ventilation. The RCT compartment configuration is described in Table 3. For each configuration, the MLR was measured and the GER calculated. The heptane tray employed in the tests had an area of 0.125 m².

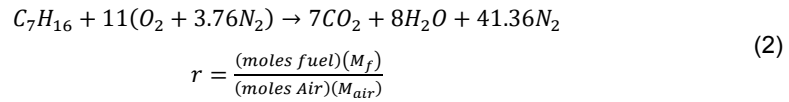
Table 3: RCT compartment experimental tests.

Scenario	$\dot{Q}$ (kW)	A_0 (m ²)	H_0 (m)	Pool fire size
T1-1	200	0.08	0.1	A3
T1-2	200	0.64	0.8	A3
T1-3	200	1.6	2	A3

In fire science, it is widely used the equivalence ratio in order to analyse combustion reactions. This parameter defines the ratio of the fuel mass flow rate to the air mass flow rate divided by the same ratio at the stoichiometry of the reaction considered.

$$\phi = \frac{[\dot{m}_f/\dot{m}_a]}{[\dot{m}_f/\dot{m}_a]_{st}} = \frac{[\dot{m}_f/\dot{m}_a]}{r} \quad (1)$$

This equation is valid to analyse gas combustion conditions where fuel inflow ($\dot{m}_f$) and air inflow ($\dot{m}_a$) can be adjusted, being r the stoichiometric fuel-air-ratio. To calculate r we need to define theoretical perfect reaction of the fuel with oxygen. Then, we define the stoichiometric combustion and calculate the stoichiometric moles of O₂ per moles of heptane consumed.



Nevertheless, this approach is not easily applicable in fire safety engineering where the complexity of scenarios disables an accurate quantification of the air mass flow contributing to the combustion and neither the fuel mass flow. As a consequence, fire science has been using some analogous expressions for equivalence ratio to consider the global conditions of the fire scenarios. In ventilated compartments, GER can be defined with the previous equation

considering $\dot{m}_f$ as the instantaneous fuel mass loss rate, and $\dot{m}_a$ as the total air flow rate into the compartment. In naturally ventilated compartment fires, it is not really hard to directly impose and measure the air flow, but estimations can be made based on well-known equations [7]:

$$\dot{m}_a = \frac{1}{2} A_0 \sqrt{H_0} \quad (3)$$

Where A_0 is the area of the opening (m^2) and H_0 the height of the opening (m). In compartment fires, oxygen concentration in the combustion atmosphere is not necessarily constant. Therefore, in GER calculation associated with compartments fires [7], the oxygen concentration in the inlet should be considered (γ_{O_2}), and the stoichiometric fuel-oxygen ratio (r_o):

$$\begin{cases} \phi = \frac{\dot{m}_f}{\dot{m}_a \gamma_{O_2} r_o} & \text{mechanical ventilated} \\ \phi = \frac{\dot{m}_f}{\frac{1}{2} A_0 \sqrt{H_0} \gamma_{O_2} r_o} & \text{natural ventilated} \end{cases} \quad (4)$$

If $\phi < 1$ the compartment is considered “well-ventilated”, as there is an excess of oxygen available for combustion and all gases released from the fuel pyrolysis have available oxygen atoms for combustion. On the other hand, if $\phi > 1$, the compartment is considered “under-ventilated”, since there is not enough oxygen for the combustion of all pyrolysis fuel gases, and unburned gases are being releasing.

Table 4 summarizes the theoretical GER calculated for the tests at different scales, based on the formulations described.

Table 4: Comparison of the theoretical GER calculated at different scales

FPA tests	Theoretical GER	Medium scale tests	Theoretical GER	RCT tests	Theoretical GER
FPA_Hep-1,4	0.397	ME_Hep-1	2.035	T1-1	5.130
FPA_Hep-2,5	0.46	ME_Hep-2	0.719	T1-2	0.227
FPA_Hep-3,6	0.550	ME_Hep-3	0.182	T1-3	0.057

3. RESULTS

This section is organized as follows, first FPA results are presented, then medium and large scale compartment tests.

The mass signal recorded by the FPA load cell exhibited high-frequency noise and was therefore not used directly to determine the mass loss rate (MLR). Instead, mass and MLR were estimated from the heat released during combustion using the procedure proposed by Lázaro [8]. Figure 4 and Figure 5 compare the raw MLR obtained. For the tests performed without external heat flux (Figure 4), the MLR inceases gradually and combustion lasts longer. The highest peak is observed in air, while reucing oxygen decreases the peak and spreads the combustion over a longer period. When an external heat flux is applied (Figure 5), burning becomes faster and more intense, as reflected by higher MLR peaks and shorter burning durations. In this tests, it can be observed that decreasing the oxygen concentration does not modify the MLR peak, but it affects the duration of the combustion process.

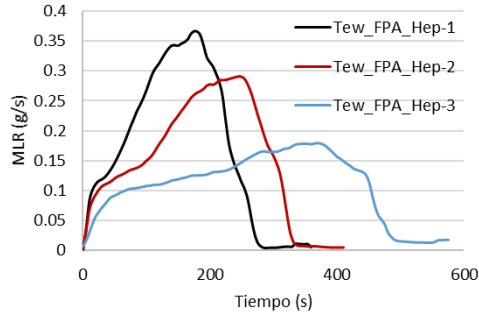


Figure 4: MLR obtained in the FPA_Hep 1,2 and 3 tests.

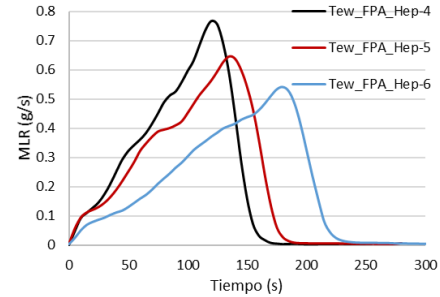


Figure 5: MLR obtained in the FPA_Hep 4,5 and 6 tests.

In the FPA tests, the GER curves shown in Figure 6 and Figure 7 indicate that in the absence of incident heat flux, the parameter remains relatively stable during the steady combustion phase. In contrast, when an incident flux is applied, combustion efficiency decreases and the GER reaches values around 3.

Figure 6 and Figure 7 show the Global Equivalence Ratio (GER) evolution. In the absence of external heat flux, GER curves exhibit clear differences in both transient evolution and peak levels, indicating that oxygen availability influences the combustion. The GER values are around 1.4 and 1.3 for the tests performed in air and with 18% oxygen, respectively, while in the 15% oxygen test, the GER reaches a maximum of 1 and the test duration is significantly longer than in the other configurations. In contrast, when an external heat flux is applied, the GER rises higher values, approximately twice those observed in the no flux tests. Furthermore, variations in the oxygen concentration do not produce significant changes in the evolution of the GER, which is mainly attributed to the ingress of air into the system, since the tests are not performed in a fully enclosed compartment.

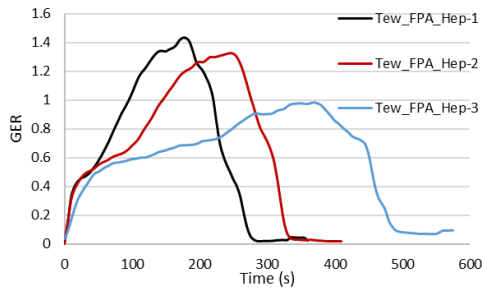


Figure 6: GER obtained in the FPA_Hep 1,2 and 3 tests.

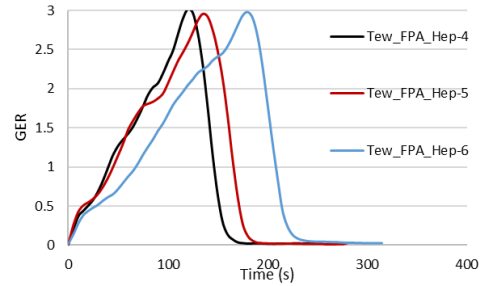


Figure 7: GER obtained in the FPA_Hep 4,5 and 6.

In order to bridge the gap between bench-scale experiments- conducted in FPA- and full-scale compartment tests, a series of medium scale experiments were performed. Three repeatability tests were conducted to ensure the reliability of the measurements.

By analysing Figure 8, a consistent trend is observed between ME_Hep-1, ME_Hep-2 and ME_Hep-3 tests with increasing ventilation, which results in progressively higher MLR values and a more sustained combustion. In ME_Hep-1 (smallest opening), the combustion occurs in under ventilation conditions, as further supported by the GER evolution shown in Figure 9. In ME_Hep-2 (intermediate opening), combustion stabilizes and reaches higher peak values, indicating that oxygen availability is sufficient to sustain the flame for a longer period, although still partially limited compared to the most ventilated case (blue curve). Finally, ME_Hep-3 (largest opening) curve clearly exhibits higher values of MLR, consistent with a better ventilation in the compartment during combustion.

In Figure 9 it is shown GER evolution. For the reduced ventilation case (black curve), tests show a progressive increase in GER, reaching a combustion regime under, a vitiated atmosphere followed by a sudden drop in GER corresponding to fire extinction due to oxygen depletion. In those tests the GER exhibits an oscillatory behaviour, indicative of unstable combustion. At the beginning of the test, GER increases until oxygen-limited conditions are reached, causing the heptane fire to decrease due to insufficient oxidizer. However, as the compartment temperature drops, air re-enters through the opening, temporarily enhancing combustion and increasing the temperature, which again reduces the available oxygen. In tests with larger openings (red and blue curves), GER increases progressively during combustion for both height sizes. This trend reflects a higher availability of oxygen, which allows the fire to sustain a more stable combustion.

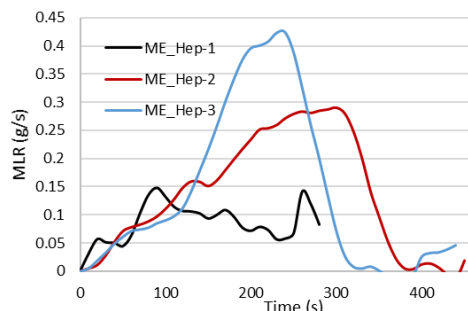


Figure 8: Comparison of the MLR obtained in the ME_Hep 1,2 and 3 tests.

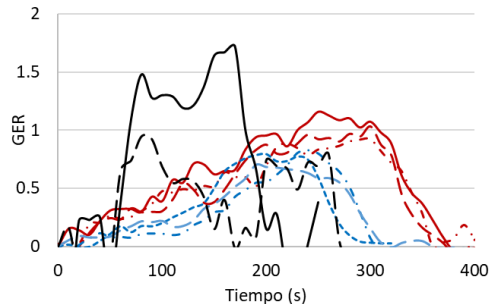


Figure 9: Comparison of the GER obtained in the FPA_Hep 1,2 and 3 tests.

Finally, a full-scale experimental campaign was performed in the RCT set up, in which heptane tray tests were performed on the floor of the compartment, with the ventilation regime varied by adjusting the door opening height to 0.1m, 0.8m and 2m. Two tests were conducted for each configuration.

In the full-scale RCT tests, the MLR curves are shown in Figure 10. In the most restricted ventilation conditions (T1-10), the combustion occurs in an under-ventilated regime, in which MLR remains low and decay to extinction when the oxygen concentration is insufficient to sustain the flame. For the intermediate opening (T1-13), a transitional behaviour is observed, the fire reaches higher MLR values than in the under-ventilated case and exhibits a more sustained burning phase, although still partially limited compared to the most ventilated case. Finally, the door completely opened (T1-16), MLR is the highest and combustion tends to be more stable,

consistent with conditions approaching a well-ventilated regime, in which air inflow through the door promotes fire development. The curves clearly exhibit the typical fire development phases: growth, steady burning, and decay, as observed in theoretical fire curves [9].

Figure 11 shows the evolution of GER for the three configurations. In T1-1 (black curves), the GER exhibits a rapid initial growth, reaching peak values of approximately 3, followed by a sharp decay, which indicates a transition to a ventilation-controlled regime and the extinction due to oxygen depletion. In T1-2 and T1-3, corresponding to the configurations with higher ventilation, the GER exhibits a stable tendency throughout the tests. This trend is more evident in the case T1-3, which has conditions of more ventilation. The low GER values indicate well-ventilated conditions, and the absence of a pronounced growth phase suggests that the fire remains relatively weak and quasi-steady, following the same trend observed in the MLR curves (Figure 10).

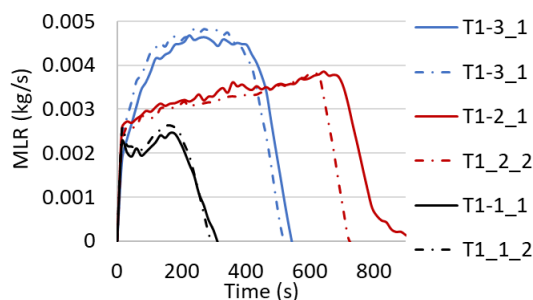


Figure 10: Comparison of the MLR obtained in the T1-1, T1-2 and T1-3.

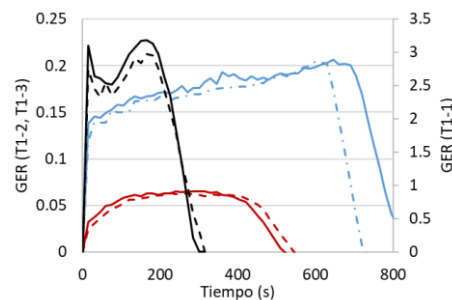


Figure 11: Comparison of the GER obtained in the T1-1, T1-2 and T1-3.

Finally, Table 5 and Table 6 present the maximum values of MLR and GER obtained for each fire scenario configuration. As shown in Table 5, a trend is observed across all scales, either higher oxygen concentration in FPA tests or larger door openings, lead to higher MLR peak values. External heat flux also influences in the maximum MLR according to the FPA tests results. Medium scale and FPA tests, performed without external heat flux, get similar values of the maximum MLR.

Table 5: Comparison of the maximum value of MLR obtained in the experimental tests at different scales

FPA tests	Max. MLR value (g/s)	Medium scale tests	Max. MLR value (g/s)	RCT tests	Max. MLR value (g/s)
FPA_Hep-1	0.36	ME_Hep-1	0.42	T1-1	2.6
FPA_Hep-2	0.29	ME_Hep-2	0.29	T1-2	3.8
FPA_Hep-3	0.18	ME_Hep-3	0.15	T1-3	4.8
FPA_Hep-4	0.77				
FPA_Hep-5	0.64				
FPA_Hep-6	0.53				

The experimental tests ME_Hep-1 (medium scale) and T1-1 (RCT) were extinguished due to oxygen depletion, with maximum GER values of 1.7 and 3.2, respectively. In contrast, FPA tests with higher maximum GER values did not experience extinction. This difference can be attributed to the use of different GER calculation methods (mechanically ventilated versus naturally ventilated) and to the FPA configuration, where the combustion flame is surrounded by an incoming airflow, whereas in the medium- and large-scale tests, not all available oxygen may contribute to combustion.

Table 6: Comparison of the maximum value of GER obtained in the experimental tests at different scales

FPA tests	Max. GER value	Medium scale tests	Max. GER value	RCT tests	Max. GER value
FPA_Hep-1	1.4	ME_Hep-1	1.7	T1-1	3.2
FPA_Hep-2	1.3	ME_Hep-2	1.3	T1-2	0.2
FPA_Hep-3	1.0	ME_Hep-3	0.8	T1-3	0.1
FPA_Hep-4	3.0				
FPA_Hep-5	2.9				
FPA_Hep-6	3.0				

4. CONCLUSIONS

This study presents an experimental campaign which analyse the combustion of a heptane pool fire under vitiated conditions across three scales: bench scale (FPA), medium-scale compartment tests, and full-scale compartment (RCT). The results show that oxygen availability affects combustion stability, and governs the transition between well-ventilated and under-ventilated regimes.

The bench-scale FPA experiments show that the application of an external incident heat flux increases fuel vaporization which leads to higher GER values, reflecting a reduction in global combustion efficiency under high concentration of oxygen conditions.

The medium-scale compartment experiments demonstrate an influence of ventilation on both MLR and GER. Reducing the opening size leads to under-ventilated conditions characterized by an oscillatory behaviour, and eventual extinction due to oxygen depletion in the experiments with the lowest ventilation. Increasing the opening causes higher peak MLR values. The corresponding GER confirms this tendency. The tests with the lowest ventilation got the maximum values of GER, which means that combustion is taking place in an under-ventilated regime. Whereas, increasing ventilation remains in lower values of GER.

The full-scale RCT experiments confirm the observed trends under more realistic conditions. Restricted ventilation produces under-ventilated combustion and extinction due to oxygen depletion, intermediate ventilation produces transitional behaviour, and the full opening experiments got the most stable MLR curves and the lowest GER values (near 0.1).

Overall, the results demonstrate that the Global Equivalence Ratio is a physically consistent parameter to correlate oxygen availability and combustion regime across different experimental configurations. Despite the inherent differences between bench-scale, medium-scale, and full-scale setups, GER captures the effect of ventilation on combustion behaviour in heptane pool fires.

5. ACKNOWLEDGEMENTS

The authors would like to thank the Consejo de Seguridad Nuclear for the cooperation and co-financing of the project “Análisis de modelos numéricos y experimentales para la investigación de incendios en centrales nucleares” (FIRENUC) and the project Determinants of Enclosure effects related to fire dynamics in infrastructures and buildings (DEFIANCE).

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ESTUDO COMPARATIVO ENTRE OS TIPOS DE DISPOSITIVOS HIDRÁULICOS PARA COMBATE A INCÊNDIO UTILIZADOS NOS SISTEMAS DE HIDRANTES EM EDIFÍCIOS RESIDENCIAIS MULTIFAMILIARES

Vitor Goulart Oliveira

Aluno Bolsista, IFSC, Florianópolis, Brasil

Ana Paula Pupo Correia¹

Professora Pesquisadora, IFSC, Florianópolis, Brasil

Bernardo Brasil Bielschowsky

Professor Pesquisador, IFSC, Florianópolis, Brasil

Deives de Paula

Investigador, IteCons, Coimbra, Portugal

Juliana Guarda de Albuquerque

Professora Pesquisadora, IFSC, Florianópolis, Brasil

Palavras-chave: Hidrantes; Mangotinhos; Modelagem da informação da construção (BIM).

1. INTRODUÇÃO

A crescente verticalização das cidades brasileiras, especialmente em estados como Santa Catarina, tem intensificado a demanda por soluções eficazes e acessíveis de proteção ativa contra incêndio em edificações residenciais multifamiliares, sendo estas exigidas nos regulamentos estaduais para este tipo de ocupação, sob a forma de Sistemas Hidráulicos Preventivos (SHP).

O SHP é um sistema fixo de combate a incêndio composto por tubulações, equipamentos e dispositivos destinados a disponibilizar água em pontos estrategicamente distribuídos na edificação durante a ocorrência de um incêndio. De modo geral, o sistema é constituído por reserva técnica de incêndio, bombas de incêndio (quando necessárias), rede de tubulações, hidrantes ou mangotinhos e demais acessórios, responsáveis pelo armazenamento, condução e lançamento da água no local do incêndio. Sua função é permitir o combate inicial ao fogo por meio da aplicação de água, o agente extintor, sobre os materiais em combustão, sendo necessária a ação humana para o início das operações.

Nesse contexto, o correto dimensionamento do SHP e o atendimento às normas técnicas vigentes constituem premissas fundamentais nas etapas de projeto e execução da edificação, contribuindo para a segurança da edificação, a viabilidade técnica e econômica do sistema.

No entanto, observa-se uma lacuna quanto aos esclarecimentos técnicos relacionados à definição do tipo de dispositivo hidráulico a ser adotado nos pontos de combate a incêndio distribuídos nas edificações, especialmente em edifícios residenciais multifamiliares. Nesse contexto, destaca-se a necessidade de maior clareza quanto à escolha entre hidrantes ou

¹ Autor correspondente – Departamento Acadêmico de Construção Civil (DACC) do Instituto Federal de Santa Catarina (IFSC), campus Florianópolis. Rua Mauro Ramos, 950. Centro, 88010-400. Florianópolis. BRASIL. Telef.: +55 48 99114-3677. e-mail: ana.pupo@ifsc.edu.br

mangotinhos, considerando aspectos relacionados à operação do sistema, às características da edificação e às exigências normativas vigentes.

A escolha entre o sistema com hidrantes ou com mangotinhos em edificações residenciais multifamiliares ainda gera dúvidas quanto à sua aplicabilidade, viabilidade técnica e econômica, especialmente no contexto do estado de Santa Catarina.

Neste trabalho, realiza-se uma análise comparativa de duas soluções de projeto para o Sistema Hidráulico Preventivo (SHP) em um edifício residencial multifamiliar: a utilização de hidrantes ou mangotinhos. O dimensionamento do sistema foi desenvolvido com base nas normas técnicas brasileiras e nos regulamentos vigentes no estado de Santa Catarina.

Os projetos hidráulicos de ambas as soluções foram elaborados por meio de modelagem da informação da construção (BIM), utilizando o software Revit Autodesk [1]. A comparação considera o dimensionamento do sistema, o quantitativo de materiais e a estimativa de custos, com o objetivo de avaliar as diferenças técnicas e econômicas entre as alternativas analisadas.

O presente artigo tem como objetivo auxiliar no dimensionamento e na elaboração de projetos que contemplem sistemas hidráulicos preventivos para o combate ao incêndio, contribuindo para a aplicação prática em novos empreendimentos residenciais no estado de Santa Catarina.

2. MATERIAIS E MÉTODOS

A metodologia adotada neste trabalho foi estruturada nas seguintes etapas: definição da edificação, parâmetros e normas adotadas, procedimentos e dimensionamento, ferramentas BIM e template utilizados e criação de famílias paramétricas, conforme descrito a seguir.

2.1 Definição da edificação de estudo

A Figura 1 apresenta uma perspectiva do exterior da edificação utilizada como objeto de estudo, caracterizada como um edifício residencial multifamiliar. A edificação foi projetada em concreto armado, possui área total construída de 3.768,46 m² e altura total de 21,50 m. O projeto está distribuído em sete pavimentos, sendo: garagem, pavimento térreo (destinado a área de uso comum e garagem) e cinco pavimentos tipo, com quatro unidades residenciais autônomas em cada pavimento.

De acordo com suas características construtivas e de ocupação, a edificação é classificada como risco baixo de incêndio [2], devendo ser considerada uma carga de incêndio específica de 300 MJ/m².



Figura 1: Perspectiva Isométrica – Residencia Multifamiliar.

2.2 Parâmetros e normas adotadas

O dimensionamento do sistema foi desenvolvido a partir do projeto apresentado no item anterior, com base nas Instruções Normativas do Corpo de Bombeiros Militar de Santa Catarina (CBMSC), especificamente a IN 01 – Sistemas e Medidas de Segurança Contra Incêndio e Pânico – Parte 2 [2] e a IN 07 – Sistema Hidráulico Preventivo [3].

Além disso, foram consideradas as normas técnicas da Associação Brasileira de Normas Técnicas (ABNT), em especial a NBR 13714, que estabelece os requisitos para os sistemas de hidrantes e mangotinhos para combate a incêndio [4], e a NBR 16642, que define os requisitos para o conjunto de mangueira semirrígida e seus acessórios [5]. Esses documentos normativos forneceram os parâmetros técnicos necessários para o desenvolvimento do projeto e para a realização do cálculo hidráulico do sistema.

2.3 Procedimento de dimensionamento

Foi elaborado um roteiro automatizado para o dimensionamento do sistema SHP, incluindo: a determinação do número de pontos de uso (hidrante e mangotinho), o cálculo da vazão mínima exigida e da pressão no ponto mais desfavorável, a aplicação da equação de Hazen-Williams para o cálculo das perdas de carga nas tubulações, reserva técnica de incêndio, a altura mínima do reservatório superior e o dimensionamento do sistema de pressurização. Os resultados obtidos foram organizados em uma planilha de cálculo, que serviu como base para o lançamento do projeto no modelo BIM.

2.4 Ferramentas BIM e template utilizados

O projeto foi desenvolvido no software Revit Autodesk [1], utilizando-se o modelo arquitetônico previamente elaborado. Para modelagem do sistema hidráulico preventivo, foi adotada a base da família de objetos de dispositivos de segurança contra incêndio em Revit, disponibilizado pelo Instituto Federal de Santa Catarina (IFSC), desenvolvida por Piccoli [6], utilizada como apoio à disciplina de Projeto Preventivo Contra Incêndio do curso de Engenharia Civil do IFSC.

3. RESULTADOS

A Tabela 1 apresenta o resumo dos parâmetros técnicos para o dimensionamento dos sistemas hidráulicos de proteção contra incêndio para a edificação em estudo, levando em conta os dois equipamentos distintos: o Hidrante (Tipo I) e o Mangotinho (Tipo II) [2].

Tabela 1: Parâmetros para o dimensionamento dos sistemas (SHP)

Características	Diâmetro da mangueira	Tipo de esguicho	Vazão mínima	Nº saídas simultâneas
Hidrante (Tipo I)	40mm (1½")	Regulável	70 L/min	4
Mangotinho (Tipo II)	25mm (1")	Regulável	80 L/min	4

A quantidade de dispositivo hidráulico da edificação foi determinada pela cobertura proporcionada pelas mangueiras, de modo que qualquer ponto da área protegida seja alcançado pelo esguicho, considerando o comprimento e o trajeto real da mangueira, sem levar em conta o alcance do jato d'água. A IN 07 do CBMSC [3], exige que a instalação tenha, no mínimo, um dispositivo hidráulico por pavimento. Foram previstos no projeto 1 dispositivo no subsolo (garagem), 1 dispositivo no pavimento térreo (circulação) e 1 dispositivo por pavimento (do 1º ao 5º pavimento) totalizando 7 dispositivos hidráulico.

A Figura 2 apresenta as etapas do dimensionamento do sistema. Inicialmente, foram levantados os dados da edificação (Figura 01) quanto ao uso e ocupação, área total construída, altura e classificação de risco.

Em seguida, foi realizado o cálculo do Sistema Hidráulico Preventivo (SHP), incluindo: determinação da pressão e vazão no ponto mais desfavorável (Figura 4), cálculo da perda de carga no ramal do hidrante mais desfavorável, verificação da pressão no ponto de conexão com a coluna de incêndio, determinação do coeficiente de descarga, cálculo da perda de carga entre o reservatório e o Ponto A (Figura 4), definição da altura mínima do reservatório superior, cálculo da vazão nos hidrantes mais favoráveis, verificação do diâmetro da coluna de incêndio e dimensionamento do volume da reserva técnica de incêndio (RTI).

Por fim, realizou-se o lançamento do SHP, com a modelagem da reserva técnica de incêndio, prumadas, hidrantes e hidrante de recalque, seguido do detalhamento do projeto, elaboração do memorial descritivo de cálculo e extração do quantitativo de materiais

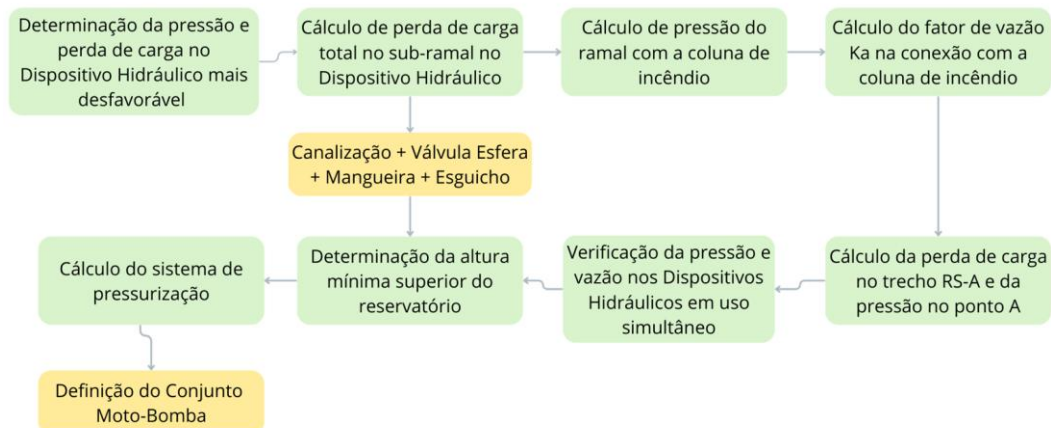


Figura 2: Fluxograma Dimensionamento SHP – Dispositivos Hidráulicos

O volume de água da Reserva Técnica de Incêndio (RTI) foi definido com base na carga de incêndio e na área total da edificação, conforme estabelecido na IN 07 do CBMSC [3]. Considerando que a área total do imóvel é de 3.768,46 m² e que a carga de incêndio é inferior a 300 MJ/m², enquadrando-se, portanto, no menor nível de exigência da norma, o volume mínimo requerido para a RTI é de 10 m³.

Na Tabela 2 apresenta o resumo do dimensionamento do Sistema Hidráulico Preventivo (SHP) com Hidrante e Mangotinho. Ambos os sistemas foram dimensionados conforme os critérios normativos aplicáveis [2], considerando as vazões mínimas e os diâmetros estabelecidos, a fim de garantir o desempenho hidráulico adequado.

Tabela 2: Resumo do Dimensionamento (Hidrante e Mangotinho)

Dimensionamento	Hidrante	Mangotinho
Vazão mínima	70 l/min	80 l/min
Diâmetro da coluna de incêndio	65 mm	40 mm
Diâmetro dos ramais de alimentação	50 mm	25 mm
Diâmetro da mangueira	40 mm	25 mm
Pressão mínima no esguicho	100 m.c.a.	140 m.c.a.
Volume RTI	10 m ³	10 m ³

Com base no levantamento realizado, o projeto foi modelado no software Autodesk Revit [1]. As Figuras 3 e 4 apresentam, respectivamente, a perspectiva isométrica do sistema e o detalhe do trecho entre o reservatório superior e o hidrante mais desfavorável (Ponto A). O lançamento do sistema é idêntico nas duas configurações analisadas, hidrante e mangotinho, sem alterações no traçado ou nas soluções adotadas no modelo.

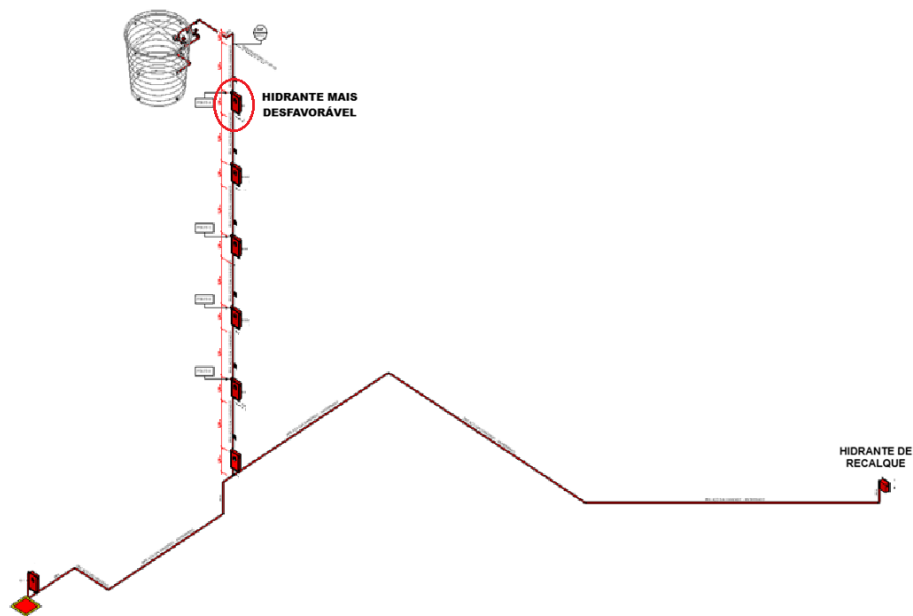


Figura 3: Perspectiva Isométrica do SHP

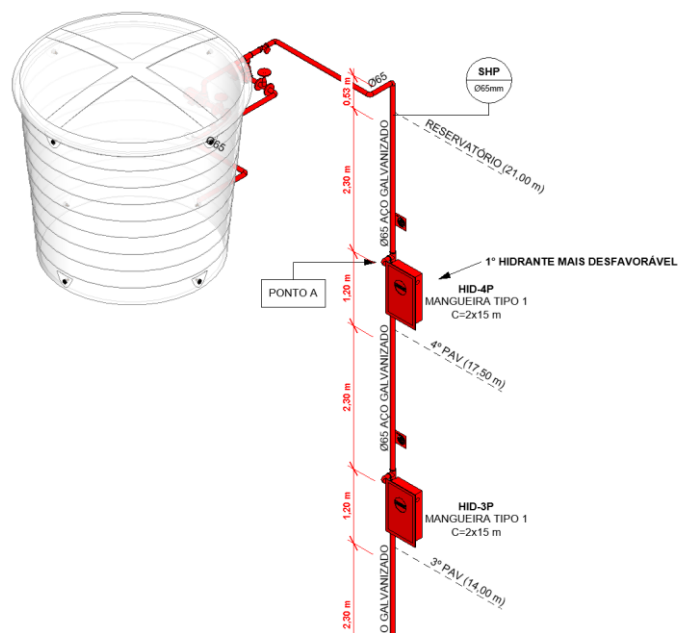


Figura 4: Detalhe do Reservatório Superior até o Hidrante mais desfavorável (Ponto A)

Para o desenvolvimento do projeto em BIM, além da utilização da família em REVIT do projeto preventivo de incêndio [5], foram elaborados e modelados os detalhes dos sistemas hidráulicos preventivos por mangotinho e por hidrante. As imagens apresentadas na Figura 5 e 6 ilustram exemplos da modelagem da tomada d'água para ambos os sistemas.

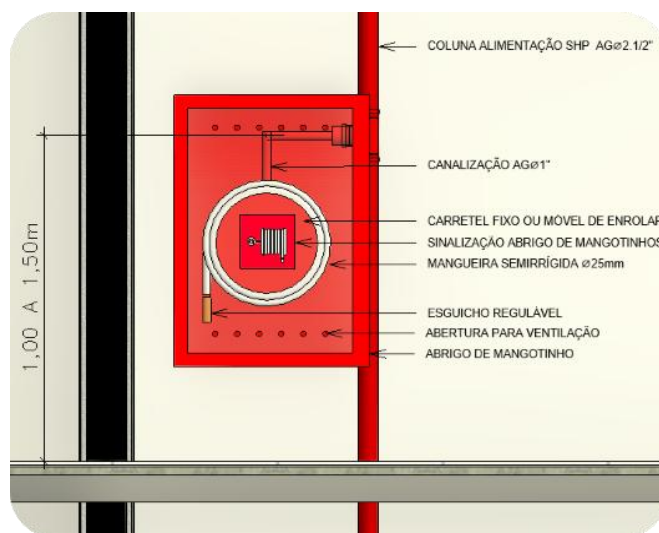


Figura 5: Detalhes em BIM tomada d'água Mangotinho

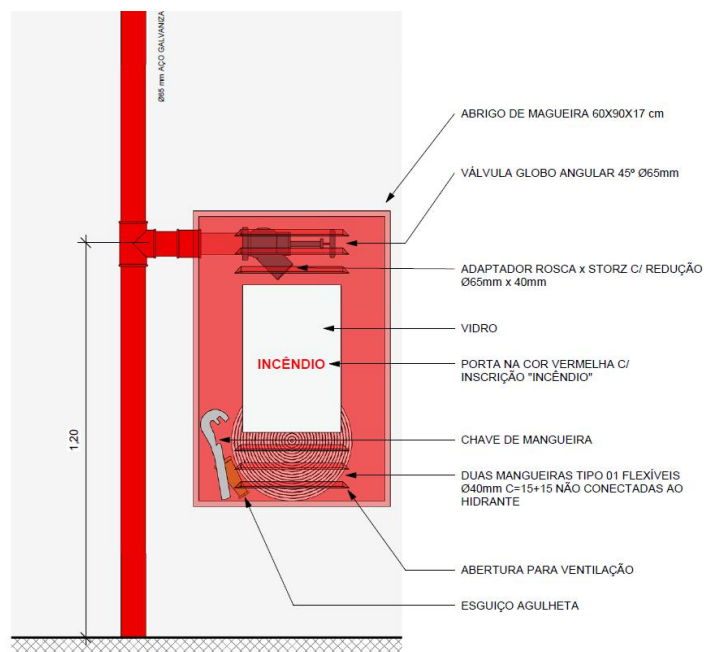


Figura 6: Detalhes em BIM tomada d'água Hidrante

Após a elaboração do projeto, realizou-se a extração do quantitativo de materiais do Sistema Hidráulico Preventivo. Esse processo foi executado diretamente a partir do modelo tridimensional desenvolvido no Revit, por meio de tabelas nativas vinculadas aos parâmetros de cada família. Como o modelo estava totalmente parametrizado — incluindo tubulações, conexões, acessórios, bomba hidráulica e componentes de hidrantes ou mangotinhos — foi possível gerar automaticamente a listagem completa de todos os itens, eliminando a necessidade de medições manuais ou verificações adicionais.

Foi elaborado um levantamento dos equipamentos e materiais essenciais para a instalação de um sistema hidráulico de combate a incêndios, detalhando os requisitos tanto para o Sistema Preventivo por Hidrante quanto para o Sistema Preventivo por Mangotinho. Os componentes especificados abrangem desde a infraestrutura básica, incluindo as tubulações de aço galvanizado, a caixa d'água de 10.000 litros, até os acessórios hidráulicos complexos.

Após o levantamento dos materiais referentes ao Sistema Hidráulico Preventivo (SHP) por hidrante e ao SHP por mangotinho, foi elaborado o orçamento para a implantação de cada sistema. Constatou-se que o custo estimado do SHP por hidrante foi de R\$ 55.836,37, enquanto o SHP por mangotinho apresentou valor total de R\$ 61.518,46. Essa diferença decorre, principalmente, do maior custo dos componentes do sistema por mangotinho, que utiliza mangueiras semirrígidas, carretéis metálicos e dispositivos de acionamento de uso imediato, os quais possuem valor unitário superior quando comparados aos equipamentos empregados no sistema por hidrante.

Mesmo com a diferença de custo de aproximadamente 10,2% em relação ao sistema por hidrante, o Sistema Hidráulico Preventivo (SHP) por mangotinho apresenta vantagens operacionais relevantes. O uso de mangueiras semirrígidas e carretéis metálicos permite acionamento mais rápido, maior facilidade de manuseio e maior durabilidade dos componentes, favorecendo sua utilização por ocupantes da edificação ou brigadistas, conforme previsto na ABNT NBR 13714 [4] e na Instrução Normativa nº 07 do CBMSC [3].

Dessa forma, embora o investimento inicial seja superior, o sistema por mangotinho pode ser considerado tecnicamente adequado e justificável, especialmente em edificações que demandam resposta rápida ao princípio de incêndio.

5. CONCLUSÕES

O sistema hidráulico preventivo por hidrantes é amplamente utilizado no combate a incêndios e previsto nos regulamentos aplicáveis em Santa Catarina para diversas ocupações. Seu desempenho depende de dimensionamento adequado e da capacitação dos ocupantes ou das brigadas de incêndio, responsáveis por sua operação em situações de princípio de incêndio.

Já o sistema hidráulico preventivo por mangotinhos é indicado para edificações com carga de incêndio de risco baixo, destacando-se pela facilidade de operação e pronta utilização. Por essas características, deveria ser adotado em ocupações como escolas, edificações residenciais multifamiliares e escritórios, com mais frequência.

Assim, a escolha entre hidrantes com mangueiras convencionais e mangotinhos deve considerar não apenas os critérios regulamentares, mas também o perfil dos ocupantes e a operação da edificação, a fim de garantir eficiência e rapidez no combate inicial do incêndio.

Destaca-se que a metodologia aplicada nesta pesquisa pode ser utilizada em projetos de edifícios residenciais multifamiliares em outros estados brasileiros. Entretanto, alguns parâmetros podem variar em função das instruções normativas locais. Como o estudo foi delimitado ao estado de Santa Catarina, recomenda-se a aplicação da mesma metodologia em outros contextos para fins de comparação.

6. AGRADECIMENTO

Ao Instituto Federal de Santa Catarina (IFSC) pelo apoio no desenvolvimento do projeto.

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Session 8

Sesión 8

Sessão 8

**ANÁLISE DE INDEFERIMENTOS DOS PROJETOS DE PREVENÇÃO E
SEGURANÇA CONTRA INCÊNDIOS DE EDIFICAÇÕES DE OCUPAÇÃO
RESIDENCIAL MULTIFAMILIAR VERTICAL LOCALIZADAS NO
MUNICÍPIO DE SANTO AMARO DA IMPERATRIZ/SC**



Yasmim Coelho
Pesquisadora
IFSC – Florianópolis
Brasil



**Ana Paula Pupo
Correia ***
Professora
IFSC – Florianópolis
Brasil

Palavras-chave: Projeto de Prevenção e Segurança Contra Incêndios; Análise de Projetos; Instruções Normativas; Cartilha de Exigências.

1. INTRODUÇÃO

A segurança contra incêndios deve ser considerada desde as etapas iniciais de planejamento e elaboração dos projetos básicos e complementares, até concepção arquitetônica e estrutural das edificações. O desempenho adequado de uma edificação está diretamente relacionado à responsabilidade técnica no processo de planejamento e execução, tornando essencial a elaboração do projeto de prevenção e segurança contra incêndios.

Entre as edificações que devem atender às Instruções Normativas do Corpo de Bombeiros Militar de Santa Catarina (CBMSC), destacam-se os edifícios residenciais multifamiliares. Entretanto, observa-se a recorrência de indeferimentos nas análises de projetos dessa natureza, ocasionando retrabalho para projetistas e analistas, atrasos na execução das obras e aumento de custo.

O Decreto Estadual nº 1.908/2022 instituiu o processo simplificado, que permite a liberação do atestado de construção em até um dia útil para edificações de até 5.000 m², sem análise prévia, ficando a responsabilidade técnica pela conformidade sob o projetista e o proprietário. Em abril de 2024, novas atualizações entraram em vigor, introduzindo uma metodologia baseada em matriz de risco e a atribuição de um único analista por projeto, com o objetivo de agilizar e

* Autor correspondente — Departamento Acadêmico de Construção Civil (DACC) do Instituto Federal de Santa Catarina (IFSC), campus Florianópolis. Rua Mauro Ramos, 950. Centro, 88010-400. Florianópolis. BRASIL. Telef.: +55 48 99114-3677, E-mail: ana.pupo@ifsc.edu.br

padronizar as etapas de aprovação, assegurando que as normas permaneçam estáveis pelos próximos dez anos.

Devido à implementação do processo simplificado, que permite a liberação do atestado de construção para os imóveis enquadrados sem análise prévia do PPCI, o número de processos analisados a partir de julho de 2022 foi reduzido. Com essa mudança, os processos são submetidos a um sorteio de fluxo simplificado, e apenas os selecionados seguem para a fila de análise.

Dessa forma, o presente trabalho tem como objetivo principal identificar as principais causas de indeferimento dos projetos de prevenção e segurança contra incêndios em edificações residenciais multifamiliares verticais localizadas no município de Santo Amaro da Imperatriz/SC, situado a aproximadamente 30 km de Florianópolis. Essa região tem apresentado crescimento urbano acelerado, com a implantação de novos empreendimentos, o que amplia a necessidade de garantir padrões adequados de segurança contra incêndios para a proteção da população e do patrimônio local.

Assim, o estudo reforça a importância da adequação dos projetos às Instruções Normativas vigentes e evidencia a necessidade de maior atenção às exigências durante sua elaboração. Por fim, os resultados da pesquisa apresentado e a cartilha servirão como um guia prático para projetistas e demais profissionais envolvidos na elaboração de projeto de prevenção e segurança contra incêndios, otimizando o processo de aprovação, reduzindo indeferimentos, evitando retrabalho, e consequentemente, promovendo a segurança contra incêndios nas edificações.

2. FUNDAMENTAÇÃO E MÉTODO

Para fundamentar a pesquisa, foram coletados dados dos relatórios de indeferimento de análise de projetos emitidos entre os anos de 2020 e 2024 pelo Corpo de Bombeiros Militar de Santa Catarina. Alguns dados foram extraídos dos documentos como ocupação, área total construída, altura da edificação e a lista de pendências destacada pelos analistas do projeto.

Essas informações permitiram identificar as causas de indeferimento mais recorrentes e fazer uma análise detalhada dos resultados obtidos, baseando-se nas instruções normativas do Corpo de Bombeiros Militar de Santa Catarina [1] e em bibliografias de autores que realizaram estudos pertinentes à segurança contra incêndio e principalmente voltado a análise e aprovação de projetos.

O método utilizado para análise dos pareceres técnicos de indeferimento resultou em 25 relatórios emitidos entre 2020 e 2024, referentes a 12 edificações de ocupação residencial multifamiliar vertical. Para o levantamento dos dados, foi elaborada uma planilha com base no método proposto por Caron [2], contendo as seguintes informações: identificação da edificação, a área total, altura, a quantidade de análises e resultados obtidos.

Para o levantamento dos dados, foi confeccionada uma planilha, apresentada na Tabela 1, com a relação dos projetos de residências multifamiliares verticais que serão utilizados na pesquisa,

como a identificação da edificação, a área total e altura das edificações, a quantidade de análises dos projetos e o resultado das análises. Os resultados das análises foram identificados como “D” para indicar que a análise foi deferida, e “I” para indicar que a análise foi indeferida.

Tabela 1: Projetos de residências multifamiliares verticais serão analisados na pesquisa

Edificação	Área total (m²)	Altura (m)	Quantidade de análises				Resultado das análises			
			1	2	3	4	1	2	3	4
1	3.151,22	21,12		X			I	D		
2	3.429,31	23,96				X	I	I	I	D
3	1.128,33	11,70			X		I	I	D	
4	1.266,59	10,00			X		I	I	D	
5	3.719,86	33,63		X			I	D		
6	1.173,40	11,90			X		I	I	D	
7	1.483,38	11,78			X		I	I	I	
8	1.449,34	3,78				X	I	I	I	D
9	9.209,37	30,00		X			I	D		
10	1.754,79	14,69				X	I	I	I	D
11	5.198,94	25,08				X	I	I	I	D
12	1.342,53	18,83		X			I	D		

Após a identificação das principais causas de indeferimento, foi desenvolvida uma cartilha que reúne as exigências necessárias para a aprovação de projetos de prevenção e segurança contra incêndio em edificações residenciais multifamiliares verticais. Essa cartilha destaca as diretrizes que demandam maior atenção, orientando os projetistas sobre os principais pontos a serem observados para evitar indeferimentos nos projetos.

A cartilha conta com um tópico de apresentação, descrevendo os objetivos da cartilha, orientações de uso e uma breve introdução de seu conteúdo. Na sequência, descreve as especificações para classificação de ocupação e os SMSCI necessários para edificações de ocupação residencial multifamiliar vertical. A cartilha também inclui uma listagem da documentação necessária a ser enviada para análise e apresenta a formatação de pranchas exigida pelo CBMSC.

3. DESENVOLVIMENTO DO TRABALHO

Os resultados foram organizados a partir das principais categorias de indeferimento identificadas, como ausência de documentação, inconformidades com as Instruções Normativas do CBMSC e falhas na representação gráfica. O desenvolvimento do trabalho foi estruturado em três partes: a análise dos pareceres técnicos de indeferimento, a identificação e discussão das principais causas desses indeferimentos e a elaboração de uma cartilha com os elementos essenciais para a aprovação do PPCI em edificações residenciais multifamiliares.

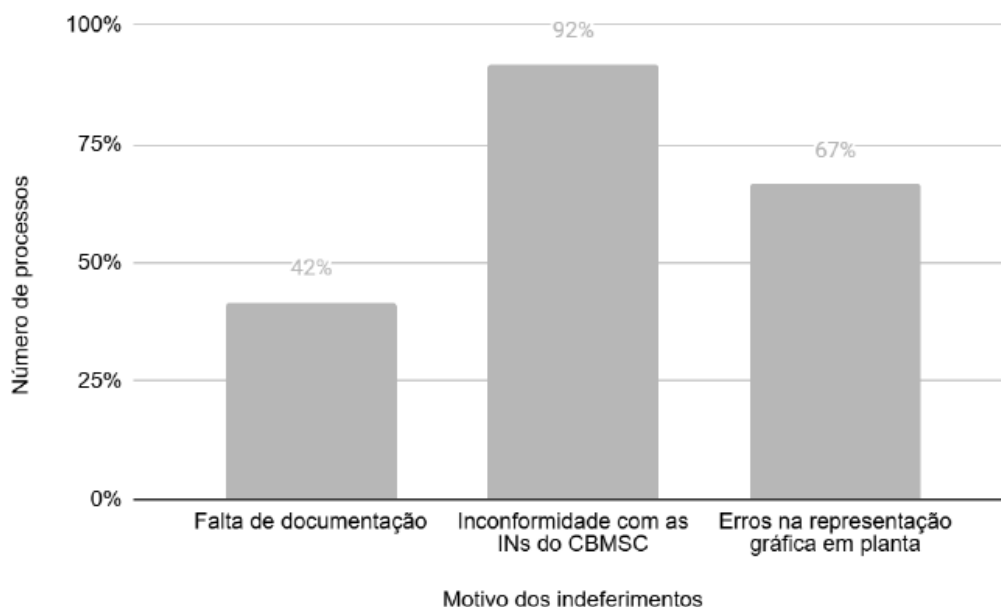
3.1 Análise dos pareceres técnicos de indeferimento

Conforme citado anteriormente, a pesquisa documental contemplou os pareceres técnicos de indeferimento emitidos pelo CBMSC nas análises de PPCIs de edificações de ocupação residencial multifamiliar vertical localizadas no município de Santo Amaro da Imperatriz. A escolha da localização e ocupação adotadas foi motivada pelo crescimento significativo no número de edifícios residenciais no município.

Os documentos necessários para a realização da pesquisa foram coletados por meio de visitas ao Serviço de Segurança Contra Incêndio de Santo Amaro da Imperatriz. Foram fornecidos à autora documentos provenientes do sistema interno o e-SCI, que se trata de uma ferramenta integrada de gestão e arquivamento, que armazena todos os documentos emitidos pelo CBMSC no município, incluindo pareceres técnicos de análises de Projeto Preventivo Contra Incêndio (PPCI), Relatório Preventivo Contra Incêndio (RPCI) e vistorias de habite-se e funcionamento.

A classificação dos motivos de indeferimento revelou que a principal causa está relacionada à inconformidade dos projetos com as instruções normativas do CBMSC, representando 92% dos processos analisados, conforme apresentado no Gráfico 1. Esse dado evidencia que o descumprimento dos requisitos estabelecidos nas instruções normativas é uma causa recorrente de indeferimento de projetos.

Gráfico 1: Incidência dos motivos de indeferimento

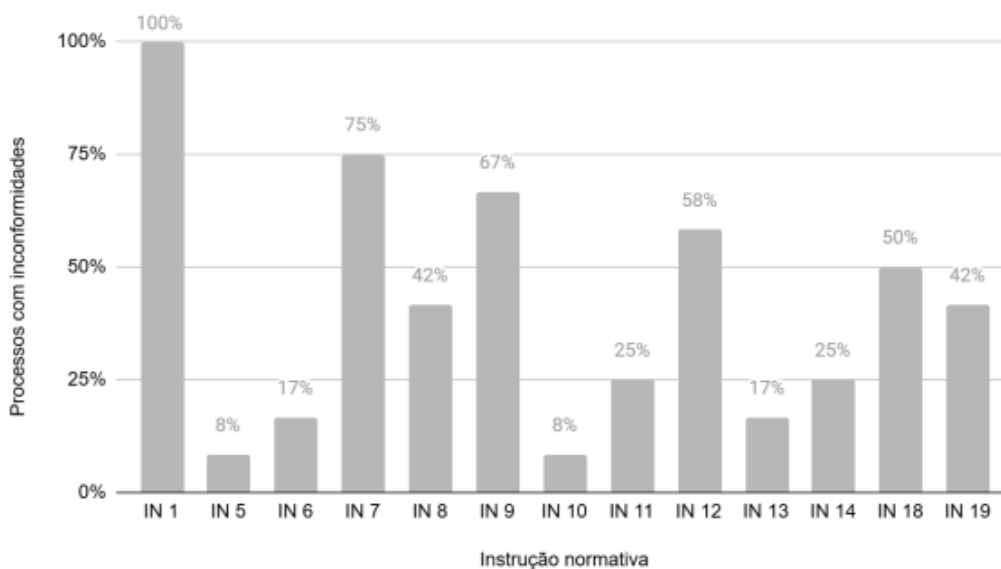


Outro motivo relevante foram os erros na representação gráfica em planta dos elementos dos PPCIs, que corresponderam a 67% dos processos analisados. Esses erros, geralmente

relacionados à falta de clareza nos desenhos e à ausência de detalhes essenciais, podem dificultar a análise dos projetos, resultando em seu indeferimento. Além disso, 42% dos indeferimentos foram atribuídos à falta de documentação. Esse tipo de erro indica a necessidade de uma maior atenção dos profissionais ao submeter os documentos solicitados pelo CBMSC, como as plantas do projeto, memorial descritivo e de cálculo, documento de responsabilidade técnica e as declarações solicitadas.

A partir da análise dos motivos dos indeferimentos, foram identificadas as instruções normativas do CBMSC nas quais os projetos estudados apresentaram inconformidades. O Gráfico 2 apresenta a incidência de projetos com inconformidades de cada instrução normativa.

Gráfico 2: Incidência de inconformidades com as Instruções Normativas



Observa-se que a IN 1 - Procedimentos administrativos e Sistemas e medidas de SCI [1, 3] concentra inconformidades em 100% dos processos analisados. Em seguida, destaca-se a IN 7 - Sistema hidráulico preventivo [4], com 75% dos processos apresentando inconformidades. A IN 9 - Sistema de saída de emergência [5] também apresenta um número significativo de inconformidades, com 67% dos processos analisados.

Diante dos resultados apresentados, a análise realizada evidencia que grande parte dos indeferimentos ocorre devido a inconformidades com as Instruções Normativas do CBMSC, ressaltando a necessidade de maior atenção à aplicação dessas normativas, a fim de reduzir a ocorrência de erros nos projetos.

3.2 Principais causas de indeferimento

Posteriormente à análise dos pareceres técnicos de indeferimento das edificações de ocupação residencial multifamiliar vertical, foram identificadas as principais causas de indeferimento contidas nos pareceres estudados.

Os resultados foram organizados de forma visual, por meio de um resumo que apresenta as principais causas de indeferimento identificadas, identificadas na Figura 1. Neste resumo, foram destacados os artigos com maior índice de incidências, pertencentes às INs do CBMSC, que se mostraram mais recorrentes nos pareceres técnicos analisados.

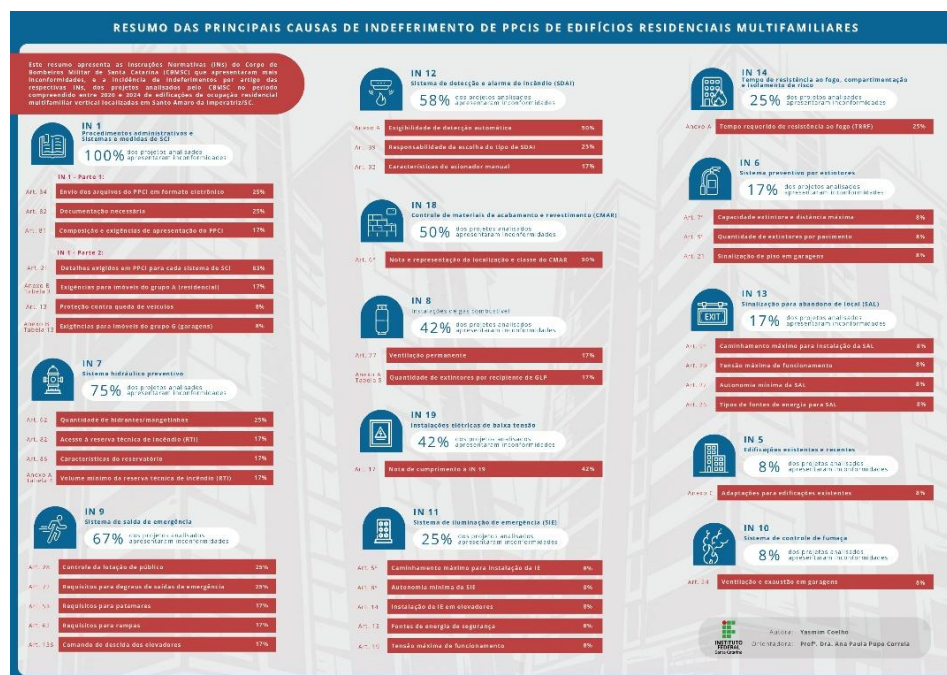


Figura 1: Resumo das principais causas de indeferimento de PPCs

O resumo das principais causas de indeferimento de PPCs pode ser acessado pelo QR Code apresentado na Figura 2.



Figura 2: QR Code de acesso ao resumo das principais causas de indeferimento

A Instrução Normativa 1 - Processos administrativos e Sistemas e medidas de SCI foi a que apresentou o maior número de inconformidades, abrangendo todos os processos analisados. Entre as principais falhas identificadas nesta IN está a ausência de detalhes exigidos no PPCI para cada sistema e medida de segurança contra incêndio, seguido de erros no envio dos arquivos do PPCI em formato eletrônico, ausência de apresentação da documentação necessária e da incorreta altura do imóvel para fins de exigência dos sistemas e medidas de segurança contra incêndio.

A Instrução Normativa 7 - Sistema hidráulico preventivo foi a segunda com maior incidência de inconformidades, sendo os problemas mais recorrentes relacionados à quantidade incorreta de hidrantes ou mangotinhos, seguido de inconformidades no acesso à reserva técnica de incêndio, características do reservatório e volume mínimo da reserva técnica de incêndio. A Instrução Normativa 9 - Sistema de saída de emergência também se destacou, com indeferimentos relacionados ao controle de lotação de público, requisitos para degraus das saídas de emergência, requisitos para patamares e rampas, e comando de descida dos elevadores.

Neste artigo, apresentamos algumas das principais causas de indeferimento identificadas ao longo da pesquisa. O resumo visual (Figura 2) permite reconhecer, de forma objetiva, as Instruções Normativas do CBMSC e os respectivos artigos com maior incidência de inconformidades, proporcionando entendimento rápido e facilitando a identificação dos resultados.

3.4 Cartilha de elementos essenciais para a aprovação do PPCI residenciais multifamiliar.

A cartilha, intitulada “Elementos Essenciais para a Aprovação do PPCI de Edifícios Residenciais Multifamiliares”, foi desenvolvida com o propósito de ser um guia prático para a elaboração do PPCI, oferecendo orientação sobre os principais elementos exigidos pelo CBMSC. Seu conteúdo foi elaborado com base nas Instruções Normativas do CBMSC, destacando os elementos essenciais que devem constar no projeto para sua aprovação.

Enquanto as Instruções Normativas do CBMSC são técnicas e detalhadas, a cartilha organiza essas informações, apresentando os itens exigidos no PPCI de forma mais prática e resumida. Dessa forma, busca facilitar a compreensão das exigências e auxiliar os profissionais na aplicação dos requisitos necessários para a aprovação dos projetos.

A cartilha aborda os itens necessários para todos os sistemas exigidos para edificações de ocupação residencial multifamiliar vertical (A-2) de até 30 metros de altura. Cada item apresentado na cartilha conta com orientações, exemplos e representações gráficas, visando facilitar a compreensão dos itens exigidos.

Destaca-se que o documento foi elaborado com base na pesquisa desenvolvida neste estudo, o qual analisou edificações localizadas em Santo Amaro da Imperatriz. Desta forma, seu conteúdo é destinado a edificações com altura de até 30 metros, em conformidade com o número máximo de pavimentos estabelecido pelo Plano Diretor Participativo vigente no município [6].

A cartilha intitulada Elementos Essenciais para a Aprovação do PPCI de Edifícios Residenciais Multifamiliares pode ser acessada pelo QR Code presente na Figura 3.

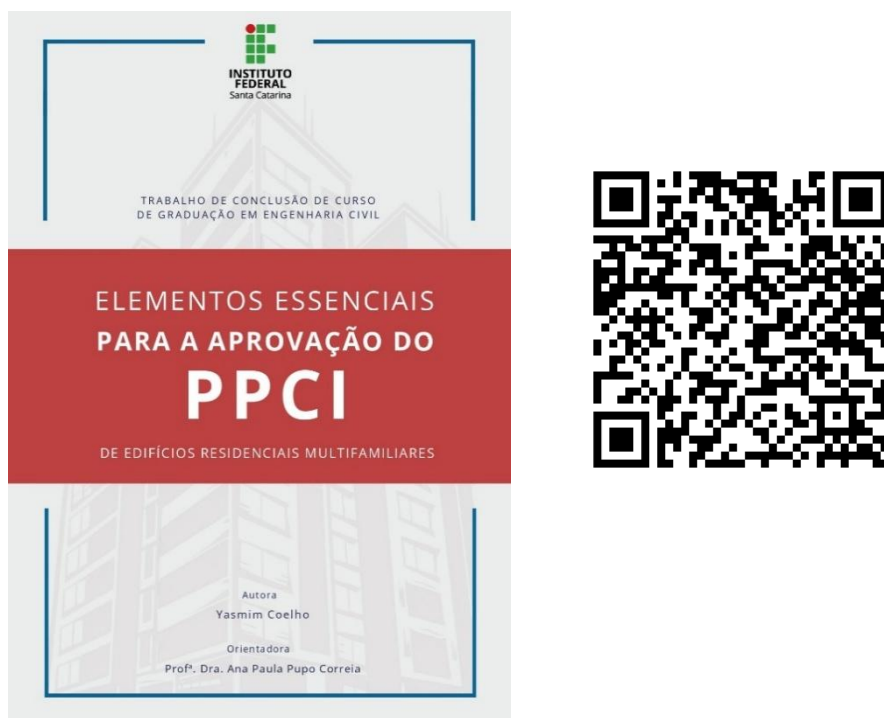


Figura 3: Cartilha de elementos para a elaboração do PPCI e QR Code de acesso à cartilha.

O material foi elaborado com o objetivo de atender às necessidades de profissionais da área, projetistas e demais responsáveis pela elaboração do PPCI de edificações localizadas em Santo Amaro da Imperatriz. Trata-se de uma ferramenta complementar às Instruções Normativas, contribuindo para maior clareza, padronização e eficiência na apresentação dos projetos.

Na Figura 4, está representada parte da cartilha. A primeira imagem destaca a documentação necessária a ser apresentada no momento da solicitação de análise do PPCI. Já a segunda imagem apresenta detalhes das exigências técnicas, com base nas Instruções Normativas do Corpo de Bombeiros Militar de Santa Catarina (CBMSC), para a concepção do sistema preventivo por extintores.



Figura 4: Exemplo conteúdo da cartilha.

A elaboração de uma Cartilha de Elementos configura-se como instrumento estratégico para promover maior clareza, padronização e segurança na elaboração dos Projetos de Prevenção e Proteção Contra Incêndio e Pânico (PPCI). Ao sistematizar as exigências normativas, a documentação necessária e as orientações técnicas aplicáveis, o material consolida-se como ferramenta de apoio aos profissionais responsáveis, contribuindo para a redução de inconsistências, retrabalhos e indeferimentos nos processos de análise. Dessa forma, favorece maior eficiência na tramitação dos projetos e reforça a conformidade com os requisitos legais e técnicos vigentes.

4. CONCLUSÕES

O presente trabalho teve como objetivo principal identificar as principais causas de indeferimento dos Projetos de Prevenção e Proteção Contra Incêndio (PPCI) de edificações de ocupação residencial multifamiliar vertical localizadas no município de Santo Amaro da Imperatriz/SC, analisados pelo Corpo de Bombeiros Militar de Santa Catarina (CBMSC) no período de 2020 a 2024. Para tanto, foram examinados pareceres técnicos de indeferimento, identificadas as

inconformidades mais recorrentes e, a partir dos resultados obtidos, elaborada uma cartilha técnica com o propósito de auxiliar na correta elaboração desses projetos.

Com base na análise realizada, verificou-se que os erros mais frequentes estão relacionados à não conformidade com as Instruções Normativas vigentes, bem como a falhas na documentação apresentada para análise. Esses resultados evidenciam a necessidade de maior rigor técnico e atenção às exigências legais durante a elaboração dos projetos, reforçando a importância do domínio normativo por parte dos profissionais responsáveis.

Além disso, a produção da cartilha configura-se como uma contribuição prática do estudo, ao oferecer um instrumento de apoio que pode reduzir inconsistências, retrabalhos e indeferimentos, promovendo maior eficiência nos processos de aprovação junto ao CBMSC.

Considerando que a pesquisa foi delimitada às edificações residenciais multifamiliares verticais, recomenda-se a aplicação da mesma metodologia em outras ocupações, como edificações escolares, comerciais ou institucionais, a fim de verificar se as causas de indeferimento se mantêm semelhantes ou apresentam particularidades específicas conforme o tipo de uso da edificação.

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ENGENHARIA DE SEGURANÇA CONTRA INCÊNDIO, LEGISLAÇÃO E ACESSIBILIDADE: UMA ANÁLISE POR MEIO DO DESIGN UNIVERSAL



Júlia Pinheiro Pires *
Arquiteta e Urbanista,
Especialista em
Engenharia de
Segurança Contra
Incêndio e Mestranda
PPGCI - UFRGS –
Rio Grande do Sul –
Brasil



Ângela Gaio Graeff
Professora, Ph.D.,
Eng. Civil - UFRGS –
Rio Grande do Sul –
Brasil



Rafaela Jongh Pötter
MSc., Doutoranda
PGDesign - UFRGS –
Rio Grande do Sul –
Brasil

Palavras-chave: Acessibilidade; segurança contra incêndio; Design Universal.

1. INTRODUÇÃO

A legislação de prevenção e proteção contra incêndio no Brasil tem sido historicamente impulsionada por eventos trágicos que evidenciaram fragilidades normativas e operacionais. No estado do Rio Grande do Sul (RS), o incêndio na Boate Kiss, ocorrido em 2013, representou um marco decisivo para a reformulação do arcabouço legal de segurança contra incêndio, culminando na promulgação da Lei Complementar nº 14.376/2013 [1], conhecida como Lei Kiss. Apesar dos avanços no licenciamento, ainda persistem lacunas na integração da acessibilidade às estratégias de evacuação em emergências.

A segurança das edificações em situações de incêndio não depende apenas da eficiência dos sistemas de detecção, alarme e combate, mas também da possibilidade de evacuação rápida, segura e acessível para todos os usuários. Rotas de fuga inadequadas, sinalização pouco perceptível e ausência de recursos compatíveis com diferentes capacidades físicas, sensoriais e cognitivas comprometem diretamente a proteção à vida, sobretudo em cenários de pânico e baixa visibilidade.

* Autor correspondente – LEME/FIRE, Universidade Federal do Rio Grande do Sul. Av. Bento Gonçalves, 9500 - Partenon, Porto Alegre – RS (Brasil) - CEP 90650-00. Telefone: +55 51 98415-8354, E-mail: juliapinheiropires@gmail.com

Dados do Instituto Brasileiro de Geografia e Estatística (IBGE) indicam que cerca de 8,9% da população brasileira apresenta algum tipo de deficiência, com destaque para limitações relacionadas à mobilidade, visão e audição (IBGE, 2022) [2]. Esses números evidenciam que uma parcela expressiva da população pode enfrentar dificuldades adicionais durante situações de emergência, especialmente quando os ambientes construídos não incorporam princípios de acessibilidade de forma sistemática. Ainda que a legislação brasileira assegure o direito à acessibilidade por meio de instrumentos como a Lei Brasileira de Inclusão da Pessoa com Deficiência (LBI) (Lei nº 13.146/2015) [3], observa-se que tais diretrizes nem sempre se refletem de maneira consistente nas normas técnicas de segurança contra incêndio.

Nesse contexto, o Design Universal (DU) surge como um referencial teórico e metodológico capaz de contribuir para uma abordagem mais inclusiva da segurança contra incêndio. Formulado por Ronald Mace, o conceito propõe que espaços, produtos e sistemas sejam concebidos para atender à diversidade humana desde a origem do projeto, sem a necessidade de adaptações posteriores. Seus sete princípios — uso equitativo, flexibilidade no uso, uso simples e intuitivo, informação perceptível, tolerância ao erro, baixo esforço físico e tamanho e espaço adequados para aproximação e uso — oferecem diretrizes fundamentais para a concepção de ambientes mais seguros, inclusive em situações emergenciais [4].

Diante desse cenário, emerge a seguinte problemática: as normas de prevenção e proteção contra incêndio atualmente vigentes no estado do Rio Grande do Sul contemplam, de forma adequada, os princípios da acessibilidade e do Design Universal? Embora existam referências normativas pontuais, como a NBR 9050 (ABNT, 2020) [5], torna-se necessário avaliar se esses parâmetros estão efetivamente incorporados às Resoluções Técnicas (RT) do Corpo de Bombeiros Militar do Rio Grande do Sul (CBMRS) e se contribuem para uma segurança verdadeiramente inclusiva.

Assim, este trabalho tem como objetivo analisar a inserção da acessibilidade e dos princípios do Design Universal nas normas de segurança contra incêndio do estado do Rio Grande do Sul, por meio de uma análise normativa e da percepção de profissionais da área. Busca-se identificar lacunas, inconsistências e oportunidades de aprimoramento, contribuindo para o desenvolvimento de uma abordagem mais integrada e equitativa da segurança contra incêndio em edificações.

2. REFERENCIAL TEÓRICO

2.1 Segurança Contra Incêndio e Acessibilidade no contexto normativo brasileiro

A segurança contra incêndio em edificações no Brasil é estruturada a partir de um conjunto de legislações, normas técnicas e regulamentos estaduais, cuja aplicação visa à preservação da vida, do patrimônio e do meio ambiente. Diferentemente de países que adotam códigos nacionais unificados, o modelo brasileiro caracteriza-se pela descentralização normativa, cabendo aos Corpos de Bombeiros Militares estaduais a regulamentação específica das medidas de prevenção e proteção contra incêndio. Nesse contexto, as regulamentações emitidas pelos Corpos de Bombeiros estaduais possuem caráter normativo no processo de licenciamento e

análise de projetos, prevalecendo sobre as normas técnicas da ABNT quando houver divergência ou especificidade local.

No estado do Rio Grande do Sul, esse arcabouço foi significativamente reformulado após o incêndio da Boate Kiss, resultando na promulgação da Lei Kiss [1] e na publicação de um conjunto de Resoluções Técnicas que passaram a disciplinar de forma mais rigorosa aspectos como saídas de emergência, sinalização, iluminação e sistemas de detecção e combate ao fogo. Apesar dos avanços obtidos, a abordagem normativa permanece majoritariamente centrada em critérios prescritivos e no desempenho de sistemas e componentes, com menor ênfase na diversidade de usuários que ocupam os espaços edificados.

As normas de segurança contra incêndio tradicionalmente consideram o comportamento médio dos ocupantes em emergências, frequentemente desconsiderando limitações físicas, sensoriais ou cognitivas. Essa lacuna torna-se especialmente crítica em cenários de evacuação, nos quais fatores como pânico, baixa visibilidade e restrições de tempo exigem ambientes intuitivos, perceptíveis e acessíveis.

A acessibilidade no ambiente construído é assegurada no ordenamento jurídico brasileiro por meio de instrumentos legais como a Lei Brasileira de Inclusão – LBI [3], que estabelece o direito ao acesso seguro e autônomo aos espaços, serviços e edificações. No campo normativo, a ABNT NBR 9050 [5] constitui a principal referência técnica para o projeto, construção e adaptação de edificações acessíveis.

A NBR 9050 [5] define critérios relacionados à circulação, à sinalização, à comunicação, ao dimensionamento de rotas e às condições de uso por pessoas com deficiência ou mobilidade reduzida. Embora não tenha como foco específico a segurança contra incêndio, diversos de seus requisitos apresentam relação direta com situações de emergência, como a largura de circulações, a continuidade das rotas acessíveis, o uso de sinalização tátil e visual e a previsão de áreas de refúgio.

Entretanto, observa-se que a aplicação da NBR 9050 [5] e das normas de segurança contra incêndio ocorre, frequentemente, de forma dissociada. Essa fragmentação normativa dificulta a consolidação de soluções integradas capazes de assegurar que rotas de fuga e dispositivos de emergência atendam, de maneira equitativa, a todos os usuários. Nesse contexto, torna-se necessário analisar criticamente o grau de convergência entre as exigências de acessibilidade e os regulamentos de prevenção e proteção contra incêndio, tema que fundamenta o desenvolvimento do presente estudo.

2.2 Design Universal como abordagem integradora

O Design Universal, conceituado por Ronald Mace [4], propõe que ambientes, produtos e sistemas sejam projetados para atender à diversidade humana desde sua concepção, reduzindo a necessidade de adaptações posteriores. Diferentemente de abordagens corretivas, o DU busca soluções inclusivas que beneficiem o maior número possível de usuários, independentemente de idade, capacidade física ou condição sensorial.

Os sete princípios do DU — uso equitativo (Princípio 1); flexibilidade no uso (Princípio 2); uso simples e intuitivo (Princípio 3); informação perceptível (Princípio 4); tolerância ao erro (Princípio 5); baixo esforço físico (Princípio 6); e tamanho e espaço adequados para aproximação e uso (Princípio 7) — oferecem um referencial consistente para a avaliação da acessibilidade em situações de emergência. Em contextos de incêndio, esses princípios contribuem para a criação de rotas de fuga mais compreensíveis, sinalizações perceptíveis em diferentes condições ambientais e dispositivos que minimizem o esforço físico e o risco de erro por parte dos ocupantes.

A aplicação do DU à segurança contra incêndio amplia o enfoque tradicional, que se limita ao atendimento de requisitos mínimos normativos, incorporando uma perspectiva centrada no usuário e em seu comportamento real durante emergências. O DU constitui base teórica para avaliar lacunas normativas e propor melhorias voltadas à evacuação inclusiva.

3. METODOLOGIA

Este estudo caracteriza-se como uma pesquisa aplicada de caráter exploratório, voltada à análise da incorporação da acessibilidade na legislação de prevenção e proteção contra incêndio. A investigação foi estruturada em duas etapas: (I) levantamento da percepção de profissionais da área de segurança contra incêndio e (II) análise normativa das RTs do CBMRS e da NBR 9050 [5], à luz dos princípios do Design Universal.

O questionário foi elaborado na plataforma Google Forms e composto por 18 perguntas (9 de múltipla escolha, 6 abertas e 3 em escala Likert de cinco pontos). A organização temática do instrumento e os objetivos de cada bloco são apresentados na Tabela 1.

Tabela 1: Estrutura do questionário

Bloco	Objetivo
Perfil profissional	Caracterizar a formação e experiência dos respondentes na área de segurança contra incêndio
Conhecimento normativo	Identificar o nível de conhecimento sobre normas relacionadas à acessibilidade e segurança contra incêndio
Percepção sobre acessibilidade	Avaliar a percepção dos profissionais sobre a importância da acessibilidade nas rotas de fuga
Experiência prática	Identificar situações reais de falhas de acessibilidade em edificações
Avaliação de recursos de evacuação	Avaliar a relevância de diferentes recursos para garantir evacuação inclusiva

Fonte: Elaborado pela autora

A Tabela 2 apresenta a lista completa das perguntas aplicadas aos participantes e o tipo de resposta correspondente.

Tabela 2: Perguntas do questionário aplicado aos profissionais

Nº	Pergunta	Tipo
1	Qual a sua área de formação?	Múltipla escolha
2	Você elabora projetos de segurança contra incêndio?	Múltipla escolha
3	Há quanto tempo você desenvolve projetos de segurança contra incêndio?	Múltipla escolha
4	Você considera aspectos de acessibilidade em seus projetos?	Múltipla escolha
5	Há quanto tempo você considera a acessibilidade em seus projetos?	Múltipla escolha
6	Cite os grupos de pessoas com deficiência que você leva em consideração em seus projetos	Aberta
7	As atuais normativas de projetos de segurança contra incêndio levam em consideração aspectos de acessibilidade?	Múltipla escolha
8	Cite as normativas e resoluções que você conhece que consideram acessibilidade	Aberta
9	Na sua opinião, qual a importância da acessibilidade nas rotas de fuga?	Escala Likert
10	Você acredita que os sistemas de prevenção e combate a incêndio consideram adequadamente pessoas com deficiência?	Múltipla escolha
11	Você já identificou falhas de acessibilidade em rotas de fuga ou saídas de emergência?	Múltipla escolha
12	Descreva situações em que percebeu falhas de acessibilidade	Aberta
13	As normas técnicas atuais são suficientes para garantir evacuação segura para todas as pessoas?	Múltipla escolha
14	Comente sobre a eficiência das normas atuais na evacuação de todas as pessoas	Aberta
15	Nível de importância de recursos de evacuação inclusiva	Escala Likert
16	Sugestão de medidas adicionais para evacuação segura	Aberta
17	Há necessidade de maior fiscalização quanto à acessibilidade nas medidas de prevenção?	Múltipla escolha
18	Comentário final sobre o tema	Aberta

Fonte: Elaborado pela autora

Na segunda etapa, realizou-se a análise normativa das RTs do CBMRS e a NBR 9050 [5]. Cada dispositivo normativo foi avaliado com base nos sete princípios do Design Universal. Para sistematizar a análise, foi adotada uma classificação qualitativa dos dispositivos normativos em quatro categorias: Atende, Atende Parcialmente, Não Atende e Fora de Escopo. Essa categorização permitiu comparar o conteúdo das normas com os princípios do DU, evidenciando convergências, lacunas e limitações na abordagem da acessibilidade no contexto da segurança contra incêndio.

A integração entre os resultados do questionário e da análise normativa possibilitou uma leitura crítica e articulada dos dados, relacionando a percepção dos profissionais às exigências formais das normas técnicas. Essa abordagem contribuiu para o fortalecimento da consistência metodológica do estudo e para a construção de uma discussão fundamentada sobre os desafios e as oportunidades para a incorporação de uma perspectiva mais inclusiva na segurança contra incêndio.

Como limitação da pesquisa, destaca-se que a amostra foi composta predominantemente por profissionais atuantes no estado do Rio Grande do Sul, o que pode influenciar a percepção sobre a aplicação das normas analisadas. Ainda assim, considera-se que os participantes possuem experiência prática relevante no desenvolvimento e análise de projetos de segurança contra incêndio, contribuindo para a compreensão do cenário normativo investigado.

4. RESULTADOS E DISCUSSÃO

4.1 Resultados do questionário aplicado aos profissionais

A pesquisa contou com a participação de 55 profissionais atuantes nas áreas de projeto, execução e análise de sistemas de segurança contra incêndio. Do total de respondentes, 52,7% declararam possuir mais de 5 anos de experiência profissional, indicando um grupo com atuação consolidada no campo da segurança contra incêndio e, portanto, com capacidade técnica para avaliar a aplicação das normas no contexto da prática profissional.

No que se refere à incorporação da acessibilidade nos projetos, 85,5% dos participantes afirmaram considerar esse aspecto em suas atividades profissionais, enquanto 14,5% declararam não adotar tais critérios. Em relação ao tempo de adoção dessas práticas, observa-se que a incorporação da acessibilidade ocorreu principalmente nos últimos 15 anos, sendo 34,5% entre 5 e 15 anos e 34,5% entre 1 e 5 anos. Apenas 18,2% indicaram considerar a acessibilidade há mais de 15 anos. Entre os perfis de usuários considerados nos projetos destacam-se pessoas em cadeira de rodas (30 menções), pessoas com deficiência visual (16), pessoas com deficiência auditiva (9) e pessoas idosas (8).

Quando questionados sobre a adequação das normas atuais de segurança contra incêndio em relação à acessibilidade, 38,2% dos profissionais consideraram que as normas não atendem adequadamente a esses requisitos, enquanto 34,5% avaliaram que atendem, e 27,3% declararam não possuir opinião formada sobre o tema. Esse resultado sugere percepções divergentes entre os profissionais, possivelmente associadas à ausência de diretrizes normativas claras ou à interpretação distinta das exigências existentes.

A percepção de limitações normativas é reforçada pelo fato de que 92,7% dos respondentes afirmaram já ter identificado falhas de acessibilidade em rotas de fuga ou saídas de emergência. Exemplos relatados incluem escadas inacessíveis, ausência de sinalização tátil e dependência exclusiva de recursos visuais ou sonoros para orientação durante a evacuação.

Referente a normas e resoluções técnicas atuais, 47,3% dos profissionais responderam ser parcialmente suficientes com relação à segurança de todas as pessoas em caso de evacuação de emergência, enquanto 40% afirmaram serem insuficientes. Além disso, 87,3% indicaram a necessidade de maior fiscalização quanto à acessibilidade nas medidas de prevenção.

Relatos de falhas em rotas de fuga e saídas de emergência, como escadas inacessíveis e ausência de sinalização tátil, indicam que a existência de normas não tem garantido sua efetiva implementação. Os resultados também apontam lacunas de conhecimento entre os profissionais, que por vezes consideram a acessibilidade apenas quando há exigência normativa ou demanda explícita. Esse cenário reforça a necessidade de integrar as normas de segurança contra incêndio aos princípios do Design Universal, ampliar a fiscalização e promover capacitação técnica na área.

4.2 Análise normativa sob a ótica do Design Universal

A análise das legislações foi conduzida a partir da leitura sistemática das RTs do CBMRS [6, 7, 8, 9, 10, 12, 15] e das NBRs [5, 13, 14, 16], confrontando seus dispositivos com os sete princípios do Design Universal. O objetivo foi identificar a presença, ausência ou inconsistência de requisitos relacionados à acessibilidade no contexto da segurança contra incêndio, especialmente no que se refere à evacuação segura de pessoas.

A fim de sintetizar os resultados da análise normativa, elaborou-se uma classificação das Resoluções Técnicas e normas analisadas segundo o atendimento aos sete princípios do Design Universal, utilizando as categorias *Atende*, *Atende Parcialmente*, *Não Atende* e *Fora de Escopo*. A Figura 1 apresenta uma síntese desta avaliação, permitindo uma leitura comparativa dos diferentes sistemas de segurança contra incêndio e evidenciando padrões recorrentes e lacunas na incorporação da acessibilidade.

Resoluções Técnicas do Corpo de Bombeiros e Normas ABNT		PRINCÍPIOS DO DESIGN UNIVERSAL						
		1	2	3	4	5	6	7
RT 11 Parte 01/2016 [6]	Saídas de Emergência	AP	AP	AP	AP	AP	A	AP
RT 12/2021 [8]	Sinalização de Emergência	AP	AP	A	A	AP	AP	AP
RT 13/2025 [9]	Iluminação de Emergência	AP	AP	AP	A	A	AP	AP
RT 14/2016 [10]	Extintores de Incêndio	AP	NA	AP	AP	AP	AP	AP
RT 15 Parte 1/2023 [12]	Brigada de Incêndio	AP	A	AP	AP	AP	AP	FE
NBR 13714/2000 [13]	Sistemas de hidrantes e de mangotinhos	NA	NA	AP	AP	AP	AP	AP
NBR 15219/2020 [14]	Plano de emergência	AP	AP	AP	AP	A	AP	AP
RT 18/2025 [15]	Alarme e detecção	A	AP	AP	A	AP	NA	AP

A = ATENDE / AP = ATENDE PARCIALMENTE / NA = NÃO ATENDE / FE = FORA DE ESCOPO

Figura 1: Avaliação das RTs e NBRs conforme os 7 Princípios do Design Universal

Elaborado pela autora

Os resultados evidenciam que nenhuma das normas e Resoluções Técnicas analisadas atende integralmente aos sete princípios do Design Universal. O padrão predominante observado corresponde ao atendimento parcial, no qual requisitos relacionados à acessibilidade são incorporados de forma pontual e não sistemática, enquanto outros permanecem ausentes ou insuficientemente contemplados.

Verificam-se, ainda, divergências normativas entre os regulamentos de segurança contra incêndio e as normas de acessibilidade, manifestadas, por exemplo, em diferenças de dimensionamento, na ausência de exigências relativas a recursos táteis e em limitações quanto à comunicação acessível. Tais inconsistências contribuem para uma aplicação não integrada da acessibilidade nos sistemas de segurança contra incêndio, especialmente em situações de emergência.

Esses resultados sugerem que a acessibilidade ainda é incorporada de maneira fragmentada e desigual, reforçando a necessidade de maior articulação entre as normas de acessibilidade e os regulamentos de prevenção e proteção contra incêndio, de modo a assegurar condições mais equitativas de uso e evacuação para todos os usuários.

4.2.1 Resolução Técnica de Saídas de Emergência

A RT 11 [6] estabelece critérios para dimensionamento de rotas de fuga, portas, corredores e escadas, com foco no fluxo de abandono da edificação. No entanto, a análise evidencia divergências relevantes em relação aos parâmetros de acessibilidade previstos na NBR 9050 [5]. O destaque positivo da RT é a previsão de área de resgate, porém este item ainda necessita ser aprofundado e melhor detalhado para ser funcional.

No quesito unidades de passagem, a RT 11 adota a medida de 55 cm, mostrando incompatibilidade com as dimensões mínimas necessárias para o deslocamento seguro e confortável de pessoas em cadeira de rodas, cuja largura padrão é de aproximadamente 63,5 cm [7]. As unidades de passagem interferem no dimensionamento de todos os itens da saída de emergência como por exemplo escadas, circulações e portas.

Esta desconexão compromete diretamente os Princípios 1 (uso equitativo) e 7 (tamanho e espaço para aproximação e uso), além de fragilizar o Princípio 6 (baixo esforço físico), uma vez que rotas subdimensionadas exigem maior esforço e aumentam o risco de congestionamentos em situações de emergência.

4.2.2 Resolução Técnica de Sinalização de Emergência

A RT 12 [8] apresenta avanços significativos no que se refere à padronização visual da sinalização, incorporando critérios de contraste, cores normatizadas, pictogramas universais e diferenciação tipológica entre sinalizações de alerta, orientação e salvamento. Esses aspectos contribuem para o atendimento parcial dos Princípios 3 (uso simples e intuitivo) e 4 (informação perceptível).

Entretanto, quando comparada à NBR 9050 [5], a RT 12 [8] revela lacunas importantes, sobretudo pela ausência de exigência de sinalização tátil no piso e nas paredes, identificação em Braille, mapas táteis e recursos sonoros complementares.

A falta de abordagem multissensorial limita o acesso à informação por pessoas com deficiência visual ou cognitiva, comprometendo também os Princípios 1 e 2 do Design Universal. Ressalta-se que a RT foi publicada após a revisão da NBR 9050 [5], o que evidencia uma oportunidade perdida de harmonização normativa.

4.2.3 Resolução Técnica de Iluminação de Emergência

A RT 13 [9] estabelece critérios mínimos de iluminância para rotas de fuga e áreas de circulação, utilizando valores expressos em lux. Contudo, observa-se divergência conceitual em relação à NBR 9050 [5], que além dos níveis de superiores de iluminância, enfatiza a qualidade da iluminação, controle de ofuscamento, uniformidade luminosa e contraste, aspectos fundamentais para a orientação espacial de pessoas com baixa visão.

A RT não aborda de forma explícita a relação entre iluminação e legibilidade dos ambientes, tampouco considera estratégias complementares, como iluminação próxima ao piso ou iluminação direcional. Essa abordagem restrita compromete o Princípio 4 (informação perceptível) e o Princípio 5 (tolerância ao erro), uma vez que condições inadequadas de iluminação aumentam o risco de desorientação e quedas durante a evacuação.

4.2.4 Resolução Técnica de Extintores de Incêndio

A RT 14 [10] apresenta lacunas expressivas quando analisada sob a ótica do Design Universal. Embora estabeleça critérios de distribuição e altura de instalação dos extintores, a amplitude permitida (com instalação podendo chegar a até 1,60m) dificulta o acesso por pessoas em cadeira de rodas, de baixa estatura ou com limitações de força e alcance.

Além disso, a norma não exige sinalização tátil, identificação em Braille ou dispositivos de acionamento intuitivo, contrariando recomendações de acessibilidade e estudos que apontam dificuldades de compreensão e uso desses equipamentos em situações de estresse [11]. Esses fatores comprometem diretamente os Princípios 1, 3, 6 e 7, evidenciando a necessidade de revisão normativa com foco em ergonomia, uso intuitivo e acesso equitativo.

4.2.5 Resolução Técnica de Brigada de Incêndio

A RT 15 [12] trata da formação e atuação das brigadas de incêndio, admitindo diferentes formatos de treinamento, o que contribui para o Princípio 2 (flexibilidade no uso). No entanto, a exigência de que os brigadistas possuam “boa condição física” e sejam alfabetizados, sem prever adaptações ou recursos acessíveis, exclui pessoas do processo formativo.

Essa abordagem contrasta diretamente com a NBR 9050 [5], que estabelece diretrizes para comunicação acessível, incluindo Libras, audiodescrição e linguagem simples. A ausência de

materiais didáticos acessíveis e de estratégias inclusivas compromete os Princípios 1, 3 e 4, além de reforçar uma lógica excludente incompatível com os fundamentos do Design Universal.

4.2.6 NBR 13714 – Hidrantes e Mangotinhos (não há RT específica do CBMRS)

A NBR 13714 [13] estabelece critérios técnicos para o dimensionamento, a instalação e a sinalização básica de sistemas de hidrantes e mangotinhos, porém não contempla diretrizes específicas de acessibilidade física ou ergonômica. Tal ausência pode ser compreendida em função do caráter especializado desses sistemas, cuja operação exige força física e conhecimento técnico, sendo destinada a profissionais capacitados, como brigadistas e bombeiros.

Ainda assim, seria pertinente que a norma enfatizasse a importância de sinalização acessível — visual e tátil — nos pontos de instalação, permitindo que qualquer ocupante, inclusive pessoas com deficiência visual, possa identificar e indicar esses recursos às equipes de resposta. Essa recomendação estaria alinhada ao Princípio 1 (uso equitativo) e ao Princípio 4 (informação perceptível) do Design Universal, mesmo que o uso direto não seja realizado por todos os usuários.

4.2.7 NBR 15219 – Plano de Emergência (não há RT específica do CBMRS)

A NBR 15219 [14] apresenta avanços ao reconhecer explicitamente a necessidade de contemplar pessoas com deficiência e mobilidade reduzida nos planos de emergência. O princípio da Tolerância ao Erro é bem representado por meio da redundância de procedimentos, definição clara de responsabilidades e segmentação de cenários de risco.

Entretanto, a norma não exige, de forma objetiva, a adoção de recursos multissensoriais, como alarmes vibratórios, sinalização tátil ou materiais acessíveis em treinamentos e simulados. Essa limitação compromete o atendimento pleno aos Princípios 4 e 6, sobretudo em contextos de baixa visibilidade e alto estresse.

4.2.8 Resolução Técnica de Alarme e Detecção

A RT 18 [15], que faz referência à ABNT NBR 17240 [16], apresenta foco predominante em alarmes sonoros e visuais, sem contemplar dispositivos vibratórios ou outras alternativas sensoriais. Essa abordagem limita a efetividade do sistema para pessoas surdas, com deficiência auditiva ou com hipersensibilidade sensorial, além de desconsiderar situações em que a percepção sonora ou visual possa estar comprometida, como em ambientes com presença de fumaça intensa.

Além disso, a norma apresenta divergências quanto às alturas de instalação dos equipamentos, permitindo posicionamentos que não observam as medidas recomendadas pela ABNT NBR 9050 [5], inclusive acima dos limites máximos por ela estabelecidos.

A ausência de exigências claras relativas à redundância sensorial fragiliza a aplicação dos Princípios 1, 4 e 5 do Design Universal. De forma complementar, as incongruências nas alturas de instalação interferem diretamente no Princípio 6, evidenciando que a lógica normativa ainda se orienta por um usuário padrão, sem incorporar de maneira efetiva a diversidade funcional presente nas edificações contemporâneas.

5. CONCLUSÕES

Este estudo analisou a incorporação da acessibilidade e dos princípios do Design Universal nas normas de segurança contra incêndio vigentes no estado do Rio Grande do Sul, a partir de uma abordagem integrada que combinou a percepção de profissionais da área e a análise normativa detalhada de diferentes sistemas de segurança. Os resultados evidenciam que, embora o arcabouço regulatório estadual tenha avançado significativamente no controle técnico dos sistemas de prevenção e proteção contra incêndio, a consideração da diversidade humana ainda ocorre de forma fragmentada e insuficiente.

A análise do questionário aplicado aos profissionais revelou que a acessibilidade, apesar de amplamente reconhecida como elemento essencial para a proteção à vida, ainda é tratada de maneira secundária na prática projetual e nos processos de análise técnica. Essa postura está diretamente relacionada à ausência de diretrizes normativas claras e integradas que orientem soluções voltadas à evacuação segura de pessoas com deficiência ou mobilidade reduzida, gerando insegurança técnica e jurídica e favorecendo o atendimento estrito aos requisitos mínimos.

A análise normativa por sistemas evidenciou divergências relevantes entre as Resoluções Técnicas do Corpo de Bombeiros Militar do Rio Grande do Sul e os parâmetros estabelecidos pela NBR 9050 [5], especialmente no que se refere às larguras de rotas de fuga, à sinalização acessível, aos critérios de iluminação, ao acesso aos equipamentos de emergência, aos sistemas de alarme e aos procedimentos previstos nos planos de emergência. Essas divergências comprometem, em diferentes níveis, o atendimento aos sete princípios do Design Universal.

Os resultados indicam que a abordagem predominantemente prescritiva das normas de segurança contra incêndio, centrada em um usuário padrão, limita a adoção de soluções mais inclusivas e alinhadas ao comportamento humano em situações de emergência. A ausência de estratégias multissensoriais, de parâmetros voltados à autonomia dos usuários e de integração efetiva com as normas de acessibilidade compromete a eficácia da evacuação e amplia os riscos em cenários reais de incêndio.

Nesse contexto, o Design Universal mostrou-se um referencial teórico e analítico adequado para revelar lacunas normativas e orientar reflexões sobre a necessidade de evolução das regulamentações vigentes. A incorporação sistemática de seus princípios às normas de segurança contra incêndio pode contribuir para a transição de uma abordagem baseada no cumprimento mínimo de requisitos para uma perspectiva orientada à segurança inclusiva, capaz de ampliar a proteção à vida para todos os usuários das edificações.

Como contribuição, este trabalho oferece subsídios técnicos para a revisão e o aprimoramento das normas de segurança contra incêndio, destacando a importância da convergência entre acessibilidade e proteção contra incêndio. Recomenda-se, para estudos futuros, a ampliação da análise para outros estados brasileiros, bem como a investigação de aplicações práticas dos princípios do Design Universal em edificações existentes, de modo a aprofundar a compreensão dos impactos destes desalinhamentos entre normas em contextos reais de emergência.

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LEGISLAÇÃO DE SEGURANÇA CONTRA INCÊNDIO EM SANTA CATARINA, NO BRASIL, E EM PORTUGAL PARA EDIFICAÇÕES RESIDENCIAIS MULTIFAMILIARES



Bruna S. Vachin
Pesquisadora
UTFPR - Curitiba
Brasil



Rodrigo E. Catai
Professor
UTFPR - Curitiba
Brasil



Gilberto A. F. Rouxinol
Professor
IPV - Viseu
Portugal

Palavras-chave: Segurança; Incêndio; Legislação; Normativa; Residencial.

1. INTRODUÇÃO

O fogo, quando fora de controle, pode resultar em morte e prejuízos materiais significativos. O avanço da vida moderna e a verticalização das edificações contribuem para um aumento nos riscos de incêndios [1]. No Brasil, o número de pessoas que moram em apartamentos em edifícios verticalizados tem crescido com o passar dos anos [2]. Já em Portugal, a maior parte das edificações do país são de edifícios com até três pavimentos [3].

Em uma pesquisa realizada no ano de 2022 com dados de 36 países, entre estes Portugal, Estados Unidos, França e Japão, foram registrados 2.768.205 incêndios, sendo que 23,1% foram incêndios estruturais em edificações residenciais. Dentre o total de mortes e feridos por incêndios no mesmo ano, 83% das mortes e 69,3% dos feridos são resultantes destes incêndios estruturais residenciais [4].

Diante deste cenário, para a mitigação dos riscos associados aos incêndios, são necessários projetos de proteção contra incêndio adequados [1]. Na elaboração destes projetos são atendidas as diretrizes contidas nas legislações de segurança contra incêndio específicas de cada país. Estas regulamentações garantem que o nível mínimo de segurança seja exigido e atendido pelas edificações, por meio da instalação de equipamentos de segurança contra incêndio e medidas construtivas [5].

No Brasil, as legislações de segurança contra incêndio passaram a se desenvolver de forma mais estruturada após os grandes incêndios na década de 1970, nos Edifícios Andraus e Joelma [6]. Em Portugal, por sua vez, apesar dos numerosos incêndios decorrentes do terremoto de Lisboa em 1755, apenas em 1951 foi publicado o primeiro regulamento com disposições específicas sobre o assunto no País [7].

Neste contexto, este estudo tem como objetivo realizar a análise comparativa entre a legislação brasileira, do Estado de Santa Catarina, e a legislação portuguesa, para projeto de segurança contra incêndio prescritivo, com foco em edifícios residenciais multifamiliares verticalizados. No Brasil a legislação de segurança contra incêndio é estabelecida em nível estadual, foi adotada a legislação do Estado de Santa Catarina, considerando o fato de o estado concentrar sete dos dez edifícios residenciais mais altos do país [8].

2. METODOLOGIA

A pesquisa é de natureza qualitativa, desenvolvida por meio de uma análise comparativa entre as legislações de segurança contra incêndio vigentes em Portugal e no Estado de Santa Catarina, no Brasil. A escolha dessas legislações justifica-se pela relevância do tema da proteção contra incêndio em edificações residenciais multifamiliares verticalizadas, bem como para análise das diferenças normativas existentes entre os dois países.

Foram analisados os diferentes sistemas e medidas de segurança contra incêndio aplicáveis às edificações residenciais multifamiliares verticalizadas, considerando distintas alturas de edificação. Com base nessa análise, foi elaborado um quadro comparativo com o objetivo de sintetizar as principais exigências normativas e evidenciar as diferenças e semelhanças observadas entre as legislações em questão.

3. RESULTADOS E DISCUSSÃO

No Estado de Santa Catarina, no Brasil, as edificações são classificadas em Grupos e Divisões, de acordo com a ocupação da edificação. As edificações residenciais multifamiliares são classificadas como Grupo A, ocupação residencial, Divisão A-2 – Habitação multifamiliar vertical. Os edifícios da divisão A-2 com área maior ou igual a 750 m² ou altura maior ou igual a 12 metros devem ser conforme a Tabela 1, que contém as exigências mínimas requeridas [9].

Tabela 1: Sistemas e medidas exigidos em Santa Catarina, no Brasil [Adaptado 9].

Sistemas e medidas	Altura da edificação em metros				
	Térrea	H≤6	6>H≤15	15>H≤30	H>30
Acesso de Viatura na Edificação	X	X	X	X	X
Segurança Estrutural Contra Incêndio	X	X	X	X	X
Chuveiros Automáticos					X ²
Compartimentação Horizontal ou de Áreas					X ³
Compartimentação Vertical				X ⁴	X ⁹⁻¹⁰
Controle de Fumaça					X ¹¹
Controle de Materiais de Acabamento			X ⁶⁻⁷	X ⁷	X ⁷
Deteção Automática de Incêndio					X ⁵
Elevador de Emergência					X ¹
Gás Combustível	X	X	X	X	X
Saídas de Emergência	X	X	X	X	X ¹²
Plano de Emergência					X ⁸
Iluminação de Emergência	X	X	X	X	X
Instalação Elétrica de Baixa Tensão	X	X	X	X	X
Alarme de Incêndio	X	X	X	X	X
Sinalização de Emergência	X	X	X	X	X
Extintores	X	X	X	X	X
Hidrantes e Mangotinhos	X	X	X	X	X

1 Exigido para imóveis que possuam altura igual ou superior a 60 m.

2 Chuveiros automáticos são exigidos para imóveis que possuam altura igual ou superior a 100 m.

3 Exigida compartimentação entre as unidades autônomas para edificação com altura superior a 75 m de altura. Pode ser substituído por chuveiros automáticos até 150 m de altura.

4 Exigido somente nos átrios, quando houver. A compartimentação em átrios pode ser substituída por controle de fumaça somente nos átrios.

5 Exigido detecção automática de incêndio a partir de 40 m de altura.

6 Somente para edificações com altura superior a 12 m.

7 Ocupação A-2 exige-se somente para áreas comuns.

8 Exigido para A-2 se imóvel com altura igual ou superior a 60 m.

9 Pode ser substituído por detecção automática de incêndio para edificações com até 40 m de altura. Havendo átrios, a compartimentação em átrios pode ser substituída por controle de fumaça somente nos átrios.

10 Para os imóveis A-2 com detecção automática de incêndio, a exigência se dá a partir de 60 m de altura. A compartimentação pode ser substituída por chuveiros automáticos para edificações com até 100 m de altura. Havendo átrios, a compartimentação no átrio pode ser substituída por controle de fumaça somente nos átrios.

11 Exigido para Átrios com altura superior a 6 m e corredores comunicantes, utilizados como rota de fuga, nas ocupações A-2 com altura superior a 90 m. Garagens e estacionamentos devem dispor de sistema de ventilação e exaustão conforme Código de Obras do Município, caso exista previsão. Caso não haja previsão, observar o artigo 24 da IN 10.

12 Reduto exigido a partir de 150 m.

Em Portugal, as edificações residenciais ou habitacionais correspondem a utilizações do Tipo I (Habitacionais). Quanto aos locais de risco das edificações, podem ser enquadrados em Locais de Risco A ou B, com exceção do interior das unidades habitacionais, que correspondem a locais sem riscos especiais e população até 100 pessoas. Quanto às categorias de risco dos edifícios tipo I, são considerados fatores de risco a altura da utilização-tipo e o número de pisos abaixo do plano de referência (pisos de descarga), conforme Tabela 2 [10]. Na Tabela 3 estão descritos os sistemas mínimos exigidos para cada categoria de risco das edificações Tipo I [11].

Tabela 2: Categorias de risco das utilizações tipo I [Adaptado 10]

Categorias de risco	Critérios referentes à utilização-tipo I (UT I)	
	Altura da UT I	Nº de pisos ocupados pela UT I abaixo do plano de referência
1ª	≤ 9 m	≤ 1
2ª	≤ 28 m	≤ 3
3ª	≤ 50 m	≤ 5
4ª	> 50 m	>5

Tabela 3: Sistemas e medidas exigidos em Portugal [Adaptado 11]

Sistemas e medidas	Categorias de risco			
	1ª	2ª	3ª	4ª
Acesso de Viatura na Edificação	X	X	X	X
Segurança Estrutural Contra Incêndio	X	X	X	X
Compartimentação Vertical		X	X	X
Controle de Materiais de Acabamento	X	X	X	X
Saídas de Emergência	X	X	X	X
Brigada de Incêndio			X	X
Iluminação de Emergência		X	X	X
Alarme de Incêndio			X	X
Sinalização de Emergência		X	X	X
Extintores			X	X
Hidrantes e Mangotinhos		X	X	X
Controle de fumaça	X	X	X	X
Detecção automática de incêndio				X
Elevador de Emergência			X	X
Plano de Emergência				X
Reduto				X

Com base nas legislações citadas, na Tabela 4 é apresentado um compilado das exigências de sistemas e medidas de segurança contra incêndio para cada altura de edificação residencial em cada local. Sendo a letra “B” para representar o Estado de Santa Catarina no Brasil, e a letra “P” para Portugal.

Tabela 4: Comparativo sistemas e medidas exigidos [Adaptado 9, 11]

Sistemas e medidas	Altura da edificação em metros							
	≤9	>9	>28	>30	>50	>60	>100	>150
Acesso de Viatura	B P	B P	B P	B P	B P	B P	B P	B P
Segurança Estrutural	B P	B P	B P	B P	B P	B P	B P	B P
Comp. Horizontal						B ¹		B
Comp. Vertical		P	P	P	P	B P	B P	B P
Chuveiros Automáticos							B	B
Controle Mat. de Acab.	P	B ² P	B P	B P	B P	B P	B P	B P
Saídas de Emergência	B P	B P	B P	B P	B P	B P	B P	B P
Brigada de Incêndio			P	P	P	P	P	P
Ilum. de Emergência	B	B P	B P	B P	B P	B P	B P	B P
Inst. Ele. Baixa Tensão	B	B	B	B	B	B	B	B
Alarme de Incêndio	B	B	B P	B P	B P	B P	B P	B P
Sin. De Emergência	B	B P	B P	B P	B P	B P	B P	B P
Extintores	B	B	B P	B P	B P	B P	B P	B P
Hidran. e Mangotinhos	B	B P	B P	B P	B P	B P	B P	B P
Controle de fumaça	P	P	P	P	P	B ³ P	B P	B P
Detec. Autom. incêndio				B	B P	B P	B P	B P
Elev. de Emergência			P	P	P	B P	B P	B P
Gás Combustível	B	B	B	B	B	B	B	B
Plano de Emergência					P	B P	B P	B P
Reduto					P	P	P	B P
1 A partir de 75 m								
2 A partir de 12 m								
3 A partir de 90 m								

Observa-se na Tabela 4 que para edificações com altura até 9 metros, o estado de Santa Catarina possui um maior número de sistemas e medidas exigidos para as edificações, sendo que somente o controle de fumaça e controle de materiais de acabamento e revestimento é exigido apenas para Portugal. Os seguintes sistemas são exigidos apenas em Santa Catarina: alarme de incêndio (até 28 metros), extintores (até 28 metros), gás combustível, hidráulico preventivo, iluminação de emergência, instalação elétrica de baixa tensão e sinalização para abandono de local.

Já para os edifícios com altura superior a 9 metros, existe uma paridade entre os sistemas exigidos para cada local, sendo que apenas os seguintes sistemas são exigidos somente em Portugal: brigada de incêndio, controle de fumaça (até 90 metros), elevador de emergência (entre 28 e 60 metros) e reduto (entre 50 e 150 metros), compartimentação vertical (até 60 metros) e plano de emergência (entre 50 e 60 metros), e os seguintes exigidos somente em Santa Catarina: chuveiros automáticos, compartimentação horizontal, gás combustível, detecção automática de incêndio (entre 30 e 50 metros) e instalações elétricas de baixa tensão.

Além das diferenças de sistemas e medidas exigidos para cada altura de edificação, existem também divergências com relação a aplicação dos sistemas em Santa Catarina, no Brasil e em Portugal. A seguir serão tratados os sistemas que possuem estas diferenças.

O acesso de viaturas para as edificações, em Santa Catarina, no Brasil, consiste em condições das vias de acesso para a edificação [12]. Em Portugal existem outras medidas além das condições das vias, como a necessidade de pontos de penetração nas fachadas, também existem exceções quanto as exigências das vias em centros urbanos antigos, devido as características históricas do país [11].

Quanto ao sistema de alarme e detecção de incêndio nas edificações, observa-se que em Santa Catarina, no Brasil, a detecção automática de incêndio contempla o interior das unidades privativas, o que não ocorre em Portugal. Também se observam diferentes exigências quanto as características nas instalações e central de alarme de incêndio [13,11].

A principal diferença observada nos sistemas de compartimentação em ambos os locais, consiste no fato de que em Portugal não existe a exigência de compartimentação entre as unidades autônomas para nenhuma altura de edificação. Para a proteção estrutural, o tempo exigido de resistência ao fogo das estruturas (TRRF) de acordo com a altura da edificação difere em ambos os locais, sendo que em Portugal o máximo de tempo é de 120 minutos, e em Santa Catarina, no Brasil, é de 150 minutos [11, 14].

No Controle de Materiais de Acabamento e Revestimento se observa que apenas em Portugal é exigido que o controle seja atendido pelos materiais de decoração e mobiliário fixo. Além disso, o sistema é exigido em Portugal nos espaços comuns dos edifícios, já em Santa Catarina, no Brasil, é exigido nas rotas de fuga e saídas de emergência [15,11].

Os extintores de incêndio são exigidos em um número mínimo de duas unidades em ambos os locais. Porém, em Portugal é permitido a instalação dos equipamentos no interior da antecâmara da escada de emergência, o que não é permitido no Brasil [16,11].

Quanto ao Sistema Hidráulico Preventivo (Hidrantes e Mangotinhos), observa-se que em Santa Catarina, no Brasil, é facultativa a escolha pelo sistema de Hidrantes ou Mangotinhos, enquanto em Portugal, a partir dos 28 metros de altura, é obrigatório o uso também de mangotinho. Também se observou que em Portugal é permitido o uso de tubulação seca para edifícios até 28 metros de altura, o que não ocorre no Brasil. Assim como os extintores, apenas em Portugal é permitido que o sistema esteja localizado nas antecâmaras ou nas escadas de emergência. A vazão mínima exigida para o sistema de mangotinhos e hidrantes em Santa Catarina é de 80 L/min e 70 L/min, consecutivamente, já em Portugal é de 90 L/min e 180 L/min [11, 17].

O sistema de saídas de emergência, por ser um sistema complexo, foi o sistema que se observaram um maior número de diferenças em ambos os locais. Para o cálculo da largura das saídas de emergência, no Brasil o valor de 1 UP (Unidade de Passagem) é igual a 55 cm, já em Portugal é de 60 cm a partir de mais de 2 UPs. A largura mínima das rotas de fuga no Brasil é de 1,20 m em todos os casos, a depender da população, já em Portugal é de 0,90 m para edifícios com altura até 9 metros, 1,20 m para alturas até 28 metros, e de 1,40 m para os demais casos. Quanto ao cálculo da população do edifício, em Portugal a normativa não especifica um parâmetro para este dimensionamento, e este valor é utilizado para a definição do número mínimo de saídas. No Brasil, é considerado um número de 2 pessoas por dormitório, para

edificações residenciais. Também são diferentes os valores de distâncias máximas permitidas a serem percorridas até a saída da edificação ou local seguro [11,18].

As escadas de emergência em Santa Catarina, no Brasil, e em Portugal são apresentadas na Tabela 5. A distância entre portas na antecâmara exigida para o Brasil é de 1,80 m, e em Portugal é de 1,20 m. Além disso, no Brasil não é permitido que a escada de emergência se comunique diretamente com a escada de acesso ao subsolo, devendo haver uma interrupção da mesma no piso de descarga, em Portugal também existe esta exigência, mas apenas para edifícios com altura superior a 3 pisos ou 28 metros de altura [11,18].

Tabela 5: Comparativo tipos de escadas [Adaptado 18, 11]

Local		Brasil	Portugal
Altura (metros)	-		
$H \leq 12$	Quantidade	1	1
	Tipo	ECM	Controle de fumo Portas E-30
$21 < H \leq 28$	Quantidade	1	1
	Tipo	EPT	Controle de fumo Portas E-30
$28 < H \leq 30$	Quantidade	1	1
	Tipo	EEE	Controle de fumo Portas E-30
$30 < H \leq 75$	Quantidade	1	2
	Tipo	EEE	Sobrepresão e desenfumagem Câmara corta-fogo
$H > 75$	Quantidade	2	2
	Tipo	EPF	Sobrepresão e desenfumagem Câmara corta-fogo

ECM: Escada comum
EPT: Escada protegida
EEE: Escada enclausurada com exaustão
EEV: Escada enclausurada com ventilação
EPF: Escada à prova de fumaça

Quanto ao Reduto Resistente ao Fogo, o mesmo é exigido em Santa Catarina para edifícios com altura superior a 150 metros, devendo estar situado a cada no máximo 75 metros. Em Portugal a exigência ocorre para edifícios com altura superior a 50 metros, e deve estar situado a cada 10 pavimentos [11,18].

4. CONCLUSÃO

As legislações de segurança e prevenção contra incêndio no Brasil e em Portugal estabelecem requisitos mínimos a serem atendidos pelos edifícios visando à preservação da vida humana e do patrimônio. A comparação entre essas legislações possibilita a identificação das diferentes abordagens adotadas em cada país quanto a este aspecto.

Nesta pesquisa inferiu-se que apesar de Portugal possuir uma predominância de edifícios residenciais com baixa altura, até três pavimentos, a quantidade de sistemas e medidas de segurança contra incêndio exigidos para estas edificações é menor comparativamente ao Estado de Santa Catarina, no Brasil. Sistemas e medidas de segurança contra incêndio vitais e consolidados no Brasil, como o extintor de incêndio, iluminação de emergência e sinalização para abandono de local, não são exigidos para estas alturas de edificação em Portugal. Por outro lado, para alturas superiores das edificações, o número de sistemas e medidas de segurança exigidos em cada país são semelhantes.

Além das diferenças de sistemas e medidas exigidos também se observaram diferentes regras para aplicação de um mesmo sistema ou medida. Dessa forma, verifica-se que a observância de determinado sistema ou medida pode ser tratado com diferentes níveis de prioridade, a depender da localidade em que são aplicados.

Existem diversos fatores que podem influenciar nestas diferenças normativas observadas entre os dois países. Para uma compreensão mais abrangente, é necessário um aprofundamento no histórico da elaboração das legislações em cada local, entretanto, observa-se que os incêndios históricos de cada país, técnicas construtivas e aspectos culturais influenciam neste resultado.

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ANÁLISE DO CONHECIMENTO DE ENGENHEIROS E ARQUITETOS SOBRE A REAÇÃO AO FOGO DOS MATERIAIS DE CONSTRUÇÃO

Ângela Gaio Graeff

Professora, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil

Felipe Risbacik*

Mestrando, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brasil.

Kauê Luís Brandão

Mestrando, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brasil.

Mônica Muller Anschau

Mestranda, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brasil.

Samuel Onofre Cavalcante

Doutorando, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brasil.

Palavras-chave: Controle de Materiais de Acabamento e Revestimento; Segurança Contra Incêndio; Reação ao fogo; Engenheiros e arquitetos; Questionário.

1 INTRODUÇÃO

A segurança contra incêndio (SCI) no Brasil passou a receber maior atenção a partir da década de 1970, em decorrência de dois grandes incêndios ocorridos na cidade de São Paulo. A partir desses eventos, a legislação foi submetida a sucessivas atualizações, com o objetivo de adequar-se às novas características construtivas das edificações [1].

No contexto da área de gestão de risco, observa-se que os avanços no campo da SCI frequentemente são impulsionados por eventos catastróficos de grande magnitude, os quais geram ampla comoção social e demandam respostas imediatas por parte do poder público. Esse cenário evidencia um caráter predominantemente reativo das políticas de segurança, nas quais a ocorrência do sinistro antecede a implementação de medidas preventivas e a revisão dos dispositivos normativos. O incêndio da Boate Kiss, ocorrido em 2013 na cidade de Santa Maria (RS), constitui um exemplo emblemático desse processo, tendo provocado mudanças significativas na legislação e na regulamentação da segurança contra incêndio no país [2 – 3].

Além de seus desdobramentos normativos, o incêndio da Boate Kiss apresenta similaridades técnicas com o ocorrido no bar Le Constellation, em 2026, na cidade de Crans-Montana, Suíça.

* Autor correspondente — Laboratório de Ensaios e Modelos Estruturais (LEME), Universidade Federal do Rio Grande do Sul. Ave. Bento Gonçalves, nº 9500, Porto Alegre (Brasil). Telef.: +55 051 995883820, E-mail: feliperisbacik@hotmail.com

Em ambos os casos, a dinâmica de início e de desenvolvimento do incêndio esteve associada ao uso de materiais de acabamento e revestimento com desempenho insatisfatório quanto à reação ao fogo. Na Boate Kiss, o incêndio teve início com o uso de um artefato pirotécnico durante um show, cujas chamas atingiram o forro do ambiente, favorecendo a rápida propagação do fogo e a intensa produção de fumaça [4]. De modo semelhante, no Le Constellation, o incêndio eclodiu durante as comemorações de Ano-Novo, quando as chamas de uma vela entraram em contato com o revestimento do teto [5]. Esses episódios demonstram que a utilização inadequada de materiais internos pode exercer influência decisiva na severidade de incêndios em edificações de uso coletivo.

Nesse contexto, a reação ao fogo dos materiais empregados nas edificações pode ser compreendida como a capacidade do material de sofrer e sustentar a ignição, de propagar chamas, de desenvolver calor e de produzir fumaça. Essas características constituem um fator condicionante para a rapidez com que a inflamação generalizada pode ocorrer no ambiente de origem do incêndio. A velocidade de evolução de um foco de incêndio pode reduzir de forma significativa o tempo disponível para o abandono seguro da edificação e limitar as possibilidades de extinção, enquanto a liberação intensa de calor e fumaça compromete rapidamente as condições de visibilidade e de respiração, ampliando o risco aos ocupantes e dificultando a atuação dos bombeiros [6].

No Rio Grande do Sul, o estabelecimento de padrões para evitar o surgimento de condições que propiciem o crescimento e a propagação de fogo e fumaça em edificações ocorre por meio do controle de materiais de acabamento e de revestimento (CMAR), instituído pela resolução técnica Nº 9 de 2025 do Corpo de Bombeiros Militar do Rio Grande do Sul (CBMRS). O CMAR estabelece que os materiais de acabamento e de revestimento devem ser classificados quanto ao seu comportamento em situação de incêndio através de ensaios de reação ao fogo e determina quais classes de materiais são admissíveis para utilização de acordo com o grupo e a divisão da ocupação e uso da edificação, considerando a finalidade do material [7 – 8].

Um estudo realizado em 2021, que quantificou incêndios de grande impacto social, evidenciou que a ausência do controle de materiais de acabamento e revestimento (CMAR) constitui um fator determinante para a ocorrência de vítimas em situações de incêndio. Como conclusão, os autores destacaram a urgência do aprofundamento técnico desse tema, especialmente no âmbito da formação superior dos profissionais da área [9]. Em outro trabalho foi mostrado que a ausência do ensino de SCI obrigatório nos cursos de Arquitetura e Engenharia do Brasil, contribui para uma formação técnica deficiente, favorecendo o desconhecimento da área e a ocorrência de erros de projeto com potencial de comprometer a segurança das edificações [10]. Por fim, um estudo sobre o comércio de materiais de revestimento e de acabamentos internos em Porto Alegre, mostrou que os fabricantes muitas vezes não realizam ensaios de reação ao fogo, apresentam laudos incompletos ou inadequados e tem reduzido comprometimento com o CMAR [11]. Diante desse conjunto de trabalhos, observa-se um possível quadro de fragilidade na formação profissional, na fiscalização e no controle técnico dos materiais, o que pode comprometer a efetividade das estratégias de segurança contra incêndio no país.

Nesse contexto, a análise do conhecimento dos profissionais que atuam na área de SCI sobre a escolha de materiais de acabamento e revestimento torna-se essencial, tendo em vista os

impactos observados em eventos como o incêndio da Boate Kiss e do Le Constellation. Avaliar o domínio desses profissionais sobre o CMAR permite diagnosticar a situação do conhecimento técnico aplicado aos projetos de segurança contra incêndio, constituindo o primeiro passo para a proposição de estratégias de aprimoramento da formação e da prática profissional. Assim, este artigo tem como objetivo compreender o grau de conhecimento de engenheiros e arquitetos do Rio Grande do Sul que atuam na área de SCI, bem como identificar possíveis incoerências entre o conhecimento declarado e a prática profissional relatada.

2 MÉTODO DE PESQUISA

O presente artigo caracteriza-se como uma pesquisa do tipo levantamento (*survey*), modalidade metodológica que se fundamenta na coleta direta de informações junto a um grupo de indivíduos cujo comportamento, conhecimento ou práticas se deseja analisar. Esse tipo de pesquisa consiste na aplicação de instrumentos padronizados – por exemplo, questionários – a uma amostra representativa da população de interesse, permitindo a obtenção de dados quantitativos passíveis de tratamento estatístico e análise sistemática [12].

Entre as principais vantagens dos estudos por levantamento destacam-se a possibilidade de acesso direto à realidade investigada, a rapidez na obtenção dos dados, a economia de recursos e a viabilidade de quantificação dos resultados. Por outro lado, esse método apresenta como limitações a ênfase nos aspectos perceptivos e declaratórios dos respondentes, bem como a restrição na apreensão de processos dinâmicos ou evolutivos ao longo do tempo [12].

Nesse sentido, o presente estudo adotou a aplicação de um questionário elaborado na plataforma Google Forms e composto por 30 questões. O instrumento foi inicialmente divulgado em cinco grupos de WhatsApp que reúnem engenheiros e arquitetos atuantes na área de segurança contra incêndio no estado do Rio Grande do Sul, totalizando 512 convidados. O questionário permaneceu disponível para resposta no período de 1º a 30 de agosto de 2025. Os dados coletados por meio do questionário encontram-se disponíveis para consulta no seguinte link:

- <https://shre.ink/5od4>

O questionário contemplou seis dimensões principais: (i) perfil profissional; (ii) conhecimento normativo; (iii) práticas de projeto e execução; (iv) dificuldades na aplicação do CMAR; (v) conhecimento técnico sobre classificação de materiais e normas de ensaio; (vi) orientação a clientes e proprietários.

3 RESULTADOS

3.1 Perfil e experiência

A pesquisa obteve 27 respostas ao questionário em um universo de 512 profissionais

convidados, o que corresponde a aproximadamente 5% de taxa de adesão. Esse baixo índice de participação pode estar relacionado à grande extensão do questionário ou ao eventual desinteresse e à baixa capacidade técnica de parte dos profissionais convidados a se manifestar sobre o tema. Dentre os participantes, 14 se identificaram como engenheiros, 12 como arquitetos e 1 como construtor. Em relação ao grau de formação acadêmica, 11 possuem apenas graduação, 15 possuem especialização e 1 possui mestrado (Figura 1). Mais de 70% dos respondentes relataram ter mais de oito anos de experiência na área (Figura 2). Essas características indicam que a amostra apresenta representatividade em termos de prática profissional consolidada.

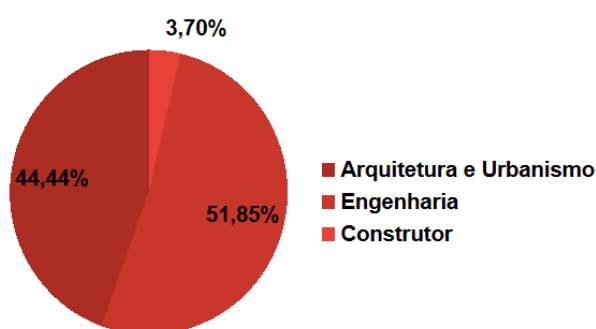


Figura 1: Respostas obtidas a partir da pergunta 1- “Você é profissional da área de:”

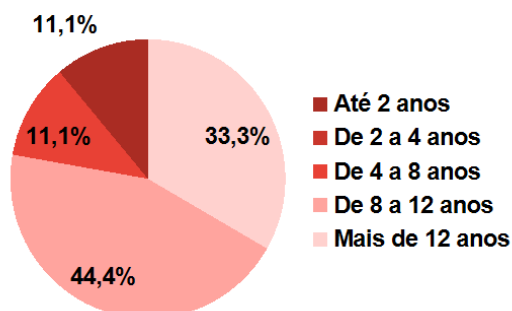


Figura 2: Respostas obtidas a partir da pergunta 5 - “Há quanto tempo você atua na área de Segurança Contra Incêndio?”

3.2 Conhecimento normativo declarado *versus* prática observada

O levantamento revelou uma divergência entre o conhecimento declarado pelos profissionais e sua aplicação prática no contexto do controle de materiais de acabamento e revestimento. Entre os 27 respondentes, 20 afirmaram possuir pleno conhecimento das normas e legislações aplicáveis ao CMAR. Entretanto, apenas seis profissionais relataram solicitar laudos técnicos de forma sistemática, enquanto a maioria restringe-se à consulta de certificações fornecidas pelos fabricantes (Figura 3). Esses resultados podem indicar que o conhecimento normativo

nem sempre se traduz em práticas consistentes de verificação e controle técnico dos materiais nas edificações.

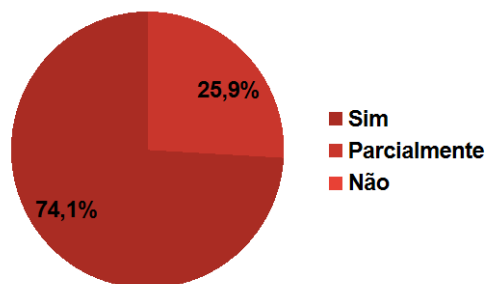


Figura 3: Respostas obtidas a partir da pergunta 6 - “Você tem conhecimento sobre as normas e legislações aplicadas ao Controle de Materiais e Acabamentos e Revestimentos – CMAR?”

Também houve uma incoerência identificada nas respostas sobre classificação de materiais: embora 17 profissionais tenham declarado conhecer integralmente a resolução técnica N° 9 de 2025 do CBMRS, somente 13 reconheceram corretamente a Classe VI como não permitida, enquanto 11 consideraram erroneamente a Classe V como proibida (Figura 4). Além disso, três profissionais declararam priorizar a Classe VI nos projetos. Nesse contexto, torna-se importante salientar que tal classe é explicitamente vedada pela normativa.

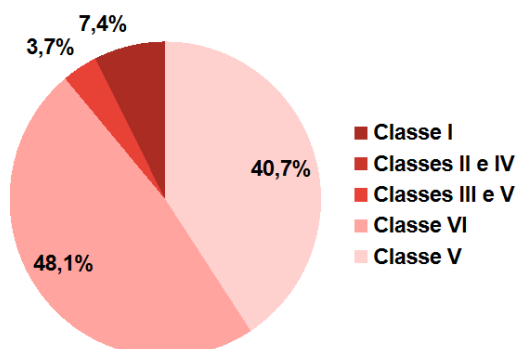


Figura 4: Respostas obtidas a partir da pergunta 20 - “Sabendo-se que os materiais de Revestimentos e Acabamentos se classificam em 6 classes, qual a classe que não é permitida utilizar nas edificações que necessitam de CMAR?”

3.3 Documentação e rastreabilidade técnica

A documentação dos materiais de acabamento e revestimento junto aos projetos utilizados apresenta fragilidades significativas. Apenas cinco profissionais afirmaram registrar de forma detalhada a origem e as especificações técnicas, enquanto 17 limitaram-se a fornecer informações básicas. Observa-se, entretanto, que 20 declararam sempre revalidar a

compatibilidade dos materiais diante de alterações de projeto. Essa divergência pode mostrar que, embora haja reconhecimento da necessidade de atualização, os registros produzidos não asseguram rastreabilidade suficiente para auditorias ou vistorias, comprometendo a confiabilidade do processo (Figura 5).

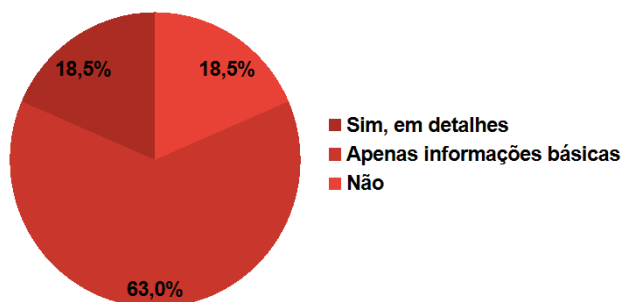


Figura 5: Respostas obtidas a partir da pergunta 14 - "Você documenta a origem e as especificações técnicas dos materiais de acabamento utilizados (ex.: fichas técnicas e laudos)?"

3.4 Principais dificuldades relatadas

A dificuldade mais recorrente refere-se à falta de informações claras fornecidas pelos fabricantes, apontada por 14 respondentes. Também foram mencionados laudos confusos, ausência de critérios normativos objetivos e pressões relacionadas a prazos ou custos. Apenas três profissionais declararam ter submetido materiais a ensaios laboratoriais independentes (Figura 6).

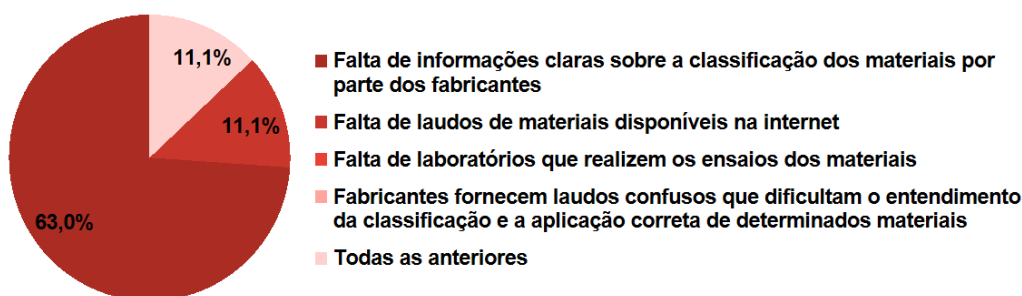


Figura 6: Respostas obtidas a partir da pergunta 22 - "Quais as principais dificuldades que você encontra quando está selecionando e/ou classificando os materiais que serão empregados em uma edificação?"

Logo, é possível concluir que a principal dificuldade enfrentada pelos profissionais na aplicação do CMAR consiste na obtenção de informações técnicas claras, confiáveis e de qualidade

sobre os produtos de revestimento e acabamento. Tal cenário pode estar associado à insuficiência de fiscalização governamental, ao baixo interesse da indústria e do comércio em relação a SCI dos seus produtos e à escassez de instituições habilitadas para a realização de ensaios. Ressalta-se que a responsabilidade pela realização de ensaios para a comprovação do desempenho dos produtos de revestimento e acabamento não deve recair sobre os profissionais, mas sobre os fabricantes e fornecedores que os produzem e comercializam.

3.5 Conhecimento técnico sobre ensaios e normas

A análise revelou lacunas significativas no conhecimento normativo dos profissionais: seis respondentes declararam não conhecer nenhuma norma de ensaio aplicável ao CMAR, enquanto apenas três relataram domínio abrangente das normas nacionais e internacionais (ABNT, EN, ASTM, ISO) (Figura 7). Essa limitação pode contribuir para a dificuldade na interpretação de laudos técnicos e pode ampliar a dependência das informações simplificadas presentes em certificados comerciais.

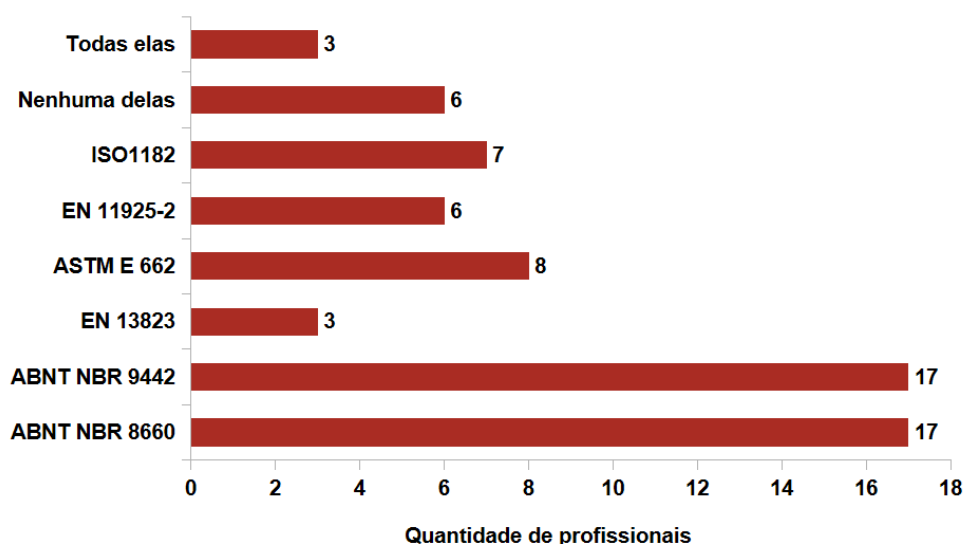


Figura 7: Respostas obtidas a partir da pergunta 19 - “Das normas de ensaios apresentadas no Laudo CMAR dos bombeiros, quais você conhece?”

3.6 Orientação a clientes e proprietários

Um aspecto positivo observado refere-se à comunicação com os responsáveis pelas edificações. A maioria dos profissionais relatou orientar quanto à manutenção preventiva e à necessidade de arquivamento dos laudos técnicos para fins de vistoria. Entretanto, apenas oito declararam indicar sistematicamente empresas qualificadas para manutenção, enquanto 14 indicaram apenas mediante solicitação (Figura 8). Esses dados podem sugerir a ausência de

padronização nas práticas e uma fragilidade no acompanhamento do ciclo de vida dos sistemas de proteção contra incêndio.

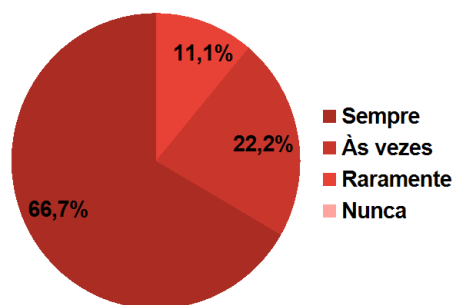


Figura 8: Respostas obtidas a partir da pergunta 29 - “Você orienta o responsável ou proprietário da edificação a manter os laudos técnicos e resultados de ensaios arquivados junto à edificação para eventuais vistorias extraordinárias?”

4 CONCLUSÕES

A pesquisa evidencia que, embora os profissionais participantes possuam sólida experiência e declarem conhecer as normas aplicáveis ao CMAR, persistem incoerências significativas entre o discurso e a prática. Entre as principais constatações, destacam-se:

- Inconsistência dos profissionais entre o conhecimento declarado e a classificação efetiva dos materiais, incluindo casos em que classes proibidas foram consideradas aceitáveis;
- Fragilidade da documentação técnica por parte dos profissionais, restrita, em sua maioria, às informações básicas, ainda que se reconheça a necessidade de revalidação em situações de alteração de projeto;
- Principal dificuldade relatada pelos profissionais na aplicação do CMAR é a obtenção de informações técnicas claras, confiáveis e de qualidade sobre os produtos de revestimento e acabamento;
- Lacunas conceituais dos profissionais quanto ao domínio das normas de ensaio, o que limita a interpretação crítica de laudos técnicos.

Tais resultados apontam para a necessidade de fortalecimento da capacitação continuada, com ênfase na interpretação normativa e no domínio das normas de ensaio, além da criação de protocolos padronizados de avaliação e documentação. Adicionalmente, a ampliação da rede de laboratórios reconhecidos e o incentivo à prática de ensaios independentes podem contribuir para maior confiabilidade no processo de seleção de materiais.

Embora o número de respostas seja limitado, os dados obtidos já permitem uma primeira compreensão da situação do conhecimento e das práticas relacionadas ao CMAR. Nesse sentido, dada a limitação, recomenda-se a realização de pesquisas adicionais, a fim de gerar dados mais robustos que possibilitem uma compreensão mais aprofundada da situação.

Por fim, a consolidação do CMAR como instrumento efetivo de segurança contra incêndio no Rio Grande do Sul exige o protagonismo das instituições de ensino na capacitação de profissionais e na realização de ensaios, de modo a promover a qualificação técnica do setor e o fortalecimento das práticas de prevenção e segurança contra incêndio. Aliado a isso, é importante que exista um esforço conjunto entre universidades, profissionais, poder público, órgãos estatais reguladores e fornecedores para visar a superação das incoerências identificadas e a elevação do padrão de rigor técnico na área.

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HOLISTIC APPROACH TOWARDS FIRE SAFETY OF FACADES: PROPOSED REGULATORY FRAMEWORK FOR FIRE SAFE BUILDINGS



Franklyn Okwara¹
Fire safety Expert
Modern Building
Alliance-Belgium



Dr. Emanuela Gallo²
Technical Affairs
Manager
Association for
European
Manufacturers of
Expanded
Polystyrene- Belgium

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ABSTRACT

Recent fire incidents in high rise buildings have highlighted their vulnerability, particularly regarding flame spread across façade systems. Insulation materials, widely used for their durability, energy efficiency, and design flexibility, play a critical role in sustainable construction but require robust fire safety integration to maximize their benefits. The Modern Building Alliance (MBA) has developed the B.I.O. (Building, Installation, Organization) framework to support European Member States in establishing comprehensive fire safety strategies.

This paper extends MBA's previous work by adapting the B.I.O. framework to address façade fire safety specifically. It emphasizes that fire performance of façade systems must be assessed holistically, considering the interaction of insulation materials, cladding types, and building design rather than isolated component performance. The study highlights the importance of large-scale testing and performance-based regulatory approaches to ensure occupant safety and effective firefighting conditions. By providing structured guidance for regulators and the construction sector, the adapted framework identifies gaps, promotes best practice, and reinforces the shared responsibility of the entire value chain in achieving safe and sustainable high-rise buildings.

¹Franklyn Okwara — Modern Building Alliance, MBA, Rue Defacqz 52 • 1050 Brussels (Belgium)
Tel.: +32491159473, E-mail: franklyn@modernbuildingalliance.eu

²Dr. Emanuela Gallo -Association for European Manufacturers of Expanded Polystyrene- EUMEPS, Avenue de Cortenbergh 71, 1000 Brussels (Belgium)
Tel: +49 1567916046 E-mail: e.gallo@eumeps.org

1. INTRODUCTION

High-rise buildings represent a hallmark of modern urban architecture, often linked to premium living spaces. Modern façade systems that envelop them function not only as visually expressive components, but also as advanced, multifunctional envelopes engineered to provide protection against environmental factors including wind, precipitation, solar radiation, thermal variations, and noise [1]. Facade systems commonly fall into two categories: External Thermal insulation Composite Systems (ETICS) and external ventilated cladding systems. Another system to mention is the curtain wall system. These systems include insulation materials of various reaction to fire classes (e.g., A1 to E based on EN 13501-1) [2] and the system's fire performance under specific conditions, can significantly influence overall fire dynamics and behavior. Integrating these materials' fire properties into the building's holistic fire strategy is essential.

While high-rise buildings positively enhance modern cities, their vulnerability to fire has become evident in the increasing number of high-rise fire incidents, worldwide. Recent fire patterns in high-rise buildings such as Torre dei Moro, Milan August 2021, Torre Ambar, Madrid in August 2020, Grenfell Tower, London in June 2017, The Marina Torch, Dubai in 2015 reveal the need to address the critical role of flame spread on façade systems to guarantee the safety of the occupants. Without robust compartmentalization, smoke free evacuation routes and reliable alarm systems, conditions for the evacuation of occupants can be challenging, and firefighting efficiency can be reduced.

In response, the Modern Building Alliance (MBA) presented its original B.I.O (Building, Installation, Organization) framework in 2019, with a comprehensive and structured list of elements for consideration by European Member States in formulating their regulatory approach to the fire safety of buildings. This holistic approach addresses the need for adequate building design and construction, technical installations and ongoing fire safety management throughout the building's lifecycle [3]. Numerous studies and applied research projects demonstrate the effectiveness of this approach [4,5].

This paper extends MBA's previous studies [3] to ensure not only a valid fire safety concept for buildings is in place; it particularly explains how to ensure the fire safety of façade systems. It emphasizes that facades must be considered holistically and cannot be designed based on the performance of isolated components only. The adapted framework offers guidance for performance-based façade assessment, based on large-scale testing and B.I.O principles.

2. ADAPTATION OF THE B.I.O FRAMEWORK

In the framework, the three identified key aspects -Building, Installation and Organization- are investigated to provide a clear foundation for Member State (MS) regulators and the construction sector, supporting identification of gaps and best practices in fire safety. National and regional regulations define requirements for these elements while member states are responsible for ensuring proper enforcement and compliance. This approach is consistent with findings from the JRC technical report on fire safety engineering in Europe, which highlights the importance of coherent regulatory frameworks in enabling effective and harmonized fire safety practices across Member States [6].

2.1 Building Requirements

The definition of building categories in national regulations is based on many factors like height, occupancy and risk profile. Some countries have developed different regulatory requirements, for example for small, mid-height and high-rise buildings, other countries have specific requirements only for "normal" structures and for high-rise buildings.

A building's fire safety strategy must be an integral part of the building design process. To begin with, comprehensive fire prevention measures must be implemented. If the fire cannot be extinguished immediately, the foremost priority is to evacuate all occupants to safety. Effective fire compartmentation helps to contain both flames and smoke, preventing their spread to adjacent areas. Even if the fire escalates, the building's structural integrity must be maintained to protect both occupants and emergency responders. This is illustrated in Figure 1.

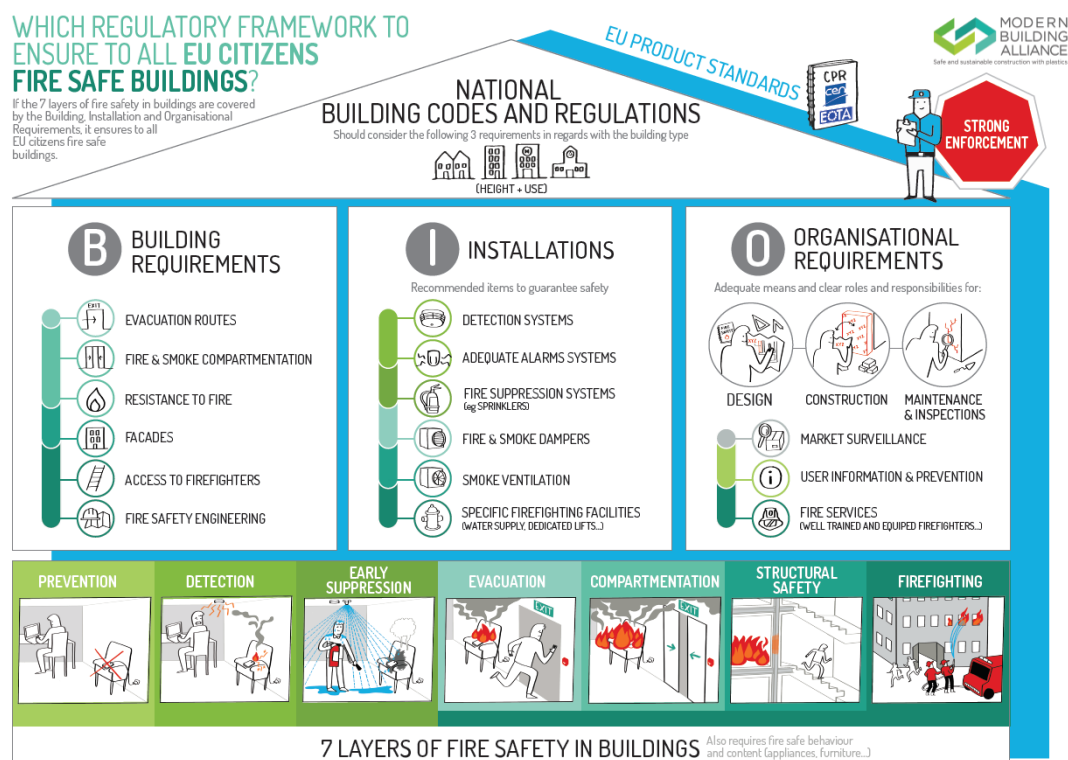


Figure 1: BIO framework [3]

The fire performance of a façade is just one critical factor among many that influence occupants' safety during a building fire. It is important to prevent fire spread over the façade and if fire enters the building, fire detection must be effective and smoke-free escape routes must be provided. All these elements together collectively contribute to the level of safety. For tall buildings, it is critically important to avoid fast fire spread along the façade system, which potentially would bypass internal compartmentation. Façade cladding system's fire performance cannot be assessed solely by reaction-to-fire classifications of individual products, as system behavior depends on several interacting factors:

- The combination of different products in a façade cladding system leads to a different fire performance than for the individual product, due to interactions like heat transfer and synergies.

- Fire spread due to geometry can be enabled for all façade types (i.e. ventilation gaps, windows detailing).
- Fire barriers have been developed for different types of façade systems (ventilated façade systems, ETICS, cavity walls). Small-scale tests alone are not sufficient to capture the effectiveness of these barriers and the fire performance of the complete cladding and insulation system.

2.2 Installation of Façade Systems and Relevant Fire Safety Provisions

For a facade fire safety strategy to succeed, precise and correct installation of facade systems based on manufacturer's instructions and best practice is essential. This includes assembly and mounting and fixing of various facade systems. Misalignment, improper sealing, or incorrect fixing methods may result in moisture ingress, thermal bridging, or structural instability and increased risk for fire spread. Well-structured training programs for installers and supervisors are vital to ensure best practices are maintained and the facade system functions as intended in a potential fire scenario [7].

The fire safety concept and strategy for a facade can be ensured if the relevant installations for fire safety are in place, undamaged and working well. The most important technical installations are:

- Smoke detectors and alarm systems are an absolute must. For larger buildings it is essential to have enough smoke detectors in every compartment and connected alarms which make sure that occupants who are still far away from the fire, as well as fire brigades, are alerted immediately.
- Fire suppression installations, including sprinklers, can be very effective in many situations, such as high-rise buildings or large assembly buildings, as they assure that starting fires grow slowly or remain small and the consequences of fires are limited.
- For the fire brigades it is important, especially in high rise buildings, that all necessary installations are in place to support the fire-fighting strategy, such as adequate water supply, escape ways and building plans including information on gas and electricity supply. Firefighting equipment, whether manual or automatic, should be easily accessible and fully operational. Firefighters should be promptly notified to assist in evacuation and minimize further damage.

2.3 Organization of the maintenance and renovation process

Building and installation requirements are not sufficient on their own. They also require strong organizational measures to ensure proper enforcement. During the design phase, all players involved in the realization of the building project must collaborate responsibly to ensure the building design fully complies with all the fire safety requirements. During construction, the performance and installation of systems, products and equipment must be carefully verified so that they correspond to the design and fire safety requirements. Inspections of existing buildings are vital to ensure that maintenance is being carried out correctly and to identify possible modifications, breaches or improvements. All installations require regular maintenance and control, and occupants should be aware of the fire safety measures as well as evacuation plans. The performance of façade systems can be significantly compromised by inadequate quality control inspections. The long-term performance and safety of façade systems are influenced also by the rigor of quality control throughout the design and construction process. Lack of systematic checks during and post- installation allows defects to remain undetected, increasing maintenance costs.

Standardized procedures for material selection, handling, and installation must be established to support organizational control. Proper documentation and traceability, using digital tracking tools, will enhance compliance and facilitate transparent reporting. By integrating stringent quality control measures throughout each stage of façade system development, stakeholders can significantly reduce fire-related risks and ensure that the system meets established fire safety regulations and performance standards. An overview of the B.I.O framework application to a façade fire-safety scenario is reported in Table 1.

Table 1: B.I.O. Framework Applications to Façade Fire-Safety Scenarios

B.I.O. Pillar	Key Façade-Fire Scenario	Relevant Safety Measures	How the Pillar Mitigates Risk
B	Fire spreads externally from a window to the façade and upward to higher floors	Cavity barriers; robust fire-stopping; façade system testing (large-scale tests)	Limits ignition and vertical flame spread, preserves compartmentation, and prevents fire from re-entering the building in upper floors.
B	Fire penetrates façade cavities and bypasses compartment walls	Properly designed cavity barriers; sealed joints; compliant façade system design	Prevents hidden fire spread within façade layers, maintaining the integrity of fire compartments.
I	Fire originates inside a dwelling and threatens to break out through windows	Fire prevention, Smoke detection; automatic suppression (sprinklers); smoke extraction via smoke exhaust systems	Slows or suppresses internal fire growth, reducing heat exposure to the façade and lowering the chance of external ignition.
I	Firefighters need to intervene from outside, but façade contributes to flame spread	Firefighting access systems; façade-integrated suppression or drenchers (where applicable)	Supports external firefighting effectiveness and reduces façade involvement.
O	Poor maintenance leads to degraded façade performance (e.g., missing barriers, damaged cladding)	Inspection regimes; maintenance protocols; clear responsibilities for building owners	Ensures façade systems continue to perform as designed throughout the building's lifetime.
O	Occupants unaware of evacuation procedures during façade-involved fires	Fire-safety training; evacuation planning; communication systems	Reduces evacuation delays and ensures safe movement even when external fire affects visibility or access.
O	Renovations introduce non-tested façade materials or compromise fire barriers	Regular compliance checks; contractor oversight; documentation of modifications	Prevents unsafe retrofits and preserves the original fire-safety performance of the façade system.

- B** – Building requirements
- I** – Installations
- O** – Organizational requirements

3. HOLISTIC APPROACH

Evaluating the fire performance of façade systems requires a system-level approach that considers the interaction of all components, rather than assessing each single element in isolation. This system-based approach reflects the complex interactions between materials, design features, and installation methods that influence fire behavior during real-world incidents. Recent European initiatives, including the finalization of a harmonized test methodology by the European Commission [8], emphasize the importance of full-scale testing to assess critical factors such as flame spread, falling debris, and realistic conditions. These developments aim to address inconsistencies in national testing protocols and establish a unified framework for performance classification across member states.

A holistic approach is equally critical when examining non-fire-related attributes, such as thermal insulation, moisture control, and structural integrity [9][10]. While it is possible to enhance the fire performance of façade systems through design and material selection, such improvements must not compromise other essential functions. Maintaining a balanced integration of fire safety with environmental protection and energy efficiency remains a key objective in façade engineering through performance-based design. A performance-based design approach provides a structured framework to reduce fire-related risks and strengthen confidence in façade design. By systematically evaluating fire safety considerations at every level; from material selection and product behavior to assembly techniques and overall building performance, this methodology emphasizes the importance of clearly defined performance-based objectives. Aligning performance objectives with the building's overarching fire safety strategy, fosters safer and more efficient façade systems [11].

Since external wall systems directly impact the overall fire safety strategy, varying strategies must place distinct demands on the fire performance of these systems. The initial step involves identifying performance criteria that correspond to the specific objectives of the building. For example, in high-rise structures, a critical criterion is the prevention or limitation of vertical fire spread along the façade [12]. Large-scale testing can give an insight into the fire performance of façade systems including the rate and extent of flame spread. This information should be integrated into the overall fire safety design to actualize an effective fire safety strategy for the entire building.

4. CONCLUSION

In summary, fire safety in high-rise façades requires a holistic approach that integrates system-level assessment, targeted design criteria, and rigorous quality assurance processes. Such an approach ensures façade systems to comply with regulatory requirements while actively contributing to overall occupant safety.

The application of the revised B.I.O. framework as an analytical lens demonstrates that building-level design strategies, technical fire-safety installations, and long-term organizational management practices collectively determine how façades perform under fire conditions. This integrated perspective is essential given the complexity of modern façade systems and the well-documented risks of rapid vertical fire spread and loss of compartmentation.

The findings highlight measures that are particularly critical for strengthening façade fire resilience. Mandating regular façade inspections ensures that essential safety features such as fire barriers, and joint integrity are continuously verified and maintained throughout the building's operational life. Integrating advanced fire barriers into ventilated façade systems and in ETICS

further mitigates the risk of concealed fire propagation, reinforcing compartmentation and aligning façade design with contemporary fire-dynamics research. Complementing these technical measures, installers training programs aligned with EN 13501-1 classifications help ensure that façade systems are assembled and modified in ways that preserve their tested fire-performance characteristics.

Together, these measures form a coherent and evidence-based strategy for improving façade fire safety in both new and existing buildings. They strengthen the structural and functional reliability of façade systems, reduce the performance gap between laboratory testing and real-world conditions, and enhance the organizational capacity required to sustain fire-safety performance over time.

Embedding these practices within regulatory frameworks and industry standards will be essential as façade technologies evolve and as the built environment becomes increasingly complex. Through coordinated action, Member States and industry stakeholders can further harmonize standards, address existing regulatory gaps, and strengthen enforcement mechanisms. This integrated methodology not only enhances occupants' protection but also supports the sustainable application of performance-based design approaches in modern construction. Ultimately, consideration of all points listed in this paper by the member states in their regulatory framework, reinforces the shared responsibility across the value chain to deliver safe, resilient, and energy-efficient high-rise buildings for Europe's evolving urban landscape.

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AVAILABLE FROM:

GIDAI – Fire Safety – Research and Technology
UNIVERSIDAD DE CANTABRIA
Dpto. de Transportes y Tecnología de Proyectos y Procesos
Avda. Los Castros, s/n
39005 Santander. Spain
Tf. + 34 942 201826. Fax. +34 942 202276; gidai@unican.es ;
<http://grupos.unican.es/GIDAI>



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