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Preface

Erasmus Blended Intensive Programmes (BIP) are a new type of short and intensive mobility provided by the Erasmus+ 2021-2027 programme, which, using innovative learning and teaching methods, provide an international experience that combines a short face-to-face mobility with a mandatory virtual one. BIPs have in-person and virtual sessions, according to a defined programme.

This BIP on Fire Models in Structures has the following main objectives: to reach students from different academic backgrounds and cycles and bring them to work collectively; to implement innovative teaching and learning practices with the participating Higher Education Institutions on Fire Models in Structures; and to share competencies and skills present in the Institutions that participate and share them with students from different European regions.

This BIP consists of lectures, practical examples, demonstrations, and work groups in both virtual and presential components, with experts from educational institutions to explore the bases and practical applications of Fire Models in Structures. This programme was created to ensure an efficient exchange between students and academics from different cultural backgrounds and specialities.

This e-book is a collection of articles written by the partners of this BIP on Fire Models in Structures, providing an additional reading tool to all participants.

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Tunnel Safety: Risks and Fire Management from BEVs and Hydrogen Vehicles

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ABSTRACT

The transition toward sustainable mobility with battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (FCEVs) introduces new fire safety challenges in tunnels. This study examines the behaviour of these technologies under critical conditions and their implications for tunnel risk management. Experimental investigations at the Polytechnic of Turin analysed lithium-ion cells (INR18650 M29 and INR21700-50E, both NMC-based) subjected to mechanical, thermal, and electrical abuse. Nail penetration tests revealed thermal runaway events with peak temperatures between 600–750 °C and pressure stabilisation within minutes, while overheating experiments demonstrated temporary stabilisation by safety valve activation before escalation. External short-circuit tests did not trigger runaway, but significant energy release was observed. Gas analysis indicated hazardous emissions, including HF, CO, and CO_2, with concentrations rising alongside initial temperature, confirming the toxicity of BEV fires in confined spaces. Fire suppression is further complicated by prolonged burning, high water demand, and rapid smoke accumulation. For hydrogen vehicles, the study highlights risks associated with compressed storage (up to 1000 bar), including jet flames, tank ruptures, vapour cloud explosions, and BLEVE events. Safety devices such as thermally activated pressure relief devices (TPRDs) mitigate catastrophic rupture but result in full tank venting, producing intense flames. Event-tree analyses show that even minor leaks can escalate into large-scale incidents in confined environments. Current tunnel regulations, designed around conventional vehicles, inadequately address these hazards. The findings stress the urgency of adapting ventilation strategies, detection systems, and suppression technologies, as well as integrating probabilistic risk models that capture thermal runaway dynamics and hydrogen release behaviour. This technical evidence provides a foundation for revising international safety standards and ensuring resilient tunnel infrastructure in the era of alternative propulsion.

KEYWORDS: Tunnel safety; Battery electric vehicles; Thermal runaway; Hydrogen vehicles; Fire suppression.

1. INTRODUCTION

Tunnels are among the most complex and vital infrastructures in modern transportation systems. By definition, a tunnel is an underground passageway, usually constructed through soil, rock, or beneath water, and enclosed except at its portals. According to Britannica, it is “a passage that goes under the ground, through a hill, etc.,” while other sources emphasise its role as a passage dug through surrounding materials to enable safe transit between two points [1]. Regardless of the definition, tunnels are indispensable elements of contemporary mobility, enabling efficient movement across mountains, beneath cities, and under waterways. The Mont Blanc tunnel, which crosses the Alps between France and Italy, or the Turin underground system, are clear examples of how tunnels allow transport networks to overcome natural and urban barriers. The need for tunnels is driven by geographical, economic, and environmental considerations. In mountainous regions, tunnels shorten travel distances and reduce gradients that would otherwise demand costly detours. In urban contexts, underground tunnels minimize surface congestion and preserve land use while providing rapid transit solutions. Their design incorporates a wide range of features, such as geometric dimensions (length, section, carriageway width), traffic parameters (unidirectional or bidirectional flow, daily capacity, and average speed), environmental aspects (terrain morphology, altitude, weather conditions at portals), and technological systems (ventilation, lighting, drainage, and safety facilities). The scale of tunneling infrastructure is significant in Europe alone, where countries such as France, Italy, and Austria each operate hundreds of road and rail tunnels, with numbers exceeding 1,700 in some nations. This underscores the strategic importance of tunnels for regional and international connectivity. With their essential role in transport networks, tunnel safety has become a central concern for engineers, policymakers, and operators. Safe and resilient tunnels guarantee the reliability of road and railway systems, support economic growth, and ensure the protection of human lives. However, history has shown that tunnel environments are particularly vulnerable to accidents, especially fires, which can escalate rapidly due to confined spaces, limited ventilation, and the concentration of vehicles and passengers. Unlike open-air incidents, where smoke and heat dissipate more easily, fires in tunnels create highly challenging conditions for evacuation and firefighting. Several tragic incidents illustrate the catastrophic consequences of tunnel fires. In March 1999, a truck fire in the Mont Blanc Tunnel between France and Italy resulted in 39 fatalities and lasted more than 50 hours, severely damaging the structure [2]. That same year, in May, the Tauern Tunnel in Austria experienced another fire, causing 12 deaths [3]. Only two years later, in 2001, the Gotthard Tunnel in Switzerland suffered a collision followed by a fire that killed 12 people and burned for 24 hours [4]. In the United States, the 2007 Santa Clara Tunnel fire destroyed 34 trucks and claimed three lives. These events demonstrate how even a single incident can paralyse international corridors and cause extensive human and economic losses. Rail and metro tunnels have also witnessed devastating accidents. In 1996, a fire in the Eurotunnel beneath the English Channel caused 31 fatalities. In 2000, a fire on a funicular train in Kaprun, Austria, killed 150 people, making it one of the deadliest tunnel disasters in history [5]. Metro systems have not been immune either: in 1987, a fire in London’s King’s Cross underground station claimed 31 lives, while in 2003, an arson attack in the Daegu metro in South Korea led to 196 fatalities [6]. These tragedies underline that tunnels, regardless of whether they serve road, rail, or metro networks, are inherently hazardous when fire breaks out. Statistical analyses conducted by organizations such as PIARC and the Austrian Safety Board confirm the recurring nature of such incidents. Fires, collisions, and mechanical failures represent the primary risks associated with tunnel transport. Data collected between 1999 and 2009 highlight that, while infrequent compared to surface accidents, tunnel incidents are disproportionately severe due to the confined environment and difficulty of intervention. More recent studies continue to document significant events, emphasising that despite advances in safety standards, tunnel disasters remain a persistent risk. The high number of fatalities and the scale of economic disruption caused by these accidents have spurred international efforts to improve tunnel safety regulations and fire management strategies. Yet, challenges remain—particularly with the increasing presence of vehicles powered by alternative energy sources, such as battery electric vehicles (BEVs) and hydrogen fuel-cell electric vehicles (FCEVs). These technologies, while essential for reducing greenhouse gas emissions, introduce new fire and explosion hazards that existing safety frameworks were not originally designed to address. Therefore, a deeper understanding of tunnel risks, coupled with the development of modern fire models and suppression strategies, is essential to ensuring that tunnels continue to serve as safe and reliable transport infrastructures in the future. In this document there will be presented the main risks related to BEV and H2 vehicles in confined spaces.

2. METHODS and DISCUSSION

Battery electric vehicles and hydrogen vehicles offer substantial advantages for emissions reduction and sustainable transport, but their safety profile differs in important ways from internal combustion engine (ICE) vehicles. Especially in confined spaces (tunnels, underground car parks, etc.), and starting from the BEVs, the main hazards introduced are described:

Thermal Runaway and Fire Initiation

One of the central risks in BEVs is thermal runaway: a self-accelerating chemical reaction inside lithium-ion battery cells, often triggered by mechanical damage (e.g. from a crash), internal short circuits, overcharging, extreme temperatures, or manufacturing defects. Once initiated, thermal runaway leads to rapid heat release, gas emission, and potentially explosive flare-ups [7]. In a study of a battery module from a commercially available BEV, experiments showed that thermal runaway fires generate soot that contains heavy metals (from cathode materials), lithium and fluoride compounds, posing contamination risks to human health and infrastructure [8].

Fire Propagation, Smoke & Toxic Gas Hazard

Due to the high energy density of BEV battery packs and the materials involved (plastics, metals, separators, electrolytes), fires can spread rapidly once the battery is breached. Flame jets, high heat release and the presence of flammable or pyrolysis gases make extinguishing operations more complicated [9]. Smoke from BEV fires tends to contain more toxic compounds, especially hydrogen fluoride (HF), carbon monoxide (CO), and others generated by the breakdown of battery components. In ventilated or unventilated scenarios, smoke accumulation, gas diffusion and heat build-up vary considerably, which is very important in tunnels [10].

Extinguishment Challenges and Reignition

Once a BEV fire has started, extinguishing it is more difficult than many ICE car fires, some points to consider are reported below:

- Current battery management systems and vehicle designs are usually not capable of delivering extinguishing agents directly into the battery modules [11].
- Water is effective for cooling, but large volumes may be required. Furthermore, locating hot spots (inside the modules) is difficult if the battery pack is structurally inaccessible [12].
- Re-ignition is a serious risk. Damaged but not completely 'burnt' cells or modules could later spark again due to persistent internal heat or insulation failure. This is a recurring theme in studies on BEV fires [13].

Hazards to Emergency Responders and Infrastructure

High-voltage components can be exposed if the electric vehicle is damaged, increasing the risk of electric shock. Rescuers do not always have comprehensive, vehicle-specific instructions on how to safely disconnect or isolate these systems [14]. The intense heat (peak temperatures) of BEV fires can threaten tunnel linings, structural components, lighting fixtures, ventilation ducts, etc. Smoke and heat reduce visibility and hinder evacuation or rescue. These risks are greater in confined or semi-confined spaces, but there is a similarity for the HRR released considering the ICE vehicles, i.e. conventionally fuelled [15], [16]. The main difference to conventional vehicles, ICE, are related to emissions of toxic substances, mainly related to battery chemistry, mostly HF, HCl, etc [17].

Geometrical & Environmental Factors

Tunnel slope, ventilation rate, geometry (length, cross section) and traffic flow affect the way smoke and heat propagate, influencing the severity of human exposure and structural damage. Studies show that slopes cause smoke to accumulate at the lower ends; inadequate ventilation exacerbates toxic gas concentrations. The main difference in risk compared to conventional vehicles is the toxic gases that can be emitted by BEVs. A recent full-scale test of BEV fires in underground car parks highlighted these challenges [18].

Uncertainties & Emerging Risks

As BEVs proliferate, battery chemistries (nickel cobalt, LFP, etc.), pack designs and thermal management systems evolve, each with slightly different risk profiles. Some newer chemistries are safer (less prone to thermal runaway), but many older or cheaper designs remain in service. Charging infrastructure problems: overcharging, use of non-certified chargers, damage or degradation of battery packs can lead to failure [19]. End-of-life and recycling/disposal risks: damaged or improperly stored batteries can also be ignition sources.

Turning to the consideration of hydrogen-powered vehicles and the risks associated with confined spaces, especially related to the evolving deployment of such vehicles in current systems.

The main risks are described and summarised:

Hydrogen Leakage, Diffusion & Accumulation

Hydrogen is highly diffusive and light. When a leak occurs, especially from high-pressure tanks or connections, hydrogen gas can disperse rapidly, but also accumulate under ceilings or in the corners of low-ventilation spaces. This accumulation can lead to concentrations within the flammable range (wide range 4-75%vol) with minimal ignition energy required [20]. Obstacles (such as structural elements, vehicles, tunnel linings) influence diffusion paths, increasing concentrations in certain areas (e.g. ceiling corners) and sometimes delaying dispersion [21]. Ventilation plays a critical role: in spaces with poor or inadequate ventilation, even small ongoing leaks may lead to dangerous buildup over time [22].

Ignition / Jet Fires

If spilt hydrogen is ignited near the point of leakage, or by a thermal device, spark or hot surface, a jet fire may occur. These are characterised by narrow, high-speed flames; they can burn at very high temperatures and cause severe burns, rapid heat transfer to nearby structures and damage to people or equipment [23]. Fireball or flame radiation from jet fires, especially in confined spaces where reflection or proximity to surfaces exists, increases risk to occupants and can also raise the local temperature of hydrogen tanks or other components, worsening the scenario [24].

Tank Overpressure and Rupture

Hydrogen tanks are generally subjected to very high pressures (often ~700 bar for passenger FCEVs), which means that if the tank is subjected to thermal stress (as in the case of a fire) beyond its design or safety capabilities, it risks overpressure or rupture [25]. Studies such as the one by Park et al. (2023) have shown experimentally that hydrogen tanks exposed to fires can rupture after a certain period (e.g. several hundred seconds of exposure), resulting in explosive waves of overpressure [25]. Safety mechanisms such as thermally activated pressure relief devices (TPRDs) are intended to vent excess pressure, but do not always prevent catastrophic failure, especially in localised fire conditions [26].

Explosion & Blast Risk

If hydrogen accumulates in the ceiling of a tunnel and finds a source of ignition, the resulting hydrogen-air mixture can explode or deflagrate, producing waves of blast overpressure. These waves can injure occupants, damage structural elements, and propagate through long sections of tunnel. The distances over which deaths or serious injuries can occur are not trivial. For example, in the work of the TU Graz, it was estimated that the rupture of a tank resulting in an explosion can result in death up to ~30 metres, serious internal injuries up to ~300 metres, and less severe physical trauma (e.g. rupture of eardrums) even at greater distances [27].

Thermal Effects and Structural Damage

The heat of a hydrogen fire or jet flame is intense (the combustion temperature of hydrogen in air often exceeds 2000 °C) and can subject tunnel linings, support structures, ventilation ducts and other installed equipment to high thermal stress. Prolonged exposure to high heat can degrade fireproof materials, weaken structural steel, damage concrete, cause spalling and compromise tunnel integrity. Therefore, even if the explosion does not collapse the structure, it can reduce its long-term safety margins [27].

3. CONCLUSIONS

The increasing penetration of battery electric vehicles calls for a fundamental rethinking of tunnel safety, as conventional approaches designed around internal combustion vehicles are no longer sufficient. Ventilation systems will need to be dimensioned or upgraded to cope with the greater smoke and heat release associated with battery fires, while structural elements such as linings and fireproofing must be capable of withstanding longer fire durations and higher peak temperatures. Fire suppression and detection systems should also be adapted to account for delayed ignition and the risk of re-ignition, ensuring that protection remains effective over the full course of an incident. In parallel, first responders require specialised training and equipment to manage the particular challenges of thermal runaway and high-voltage components. Regulatory frameworks will likewise need updating, with revised standards for charging infrastructure, battery testing, and vehicle design. At the same time, the introduction of hydrogen fuel cell vehicles presents an additional set of challenges for tunnel safety. Hydrogen's tendency to leak and accumulate in confined environments, coupled with its wide flammability range, makes early detection and effective ventilation critical. The possibility of high-pressure tank rupture, jet fires, or blast waves requires that tunnel structures be designed to resist sudden thermal and mechanical loads. The near-invisibility of hydrogen flames and the asphyxiation hazard caused by oxygen displacement further complicate both evacuation and emergency response. Addressing these risks will require dedicated training for first responders, adapted firefighting strategies, and regulatory updates to tank standards, pressure relief devices, and refuelling protocols. Taken together, the coexistence of battery electric and hydrogen vehicles within modern transport systems underscores the need for an integrated, multi-technology approach to tunnel safety.

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FIRE DYNAMICS OF AN INSULATED FACADE: MODELLING AND TESTING OF POLYSTYRENE FOAM WITH FLAME RETARDANTS

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ABSTRACT

Fire safety remains a fundamental concern in modern construction, especially in facade systems where insulation materials can significantly impact the overall performance and resilience of buildings. Expanded polystyrene has gained wide application due to its favourable thermal properties and cost-effectiveness; however, its susceptibility to ignition and flame spread raises questions regarding safe use in external thermal insulation composite systems.

To address these concerns, this study investigates the fire performance of Lithuanian-manufactured EPS 70 with graphite additives in plastered facade assemblies exposed to real fire conditions as specified by DIN 4102-20. The evaluation focuses on flame propagation patterns, temperature development, and the structural integrity of the facade during exposure, with careful attention to test object design, methodological considerations, and assumptions that may influence outcomes. Results are assessed against both national and international fire safety requirements, providing a basis for determining compliance and practical suitability of EPS 70 with graphite additives for facade insulation. The findings contribute to a clearer understanding of material behaviour in real fire scenarios and support evidence-based decisions for safe application in construction practice.

KEYWORDS: fire safety; facade systems; building products; polystyrene foam; flammability

1. INTRODUCTION

The facade of a building has evolved from serving as a mere outer shell to becoming a key element of architectural identity, environmental sustainability, and occupant safety. In modern construction, where energy efficiency, environmental responsibility, and fire resistance are global priorities, the design and selection of facade systems play a decisive role [1, 2]. These concerns have been further reinforced by European Union directives that establish ambitious targets for improving the energy performance and sustainability of buildings [3]. However, while energy efficiency has gained prominence, it often conflicts with fire safety requirements. Fire safety remains one of the most critical aspects of construction, particularly when it comes to the choice of insulation and cladding materials.

Expanded polystyrene (EPS) is widely used as thermal insulation due to its affordability, installation simplicity, and excellent thermal properties. Nevertheless, its combustibility raises serious concerns, especially in facade applications where fire spread can be rapid and destructive. The hazards associated with combustible facades have been tragically highlighted by incidents such as the Grenfell Tower fire in London [4] and the Lacrosse fire in Melbourne [5]. These cases underline the necessity of carefully considering how facade systems react under fire conditions, particularly in high-rise and densely populated urban environments. The challenge, therefore, lies in reconciling the energy-saving benefits of EPS with strict fire safety requirements, which has spurred both research and regulatory innovation aimed at developing safer external thermal insulation composite systems.

The literature reflects ongoing efforts to address this balance. EPS insulation is frequently applied in ventilated facades and external insulation and finishing systems (EIFS) due to its thermal performance and cost-effectiveness [6]. To counter its flammability, regulations in some countries recommend the use of fire barriers, such as mineral wool, around openings or between stories. Yet, experimental studies [7] suggest that such horizontal barriers have only a limited effect on reducing temperatures or slowing EPS melting. This underlines the need for more comprehensive strategies. Large-scale fire testing has therefore become a central focus, as even nominally non-combustible facades can facilitate flame spread if material interactions are unfavourable [8]. Quantifying the fire behaviour of facade systems, including flame spread velocity and heat release, is increasingly recognised as essential for robust fire safety strategies [9, 10]. Comparative studies [11, 12] have also revealed discrepancies in the application of large-scale tests such as BS 8414 and DIN 4102-20 across European states, emphasising the need for harmonised methodologies.

Over the past decades, researchers have developed both small- and large-scale experimental approaches to evaluate the flammability of facade systems. Large-scale tests, in particular, capture the complex interactions between materials under realistic fire exposure. For example, studies [13, 14] highlight the influence of insulation thickness and sample orientation, with melt-flow and dripping behaviour contributing significantly to burning dynamics. Protective measures, such as stone wool barriers or masonry coatings, may reduce vertical flame propagation, but their effectiveness relies heavily on the integrity of the external layer [15]. Furthermore, melt-dripping behaviour has been identified as an additional hazard factor in EPS-based systems [16].

Alongside experimental work, numerical modelling has been applied to simulate facade fire tests under different international standards, including BS 8414-1, GB/T 29416, ISO 13785-2, NFPA 285, and JIS A 1310 [17, 18]. These studies show significant variation in outcomes depending on the method used, emphasising the challenge of cross-country

comparisons and the urgent need for standardised European testing protocols. While simulations provide valuable insight into thermal flux and flame spread, their predictive accuracy is limited by the diversity of materials, facade configurations, and construction practices.
Overall, the literature emphasises the importance of conducting large-scale fire performance tests of EPS-based facade systems under real fire conditions. Only through rigorous experimentation and harmonised testing approaches can the construction industry ensure that EPS insulation is applied safely, enabling the design of buildings that are energy-efficient, sustainable, and resistant to fire risks.

2. METHODS

The present study synthesises the findings of two Lithuanian experimental investigations that examined plastered facade systems incorporating polystyrene foam EPS 70 with graphite additives. The original investigations reported sample groups as S1–S4 in study 1 [19] and S1–S2 in study 2 [20]. For clarity and consistency, these are herein re-labelled as a continuous series S1–S6, allowing for structured comparative analysis. Both sets of experiments were conducted in accordance with the fire testing procedure defined by DIN 4102-20 [21], which governs fire reaction testing of building materials and components, including the evaluation of exterior wall decorations. By integrating and analysing the combined results, this study provides a more comprehensive assessment of the fire performance of EPS 70 with graphite additives and evaluates its suitability for application in external thermal insulation composite systems.
Experimental investigations were conducted at the Fire Research Centre of the Ministry of the Interior of the Republic of Lithuania in compliance with DIN 4102-20, which specifies procedures for assessing the fire performance of building materials and components, with particular emphasis on exterior wall finishing systems. The fire performance tests were designed to closely replicate real-world fire scenarios to evaluate the behaviour of polystyrene foam EPS 70 with graphite additives in facade systems. A fragment of an existing building was used as the test stand, with walls constructed of silicate bricks approximately 250 mm thick. The facade insulation system was installed on the test wall, and temperature measurement devices were positioned at predetermined locations to capture thermal responses during fire exposure.
The lower portion of the test wall incorporated a combustion chamber with a volume of approximately 1 m^3 to simulate a room fire. Flames from the combustion chamber were directed toward the facade surface to investigate the fire impact on the insulation system. The chamber included an air inlet to enhance airflow and increase combustion intensity. A 25 kg pile of coniferous wood shavings served as the fire load for each test, representing a standardised combustible material. The testing scenario reproduced conditions of flame spread from a window opening in order to assess the behaviour of facade insulation and decorative layers under fire exposure. Throughout the experiments, temperature measurements were performed using Type K thermocouples, with data recorded continuously using a Eurotherm 6180A recorder. Thermocouples were placed in both the surface and inner layers of the facade to capture temperature gradients throughout the

system. All measurements and procedures were conducted in accordance with DIN 4102-20 as well as relevant national fire safety regulations.
The methodological framework of this study comprised three main steps. First, the characteristics of the test objects were reviewed, including facade system composition, insulation configuration, and finishing layers. This ensured comparability of the systems tested under real fire exposure. Second, the applied methodologies were assessed, with particular attention to fire load conditions, ignition sources, measurement instrumentation, and the parameters recorded during testing. Key performance indicators included flame spread behaviour, temperature development within and on the surface of the facade, and the structural integrity of the system during fire exposure. Third, the assumptions underlying the experimental setups in both Lithuanian studies were critically examined to evaluate how these may have influenced test outcomes and interpretations.

3. RESULTS AND OVERALL FINDINGS

The results of the compiled sample series (S1–S6) are presented to compare the fire performance of plastered facade systems incorporating EPS 70 with graphite additives under simulated real-fire conditions. Key measurements include temperature profiles, flame spread behaviour, and the integrity of facade insulation and decorative layers. These findings provide a systematic basis for evaluating the material's response to fire and its suitability for use in external thermal insulation composite systems.

3.1 Temperature Development

Thermocouples were installed at multiple locations across each sample S1-S6, including the surface layer beneath decorative plaster and the inner layer between polystyrene foam EPS 70 samples with graphite additives and brick masonry. Maximum temperatures were recorded at various heights, providing insight into the heat propagation and the chimney effect at window openings, see Table 1.

Table 1: Identification of temperatures.

Sample	Study	EPS Manufacturer / Thickness	Max Temperature (°C)	Time to Max (min)	Height of Measurement (m)	Location / Thermocouple
S1	Study 1	UAB Baltijos polistirenas, 100 mm	195	16	1.0	Surface under plaster (TC7)
S2	Study 1	UAB Kauno šilas, 100 mm	175	9	1.0	Surface under plaster
S3	Study 1	UAB Šilputa, 100 mm	173	20	1.0	Surface under plaster
S4	Study 1	UAB Ukmergės gelžbetonis, 100 mm	110	29	1.0	Surface under plaster
S5	Study 2	UAB Šilputa, 100 mm	122.85	20.3	1.1	Surface under plaster (TC3)
S6	Study 2	UAB Šilputa, 100 mm	158.47	23	1.1	Inner layer (TC4)

The temperature data indicate that peak heating occurred within the first 10–20 minutes, with gradual cooling thereafter. Maximum temperatures decreased with vertical and horizontal distance from the combustion chamber, reflecting a clear thermal gradient influenced by the chimney effect and convective heat transfer.

3.2 Flame Spread and Structural Damage

Post-test inspection of the samples revealed localised polystyrene foam EPS 70 with graphite additives melting and collapsing, primarily near the combustion chamber openings. No flaming debris was observed above 3.5 m, and temperatures at heights above 3.3 m did not exceed 100 °C, satisfying the requirements of DIN 4102-20. Table 2 summarises vertical and horizontal damage for each sample.

Table 2: Vertical and horizontal structural damage.

Sample	Study	Vertical Damage (cm)	Horizontal Damage (cm)	Edge Protection	Observations
S1	Study 1	193.5	37.0	Mineral wool, reinforced plaster	The EPS melted locally, and dripping was observed
S2	Study 1	177.0	43.0	Reinforced plaster only	Localised flame spread, no continuous flaming above 3.5 m
S3	Study 1	152.0	38.5	Mineral wool, fibreglass mesh	Vertical spread reduced by edge protection
S4	Study 1	140.0	24.0	Reinforced plaster only	Smallest vertical spread, EPS collapse observed
S5	Study 2	357.0	140.0	Mineral wool, plaster	Main wall and wing affected; controlled melting observed
S6	Study 2	193.5	37.0	Mineral wool, reinforced plaster	Vertical and horizontal flame spread controlled

Visual observations confirmed plaster cracking, localised EPS collapse, and dripping in all samples S1-S6, with additional mineral wool or reinforcement layers showing reduced flame spread and lower peak temperatures, highlighting the crucial role of installation quality and protective details.

3.3. Fire Dynamics and Compliance with Fire Safety Standards

The tests revealed that flames were primarily concentrated around window openings, where the chimney effect intensified heat transfer and caused localised melting of the polystyrene foam EPS 70 with graphite additives. Despite this, the melting and dripping of the material remained controlled, and no uncontrolled flame spread occurred beyond critical areas. Inner layers of insulation were largely protected by reinforced plaster and mineral wool barriers, preventing deeper structural compromise.

Temperature measurements indicated clear vertical and horizontal gradients. Maximum surface temperatures ranged between 110 °C and 195 °C across the samples S1-S6, with the highest readings closest to the combustion chamber and lower values observed at greater distances. These results confirmed that protective layers effectively limited heat penetration into the inner EPS layers, maintaining the overall integrity of the facade.

Edge protection around window openings proved particularly effective. Samples incorporating mineral wool barriers and reinforced plaster exhibited reduced vertical flame propagation, lower peak temperatures, and more limited melting of the insulation compared to samples without such reinforcement.

Based on the results, all six samples met the requirements outlined in DIN 4102-20, demonstrating that polystyrene foam EPS 70 with graphite additives can be safely used in external thermal insulation composite systems when installed according to regulations. Specifically:

- maximum surface temperatures did not exceed 500 °C at heights ≥ 3.5 m;
- no flaming debris was observed above 3.5 m for longer than 30 seconds;
- continuous flame propagation beyond critical facade areas was not recorded;
- structural damage, measured both vertically and horizontally from the combustion chamber openings, remained within expected limits.

The combination of thermocouple data, visual observations, and structural assessments confirms that polystyrene foam EPS 70 with graphite additives exhibits controlled flammability, preserves structural integrity, and complies with national and international fire safety standards. These findings underscore the importance of proper installation, edge protection, and adherence to regulatory guidelines, highlighting that Lithuanian-manufactured polystyrene foam EPS 70 with graphite additives is suitable for safe use in residential and commercial facade systems.

4. CONCLUSIONS

The combined analysis of temperature development, flame spread, and structural integrity demonstrates that:

1. EPS 70 foam with graphite additives shows predictable fire behaviour under controlled fire exposure.
2. Protective layers and proper installation are critical for mitigating fire risk, especially at window openings.

3. Edge reinforcement and mineral wool barriers significantly improve facade fire resistance by reducing vertical flame spread.
4. Experimental observations provide benchmark data for fire dynamics modelling, validating simulations of plume behaviour, heat transfer, and edge effects.
5. Controlled fire spread and compliance with DIN 4102-20 confirm that EPS 70 with graphite additives can be safely integrated into modern ETICS systems when proper construction and protection measures are applied.

These results provide a robust foundation for both practical facade design and future numerical modelling studies, enabling improved understanding and prediction of fire dynamics in insulated building facades.

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Design of timber structures in standard and non-standard fire conditions

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ABSTRACT

This paper is an engineering-oriented study on the design of timber structures exposed to non-standard fire conditions. Conventional fire design methods, typically based on standard fire curves, often underestimate the complex thermal and structural response of timber in real fire scenarios. The research investigates how parameters such as fire load, ventilation, and cooling rate influence temperature development, charring behaviour, and residual load-bearing capacity. A key focus is the determination of the zero-strength layer, which defines the remaining effective cross-section of fire-exposed timber elements. Advanced numerical models are used to assess its evolution under varying thermal exposures. These results provide a more accurate basis for evaluating residual strength beyond standardized design assumptions. Additionally, a pyrolysis model is presented to simulate charring behaviour and depth progression as functions of temperature and time, accounting for both heating and cooling phases. This approach improves the prediction of material degradation and structural performance under non-standard fires.

KEYWORDS: Timber structures; Non-standard fire; Zero-strength layer; Charring behaviour; Fire resistance.

1. INTRODUCTION

Wood has become a key material in the development of sustainable and environmentally conscious buildings, often forming the main structural system. The recent trend of constructing tall timber buildings has increased the demand for a deeper understanding of timber behaviour under both normal and extreme conditions, including fire, as well as the fire resistance of timber structures.

In engineering practice, timber fire resistance is generally evaluated using prescriptive approaches, which rely on simplified methods outlined in standards such as the Eurocodes. These approaches typically assume exposure to a standard fire. For example, Eurocode EN 1995-1-2 [1] provides two assessment methods, with the reduced cross-section method being the most widely applied. This method estimates the fire performance of timber elements under bending, tension, and compression [2, 3, 4], as well as timber frame assemblies [5, 6]. It does so by accounting for the charred layer and the zero-strength layer (ZSL), both of which do not contribute to the timber's load-bearing capacity. Currently, the Eurocode specifies a ZSL thickness of 7 mm for standard fire, a value often extended to natural fire scenarios due to the lack of dedicated guidance.

Recent studies suggest that this prescribed thickness may not accurately represent real fire behaviour. Research has shown that ZSL thicknesses can vary considerably, sometimes reaching 30 mm under standard fire, with scatter attributed to natural material variability and incomplete room-temperature property data [2]. Other studies [3, 4] have demonstrated that fire type, cooling rate, maximum temperature, and fire duration all significantly influence the ZSL. For example, Lange et al. [4] reported values of 15 mm, 16 mm, and 8 mm for standard, long-cool parametric, and short-hot parametric fires, respectively. Similarly, Huč et al. [7, 8] claim that the ZSL thickness for a timber beam exposed to parametric fires is not a constant value, but depends on parameters characterizing the parametric fire curve.

These observations underline the need for further research to refine the estimation of ZSL thickness under different fire exposures, enabling safer and more reliable timber design. These findings also highlight the need for further research to accurately determine the ZSL under different fire exposures, ensuring both safety and reliability in the design of timber structures. Thus, the aim of this study is to present the findings of extensive analyses where thickness of ZSL was numerically investigated in case of various non-standard fire scenarios as presented in [7, 8, 9]

2. CALCULATION OF FIRE RESISTANCE OF TIMBER ELEMENTS

2.1 EN 1995-1-2 approach

The Effective Cross-Section method [1] is the most commonly used approach for calculating the fire resistance of timber elements. It is based on the assumption that fire exposure gradually reduces the structural capacity by charring the outer layers of timber, while the inner portion remains effective. The reduced cross-section method is based on the assumption that an inner, rectangular part of timber cross-section, also named the effective cross-section, is not affected by elevated temperatures and has a strength equal to that at room temperature. The outer part of the cross-section is assumed to be affected by elevated temperatures to such extent that timber has no strength. The effective thickness of the outer part of timber cross-section with no strength is constant around the perimeter of the initial, rectangular cross-section and is equal to the sum of the charring depth and the thickness of ZSL, i.e., $d_{ef} = d_{char} + d_0$. It is worth emphasizing that the charring depth d_{ch} and therefore the effective thickness d_{ef} are invented parameters that have no physical meaning and cannot be measured, since the charring depth is realistically not constant around the perimeter as it is greater at the bottom $d_{ch,b}$ than at the sides $d_{ch,s}$ of the cross-section [10] as illustrated in Figure 1.

The steps of the calculation of the structural resistance in fire conditions are:

1. Determine the charring depth, d_{ch}
2. Account for ZSL, d_0
3. Determine the effective cross-Section reduced by the effective thickness $d_{ef} = d_{ch} + d_0$
4. Structural Verification. Apply standard structural formulas using reduced strength values for timber at elevated temperatures (provided in EN 1995-1-2 [1]).

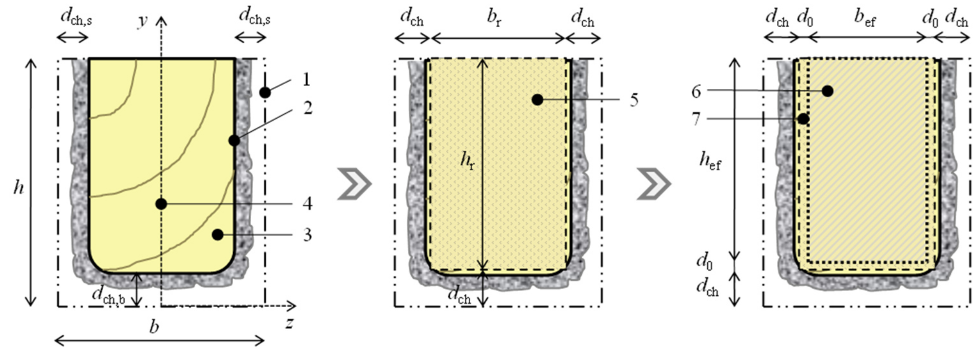

Figure 1: Schematic of the reduced cross-section method. 1 Initial cross-section; 2 Charring line; 3 Residual cross-section with rounding; 4 Coordinate system; 5 Rectangular residual cross-section; 6 Effective cross-section; 7 ZSL [8].

2.2 Determination of the charring depth

2.2.1 Standard fire exposure

For standard fire exposure the charring depth is defined as:

$$d_{ch} = \beta_n \cdot t, \qquad (1)$$

where β_n is nominal charring rate (mm/min), depending on wood type (softwood, hardwood, OSB, etc.) and protective measures (cladding, coatings) and t is time in minutes.

2.2.2 Non-standard fire exposure

For non-standard fires the 300 °C isotherm is an important concept in timber fire design because it's often used to define the boundary of the charred layer and the ZSL. This concept is related to surface carbonatization of timber which occurs around 300 °C.

More advanced approach is the use of various pyrolysis models and provide time-dependent charring depth for design under non-standard fire exposures. For example, the charring depth model developed by Pečenko et. al [12], known as PyCiF (Pyrolysis Coupled with Heat and Moisture Transfer), provides a comprehensive numerical approach to simulate the charring process of timber exposed to both standard and natural fire conditions. The PyCiF model integrates a two-dimensional heat-mass transfer framework with a detailed pyrolysis reaction mechanism. This coupling enables the simulation of heat and mass transfer within timber, alongside the pyrolysis process, which involves the thermal decomposition of wood into char, volatile gases, and water vapor. A key feature of the model is its charring criterion, which is based on the physical phenomenon of char formation, eliminating the need for an arbitrary char front temperature (e.g., 300 °C) commonly used in traditional models. This approach allows for a more accurate prediction of charring depths without relying on empirical assumptions

2.3 Determination of the zero-strength layer

As already mentioned in the introduction, the thickness of ZSL is given in Eurocodes [1] for standard fire exposure, d_0 = 7 mm, while for non-standard fire no specific rules are given. For this reason, authors preformed extensive numerical study with advanced calculation tools in order to determine the thickness of ZSL for various non-standard fires. The results of the study are presented in papers [7, 8, 9]. In next chapter, summary of the approach with key results is presented

3. THICKNESS OF ZERO-STRENGTH LAYER FOR NON-STANDARD FIRE EXPOSURE

In the studies [7, 8, 9] authors analysed simply supported timber beam exposed to various fire conditions. The beam has a length of l = 3.6 m, and a rectangular cross-section with a height h = 0.24 m and a breadth b = 0.2 m. It is loaded in four-point bending on the thirds of a span with point loads F_i and simultaneously exposed to natural fire from three sides, as shown in Figure 2.

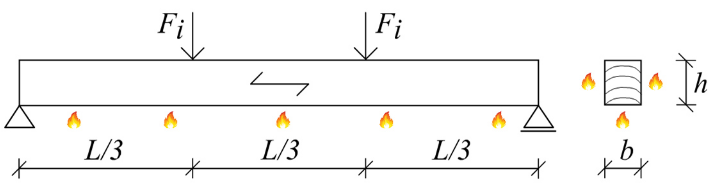

Figure 2: Schematic of the analysed simply supported timber beam layer in studies [7, 8, 9].

The authors employed a four-phase numerical analysis (shown schematically in Figure 3) to assess the ZSL thickness in timber beams exposed to fire:

- Phase 1: A fire model is applied to obtain a parametric fire curve [7, 8] or natural fire curves [9] to simulate the temperature development in the fire compartment.
- Phase 2: An hygro-thermal model is used to conduct a hygro-thermal analysis to determine the temperature distribution across the timber beam's cross-section.
- Phase 3: A mechanical model is applied in a mechanical analysis to evaluate the timber beam's mechanical resistance under fire conditions.
- Phase 4: Determining the ZSL thickness by equating the mechanical resistance in fire conditions to the beam's capacity.

Short description of the models used is given in what follows.

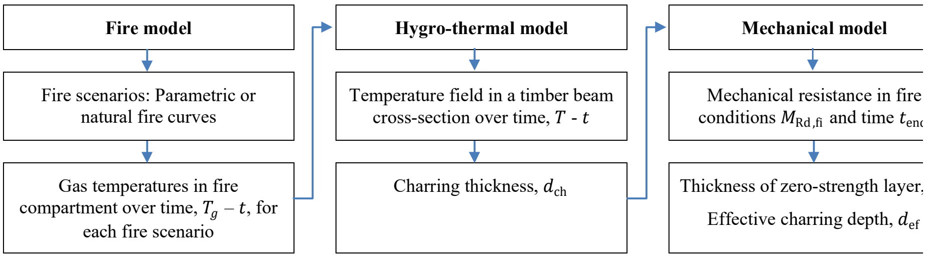

Figure 3: Schematic of sequentially performed analyses by means of the fire, the hygro-thermal, and the mechanical models and the outcomes used in [7, 8, 9].

3.1 Fire model

In the studies presented in [7] and [8] fire scenarios were created with use of parametric fire curve given in EN 1991-1-2 [12]. In the first study [7], only ventilation-controlled (VC) fires were considered, whereas the follow-up study [8] included fuel-controlled (FC) fires to examine timber behaviour under both fire scenarios. In the most recent study [9], more complex fire model Ozone V2 [13] was used to obtain different natural fire curves including a cooling phase. Figure 4 shows fire curves considered in study [7] and [8].

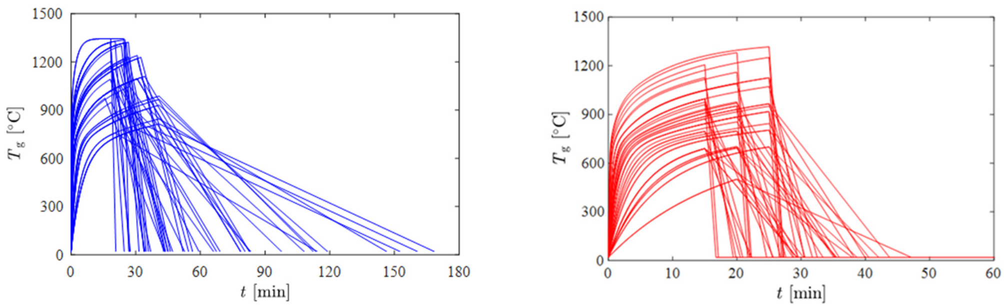

Figure 4: On the left different ventilation controlled parametric fire curves in considered [7] and on the right fuel controlled parametric fire curves [8].

3.2 Hygro-thermal model

The hygro-thermal model developed by Pečenko et al. [14] is a finite element framework for simulating coupled heat and moisture transport in timber beams exposed to fire. It simultaneously solves four coupled non-linear equations describing the transfer of air, bound water, water vapor, and heat across the timber cross-section, allowing prediction of temperature and moisture evolution over time. The governing equations, along with appropriate initial and boundary conditions, are solved in MATLAB® using the Galerkin finite element method with an implicit finite difference scheme.

The model has been validated against experiments and extended to various fire exposure scenarios, providing a robust tool for analysing the timber's thermal and moisture response under fire [14, 15]. It enables prediction of key fire-induced phenomena in timber, including temperature distribution, moisture redistribution, charring depth, supporting performance-based fire design of timber structures. A detailed description of the formulation and solution procedure is given in [14].

3.3 Mechanical model

The temperature distribution in the timber beam cross-section, obtained from the hygro-thermal model, serves as input for the mechanical model. This model, developed and validated in previous studies [14, 15] is a finite element framework for evaluating the mechanical resistance of timber beams under fire conditions.

The mechanical model is based on Reissner's kinematically exact beam theory [17] and numerically solves a system of nine equations: three equilibrium, three kinematic, and three constitutive equations. These equations account for the axial force, shear force, and bending moment along the beam, as well as corresponding strains, displacements, and cross-sectional rotations. The constitutive relationships link axial force and bending moment to the material stress–strain behaviour. In this study, a bilinear material model in tension and compression is adopted with reductions of strength and elastic modulus at elevated temperatures following EN 1995-1-2 [1]. The shear force is computed as the product of shear modulus, shear area, and shear strain.

Beam discretization uses strain-based finite elements with five integration points per element, and the Euler–Lagrange system is solved with an incremental-iterative Newton method. Ultimate mechanical resistance under fire is identified when the tangent constitutive matrix of the cross-section becomes singular, signalling material or stability failure. This approach enables the combined assessment of thermal and mechanical behaviour, linking hygro-thermal simulations directly to structural performance under fire conditions.

3.4 Key Results

In this chapter we present key results of the extensive studies presented in [7, 8, 9]. Figure 5 illustrates the development of the mechanical resistance under fire conditions $M_{Rd,fi}$, the charring thickness d_{ch} and the ZSL thickness d_0 over time for a selected fire scenario presented in [7]. As seen in Figure 5 (left) the maximum gas temperature $T_{g,max}$ = 881°C is reached at $t_{g,max}$ = 20.5 min and the cooling phase ends at $t_{g,end}$ = 66.0 min. $M_{Rd,fi}$ decreases from the initial value of 67.2 kNm at t = 0 min to the final value of $M_{Rd,fi,end}$ = 20.3 kNm at t_{end} = 70.8 min. The thicknesses d_{ch} and d_0 as a function of t are depicted in Figure 5 (right), where it can be seen that $d_0$non-linearly increases over t, while d_{ch} reaches a constant value of 31.2 mm at t = 42.9 min. Although the constant value of d_{ch} is reached, $M_{Rd,fi}$ still decreases from 22.7 kNm at t = 42.9 min to $M_{Rd,fi,end}$ = 20.3 kN m due to the reduced strength and stiffness of timber below the charring layer at elevated temperatures (20°C < T < 300°C). These reductions are included in the parameter $d_0$that consequently increases from 16.3 mm at t = 42.9 min to the end value $d_{0,end}$ = 19.9 mm.

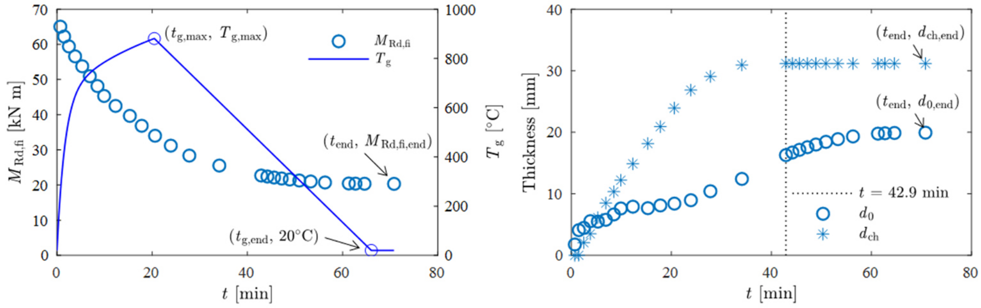

Figure 5: The development of $M_{Rd,fi}$, and T_g, over time (left) and developments d_{ch} and d_0 over time (right) [7].

In study [7, 8] the ZSL thickness was determined for various parametric fire exposure. As seen in Fig. 6 (left) the ZSL thicknesses are substantially higher for ventilation controlled (VC) than for fuel controlled (FC) parametric fires in the range of maximum gas temperatures between 800°C and 1200°C.

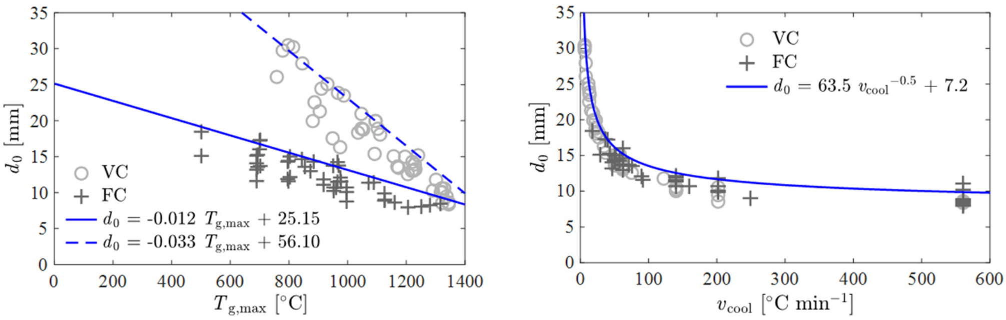

Figure 6: Expressions for the ZSL thickness d_0 depending on parameters $T_{g,max}$ (left) and v_{cool} (right) [8].

Therefore, two separate, linear equations are proposed to determine the ZSL thickness in dependence on the parameter $T_{g,max}$ in case of FC and VC parametric fire exposures, respectively. While for other observed parameters, ZSL thickness shows good alignment for VC and FC fires, thus a single equation is proposed to determine ZSL thickness in dependence on each of the studied parameters (e.g., opening factor O, fire growth density q_{fd}, Γ ratio, etc.). Here behaviour of ZSL thickness with respect to cooling rate v_{cool} is presented in Fig 6 (right). More detailed descriptions of the results and findings can be found in [7, 8].

In the study [9], beside ZSL thickness also behaviour of charring layer thickness d_{ch} was investigated with respect to main parameters describing the natural fire curve (Fig 7. left). In Fig 7. (right) the main parameters describing the natural fire curve are presented. Results in Fig. 8 show the behaviour of charring layer, ZSL and effective layer thickness d_{ef} with respect to $T_{g,max}$, v_{cool} and $T_{g,max}$, respectively. As observed the lowest scatter is observed for ZSL thickness, while bigger scatter is observed for d_{ch} and consequently d_{ef}.

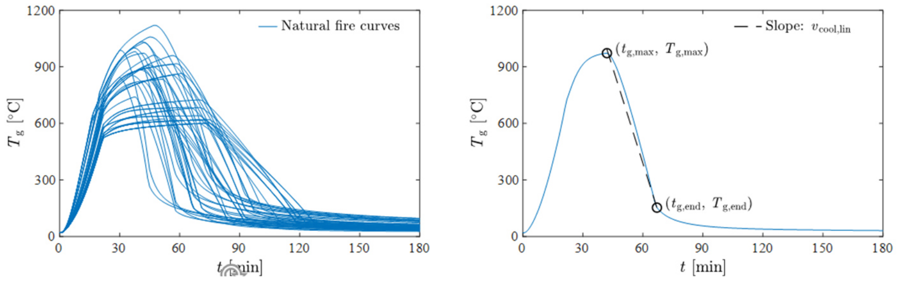

Figure 7: Modelled 44 fire scenarios, i.e., natural fire curves (left) and symbols of a natural fire curve for specific fire scenario (right) [9].

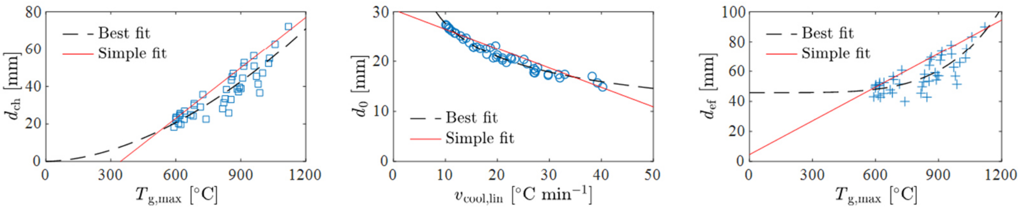

Figure 8: The charring thickness d_{ch}, the zero-strength layer thickness d_0 and the effective thickness d_{ef} at the time t_{end} in relation to $T_{g,max}$ (left), v_{cool} (middle) and $T_{g,max}$ (left), [9].

4. CONCLUSIONS

Overall, presented studies [7, 8, 9] contribute to a deeper understanding of timber behaviour under non-standard fire exposure, offering practical tools for engineers to assess and design fire-resistant timber structures. By performing simulations across a wide range of fire scenarios, the researchers were able to quantify the variation in ZSL thickness under different conditions. The ZSL thickness was found to vary significantly depending on the fire exposure scenario:

- Ventilation-Controlled parametric fires [7]: The ZSL thickness ranged from 8.4 mm to 30.5 mm, indicating that the standard 7 mm value prescribed in Eurocodes may not be applicable for non-standard fire exposure.
- Fuel-Controlled parametric fires [8]: The ZSL thickness varied between 7.9 mm and 18.4 mm, influenced by parameters defining the parametric fire curve.
- Natural Fires [8]: The ZSL thickness ranged from 14.9 mm to 27.4 mm, with end values depending on the maximum gas temperature and fire duration.

As it was found, there is no need to separate the expressions for determining the thicknesses charring depth and ZSL thickness, since both thicknesses are fictious parameters in the reduced cross-section method, which compensate for the effect of cross-section rounding due to elevated temperatures resulting from a three-sided fire exposure to a timber beam. Therefore, only one expression for a direct determination of the effective thickness can be given, which we suggest to be a linear equation depending on the maximum gas temperature [9]. Similar conclusion was found also for the parametric fires presented in [7, 8]. The simplified approach suggests that the effective cross-section is determined by reading combined thickness d_{ch} + d_0 at temperature of a timber beam cross-section of ~90°C. In case of FC parametric fire exposure combined thickness d_{ch} + d_0 should be determined at temperature ~87°C and time t_{end}.

To broaden the applicability of this results, further numerical and experimental studies are recommended. Future investigations should examine the influence of factors such as cross-section dimensions, loading conditions, and timber properties - including density, strength, stiffness, and moisture content - on the effective thickness.

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Fire and computers – the basics

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ABSTRACT

Computers are employed for fire safety in diverse ways. Fire simulation has revolutionized fire safety engineering through sophisticated computer programs that model complex fire phenomena with unprecedented accuracy. Dedicated fire simulation software such as Vulcan and Safir provide specialized capabilities for structural fire engineering, incorporating advanced material models, thermal analysis, and structural response calculations. These programs are specifically designed to handle the complex interactions between fire exposure, heat transfer, and structural behavior, offering built-in fire curves, material degradation models, and specialized boundary conditions for fire scenarios. General-purpose finite element software like ABAQUS and ANSYS offer complementary capabilities through their thermal-structural analysis modules. While requiring more user expertise to set up fire simulations, these platforms provide greater flexibility for complex geometries, advanced material modeling, and coupled multi-physics analyses. They excel in modeling heat transfer mechanisms, thermal expansion effects, and the progressive failure of structures under fire conditions. Contemporary fire simulation integrates computational fluid dynamics for smoke and heat transport, finite element analysis for structural response, and probabilistic methods for risk assessment. These tools enable engineers to evaluate fire scenarios, optimize fire protection systems, and ensure structural integrity under extreme thermal loading. The evolution from early mathematical models to today's comprehensive simulation platforms represents a fundamental advancement in fire safety engineering, enabling evidence-based design decisions and improved public safety outcomes through rigorous computational analysis of fire phenomena. The following

KEYWORDS: elevated temperature, dedicated software, general-purpose software, heat transfer, thermo-mechanical analysis.

1. INTRODUCTION

The use of computers for elevated temperature design of structural elements evolved through several distinct phases beginning in the 1960s. Early computational efforts focused on simple heat transfer calculations using mainframe computers to determine temperature distributions in steel and concrete members exposed to standard fire curves. The 1970s-1980s marked significant advancement with the development of finite element methods for thermal analysis, [1], [2], [3]. Researchers began creating specialized subroutines for temperature-dependent material properties, enabling more accurate prediction of structural behavior under fire conditions. This period saw the emergence of coupled thermal-structural analysis capabilities, though computational limitations restricted analyses to simplified geometries.

The 1990s brought dedicated structural fire engineering software including early versions of programs like FIRES-T3, which integrated thermal analysis with structural response calculations. These tools incorporated advanced material models for steel and concrete at elevated temperatures, including creep, thermal expansion, and strength degradation effects, [4].

The 2000s witnessed the development of comprehensive fire engineering software suites such as Vulcan [5], SAFIR [6], and specialized modules within general-purpose finite element programs like ABAQUS [7] and ANSYS [8]. These platforms enabled full three-dimensional thermo-mechanical analysis with sophisticated material models, geometric nonlinearity, and progressive failure simulation.

Contemporary developments focus on performance-based design approaches, probabilistic analysis methods, and integration with computational fluid dynamics for realistic fire exposure modelling. Modern software incorporates advanced constitutive models, parallel processing capabilities, and user-friendly interfaces that have made elevated temperature structural analysis accessible to practicing engineers worldwide.

2. ANALYSES

Structures are commonly designed considering permanent, imposed, snow, wind and seismic loads. Nevertheless, elevated temperature develop in case of fire which lead to material degradation. Figure 9 presents that fire is a load situation of structural design but also requires additional material considerations as well as temperature evolution in designing of structures.

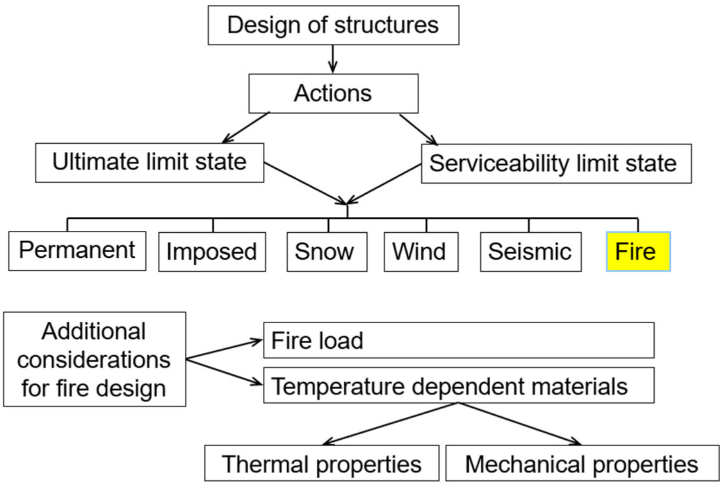


Figure 9: Position of fire load

In the case of fire situation, a thermal analysis is performed first, followed by a structural analysis.

2.1 Thermal analysis

A thermal analysis is the specialized field of engineering and materials science focused on studying how temperature affects materials, components, or entire physical systems. Essentially, it's about understanding the complex interplay between heat, time, and matter. The primary goal is to predict and measure temperature distribution within a system and analyze the various forms of heat transfer involved (conduction, convection, and radiation) to ensure safety, efficiency, and functional reliability.
Conduction represents heat transfer through the direct collision of atomic and molecular particles. It requires physical contact between objects or material components. An example of conduction is heating the handle of a metal spoon by placing the bowl of the spoon in hot tea. The property required to define conduction is thermal conductivity, measured in W/m K.
Convection represents heat transfer that occurs through the movement of fluids (liquids or gases). It involves the circulation of warmer fluid from one area to another, carrying thermal energy with it. An example is boiling water in a pot where hot water rises and cooler water sinks (natural convection), or using a fan to blow cool air over a hot computer chip. In an analysis, the properties required to define convection are density (kg/m^3), specific heat (J/kg K), and the coefficient of heat transfer by convection (non-dimensional).
Radiation represents heat transfer through electromagnetic waves. This is the only form of heat transfer that does not require a medium and can effectively transfer energy across a perfect vacuum. The classic example is the feeling of warmth of the sun. In an analysis, the properties required to define radiation is the emissivity a non dimensional material's measure of its effectiveness in emitting energy as thermal radiation having values between 0 and 1.

2.2 Structural analysis

Once the temperature profile is known, the mechanical analysis determines the structure's response. A structural analysis in a fire situation is a specialized analysis performed to predict how a building, bridge, or individual structural component will behave when exposed to the extreme temperatures generated by a fire. The primary goal is not just to determine if a structure will survive, but specifically to calculate the residual load-bearing capacity and the time until failure to ensure the structure meets its legally mandated Fire Resistance (e.g., R90, R120).
Performing a structural analysis under fire conditions is complex because it deals with three key time-dependent factors simultaneously: Heat, Material Degradation, and Stress.
The true complexity of the structural fire analysis lies in modeling the effects that are negligible at ambient temperatures but dominant during a fire: (i) material degradation and (ii) thermal expansion.
(i) Material degradation. Heat severely compromises the fundamental properties of construction materials. For steel, as steel heats up, its Yield Strength and Elastic Modulus (stiffness) decrease drastically. For concrete, high temperatures cause spalling (surface layers breaking off) due to internal moisture vaporization. Furthermore, the compressive strength of the concrete and the bond with the internal steel reinforcement are reduced.
(ii) Thermal Expansion. structural members expand significantly when heated. If this expansion is physically constrained by the surrounding cooler parts of the building (a situation called thermal restraint), massive internal forces are generated.

3. Numerical approach

The analysis of structures exposed to elevated temperatures represents a critical part of performance-based fire engineering and materials research. Broadly speaking, this type of analysis can be performed using two methodological approaches, which differ by their computational framework and level of specialization i.e. (i) the general-purpose finite element analysis (FEA) software such as Abaqus or ANSYS, and
(ii) specialized fire engineering software, such as SAFIR or VULCAN.

3.1 General-purpose finite element software

These platforms are multi-physics environments capable of simulating a wide variety of mechanical, thermal, and coupled phenomena. When used for elevated-temperature analysis, they offer great flexibility and high numerical precision but typically require more manual setup and advanced user input.
In Abaqus or ANSYS, thermal and structural problems are usually analysed through sequentially coupled simulations: first, a transient heat transfer analysis determines the temperature distribution within the structure over time, considering convection,

radiation, and conduction; then, the resulting temperature field is mapped onto a structural model to perform thermal-stress analysis, capturing thermal expansion, material degradation, and potential plastic collapse.
Because these software packages are general-purpose, they allow the user to define custom material models — for instance, temperature-dependent elastic modulus, yield strength, or creep behavior — which makes them ideal for research-oriented simulations or non-standard materials.
However, the trade-off lies in the complexity of setup and the need for detailed validation against experimental data.
Abaqus and ANSYS are therefore preferred when the study involves multi-material assemblies, nonlinear contact, or complex boundary conditions, and when the analyst needs precise control over the numerical formulation.

3.2 Dedicated software for fire and thermal-structural analysis

Unlike general FEA tools, dedicated software was developed specifically for the structural fire engineering domain. Their main strength lies in the integration of thermal and structural behavior of building components under fire exposure, according to recognized standards (e.g., Eurocode EN 1991-1-2, EN 1993-1-2, EN 1992-1-2).
In SAFIR, the temperature field can be computed directly within the program using built-in fire models (such as ISO 834 standard fire or natural fire curves). The software then automatically couples this with the mechanical response, taking into account the temperature-dependent material properties for steel, concrete, or composite elements.
This allows efficient simulation of realistic fire scenarios without the need for external coupling between thermal and mechanical analyses.
Similarly, VULCAN focuses on frame and floor systems exposed to fire, with efficient algorithms that capture large deflections, progressive failure, and thermal expansion effects in an integrated environment.
It is particularly suited for design applications, where the goal is to assess the global behavior of structural systems rather than to explore detailed local phenomena.
Both SAFIR and VULCAN prioritize user-friendly workflows, standardized material databases, and fire-specific post-processing (e.g., critical temperature, failure time, deflection limits). While they might not provide the same level of general modeling flexibility as Abaqus or ANSYS, they compensate through domain-specific efficiency and validation for fire engineering applications.

4. Validation examples

DIN EN 1991-1-2 [9] provides rules for determining thermal and mechanical actions on structures exposed to fire. Its annexes include validation examples which help to benchmark calculation procedures, especially for advanced models of fire and structural response.

4.1 Heat transfer examples

Figure 10 shows three examples of heat transfer with official results that an analysis with the same input data must comply with. In the first column the official example is given, the second and third columns are the visualization of the models in Safir and Abaqus.
The first example given in DIN EN 1991-1-2 represents a cooling process of a square section. The thermal properties of the material do not depend on the temperature, and the initial temperature of the section is 1000 °C. At t=0, the section is plunged into medium, which temperature is and remains equal to 0 °With adiabatic boundary conditions, the result of any good numerical model must lead to the temperature given in DIN 1991-1-2.
The second example represents a heating process of a square homogenous section with thermal conductivity of the material dependent on the temperature. The initial temperature of the section is 0 °C. At t=0, the section is plunged into medium, of 1000 °C. The temperature in the middle of the cross section must be checked.
A similar example of heat transfer is given for a section consisting of two layers of a steel hollow section with a thickness of 0.5 mm which is filled with material of given properties. The example should check weather conductivity between layers is assured such that the temperature in the middle of the cross section is similar to the one given in DIN 1991-1-2.

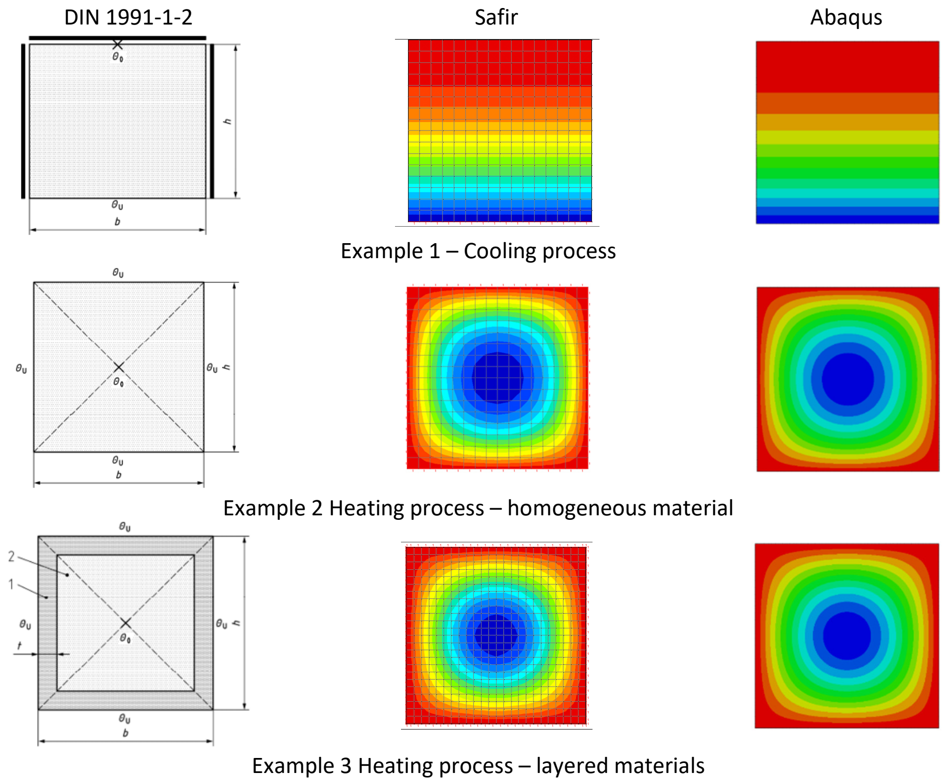


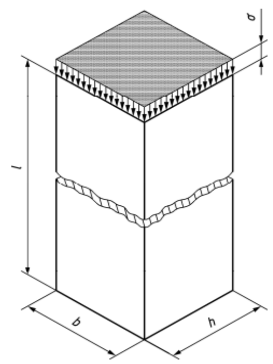
Figure 10: Heat transfer examples

For the dedicated software, the heat transfer parameters, convection and emissivity, are intuitively defined while for the general-purpose software they are defined under *Interactions* definition as *surface film condition* and *surface radiation*, respectively.
Also, when emissivity is defined the important data of the numerical model are the Stephan Boltzmann constant (5.67E-8), and the Ablsolute zero temperature (-273.15).

4.2 Mechanical examples

The same document, DIN 1991-1-2, offers examples that include the elongation of an element subjected to pressure and with a defined homogeneous temperature increase. This example proposes the analysis of a cantilever which has a height of 10 cm to verify the materials laws. The cantilever is analyzed in two instances i.e. structural steel and concrete. More precisely, the elongation Δl has to be calculated for different stress-strength ratios of 0.2, 0.6 and 0.9, at homogeneous temperatures distributions in the cross-section of the element of 20 °C, 200 °C, 400 °C, 600 °C and 800 °C. It must be stated that the numerical models can be defined either as linear, beam element or as volumetric 3D element. Figure 11 shows the geometric input reference information of example 5 in DIN EN 1991-1-2.
The EN design codes dedicated to fire, named usually with Part 1-2, give the property related to the temperature dependent deformation of the material as related thermal elongation (Δl/l). While the dedicated programs have this property already defined for common materials, in the general-purpose software this property must be cautiously defined as Expansion (expansion coefficient α) depending on the temperature increase with respect to 20°C, (ΔT), see eq. (1).

$$\Delta l = \alpha \cdot l_o \Delta T \quad (1)$$

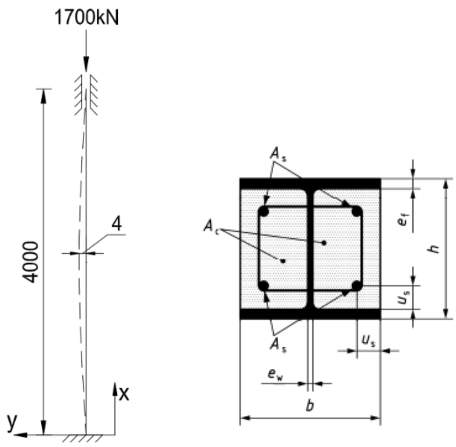


Example 5 Heating process – layered materials
Figure 11: Mechanical example

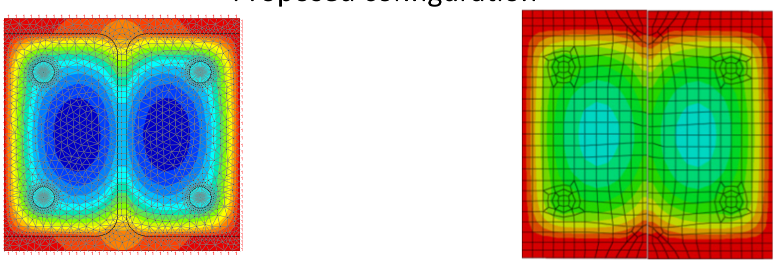
4.3 Thermo-Mechanical examples

A complex input data is given in Example 11 where a composite column with partially encased steel section having given cross-sectional dimensions and the length (height) l = 4.0 m is engulfed in fire on four sides, Figure 12. The column cross-section consists of an

H profile and reinforced encasing concrete with steel reinforcement. Both ends are rotationally restrained in case of fire. The composite column is centrically loaded with a constant longitudinal force. A parabolic pre-deformation with peak value of l/1000 accounts for the geometrical imperfection of the column.
The complexity of the problem comes from the temperature dependent thermal and mechanical properties for three different materials i.e. structural steel, reinforcing steel and concrete that must be defined according to the design codes, as they will be discussed in the following.
Both fire resistance and the horizontal displacement at the mid-span of the column is to be determined at t = 30 and 60 minutes.



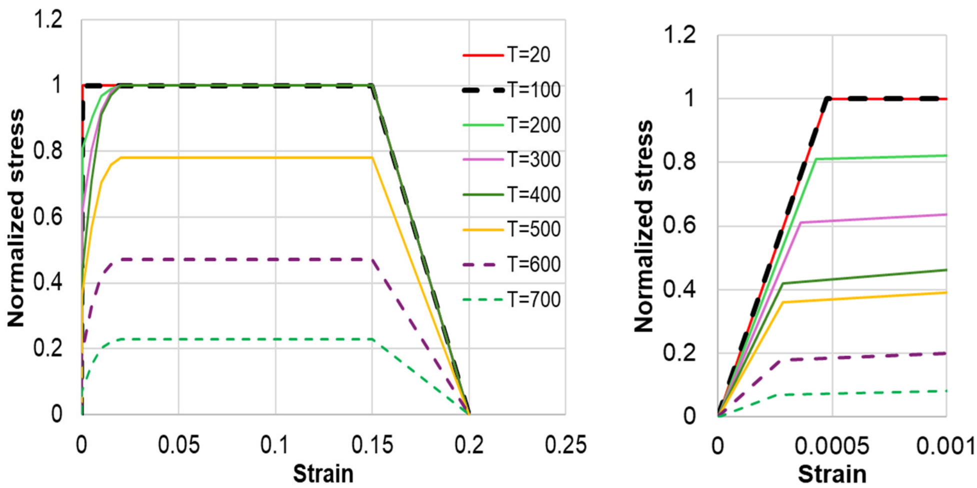
Proposed configuration



Thermal spectrum (Safir and Abaqus)

Deformed shape (Safir and Abaqus)
Figure 13: Example 11 Thermo-mechanical example

When fire resistance is to be checked, the definition of the material behaviour under stress must be clearly defined. The design codes provide relations for the stress strain curve of structural material for several temperatures while for intermediate temperatures, interpolation must be employed. Nevertheless, to easily understand the behaviour of material at elevated temperatures, Figure 14 presents the stress strain curves for a few temperatures of steel. The graph in the left side (a) shows the fact that after 400°C the strength of the steel starts to decrease and compared to the normal temperature curves, a range of parabolic distribution exist between the proportional limit and the maximum stress level. Less visible is the modulus of elasticity due to the small values of strain, but in a detailed view (b), it is observed that the modulus of elasticity decreases and this decrease is much faster than the decrease of strength with temperature.



a) b)

Figure 14: Steel response at elevated temperatures

5. CONCLUSIONS

Structural analysis in fire engineering requires comprehensive material property data including temperature-dependent strength, elastic modulus, and failure criteria for steel, concrete, and composite materials. The analysis must account for material degradation, thermal expansion effects, and potential instability modes such as lateral-torsional buckling and progressive collapse mechanisms.

Thermal analysis demands detailed heat transfer parameters including thermal conductivity, specific heat, density, and emissivity values as functions of temperature. Critical inputs encompass fire exposure conditions (standard fire curves, parametric fires, or localized heating), convective and radiative heat transfer coefficients, and initial temperature distributions. The analysis must model conduction through structural elements, convection at exposed surfaces, and radiation exchange between surfaces, requiring appropriate mesh refinement near thermal gradients and time-stepping schemes for transient solutions.

Thermo-mechanical analysis integrates both thermal and structural phenomena, requiring coupled field formulations that account for thermal expansion, temperature-dependent material properties, and stress-temperature interactions.
The choice between general-purpose and dedicated software depends on the goal of the analysis:

- General purpose software is suited for detailed, customized simulations of thermal–mechanical coupling, particularly in research and material science contexts.
- Dedicated software is optimized for engineering design and performance evaluation under fire, offering speed, reliability, and compliance with international design codes.

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An approach for the assessment of wood connections subject to fire

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ABSTRACT
The main objective is to present a methodology for designing wood connections with internal steel fasteners in fire conditions. Analytical methodologies according to Eurocodes will be used to determine the load-carrying capacity of the connections in single shear. Different wood densities and steel fasteners will be considered in the cases studied to analyse the load-carrying capacity. A thermal and transient numerical analysis using the finite element method will be presented to predict the fire resistance of the connections.

KEYWORDS: Wood connection, Fire, Finite Element Method, Eurocodes.

1. INTRODUCTION

The fire resistance of the wood connections depends on the char layer evolution, the strength reduction residual cross-section of the members. The fire performance analysis is complex because different materials and parameters are involved, geometries and dowel arrangements [1]. Both steel and wood materials have different behaviours, and the interaction between the elements is even more complex to analyse.

Wood material, when exposed to fire, presents a thermal physical degradation. The interface between the charred and non-charred wood is the transition phase between the black and brown material and is characterised by a threshold value of 300 ºC, according to Eurocode 5 part 1-2 [2]. Also, the thermal properties of wood vary considerably with temperature and should be defined according to the Eurocode 5 part 1-2 [2]. This standard code provides the design values for the density, thermal conductivity and specific heat of wood. According to Eurocode 5, part 1-2 [2], the wood connections in fire conditions can be protected by adding wood panelling, wood-based panels or gypsum plasterboard type A, H or F.

With the growing concern about climate change, the use of timber in building construction presents itself as a solution to this problem [4]. Timber is a sustainable material when compared with the use of other materials, requiring only minimal processing when compared with materials like steel, concrete, or aluminium. The major justification is related to the positive contribution to the carbon cycle and the low energy used throughout the process. In addition, timber can present good mechanical characteristics, such as strength and density properties [4].

The general material properties used in these types of components can be seen in this brief written overview [5]. To develop the heat transfer models in connections and evaluate their fire resistance, it is necessary to quantify the thermal material properties at elevated temperatures. Some of these properties are also outlined in Eurocode 3 part 1-2 for steel [6] and Eurocode 5 part 1-2 [2] for wood.

The main goal of this work is to present analytical methodologies to predict the safety of connections in simple shear, determining the load-carrying capacity and the number of dowels needed for the connection. This study brings results from the previous investigations by the author [7] about the effect of steel dowels in wooden connections submitted to fire. The connections were evaluated for different applied tensile loads parallel to the grain, dowel diameters, and timber material densities. The numerical models are based on the finite element method, using thermal and transient analysis with nonlinear materials.

2. MATERIALS AND METHODS

2.1 Materials and standard fire curve ISO 834

The core of this study is to present an analytical and numerical formulation that can be applied in the project of wood connections in conjunction with steel material, joined by dowels, as shown in some applications in Figure 1.

Figure 1: Different types of connections.

The selection of the specific dimensions depends on the type of wood connection and the necessary load-carrying capacity. Fastener strength depends on many factors, such as externally applied load, wood density, load direction of the wood grain, position of the fasteners, edge, and distances from the ends of the connection [8-11].

Table 1 represents the three different densities of glued laminated timber (referred to as glulam or GL) used for the designed connections in the study, and the S275 steel material [10] for the connectors (dowels and plates), according to the references [5, 8-10]. In the homogeneous glulam GLxh, Table 1, the value of x represents the strength class. All lamellae of the cross-section belong to the same strength class and are predominantly made from softwood. Glulam is an engineered wood product manufactured by glueing together pieces of timber, widely used in different building projects, in a range of strength classes. Glulam is characterised by high load carrying capacity, stability and ability to form different timber components than normal timber, Figure 2. The timber is technologically dried and generally contains 12% moisture.

Table 1. Density of the glulam and steel.

Mechanical Properties	GL20h	GL24h	GL32h	S275
Density, kg/m^3	370	420	480	7850

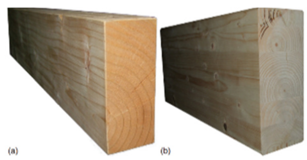


Figure 2: a) Solid. b) Glulam.

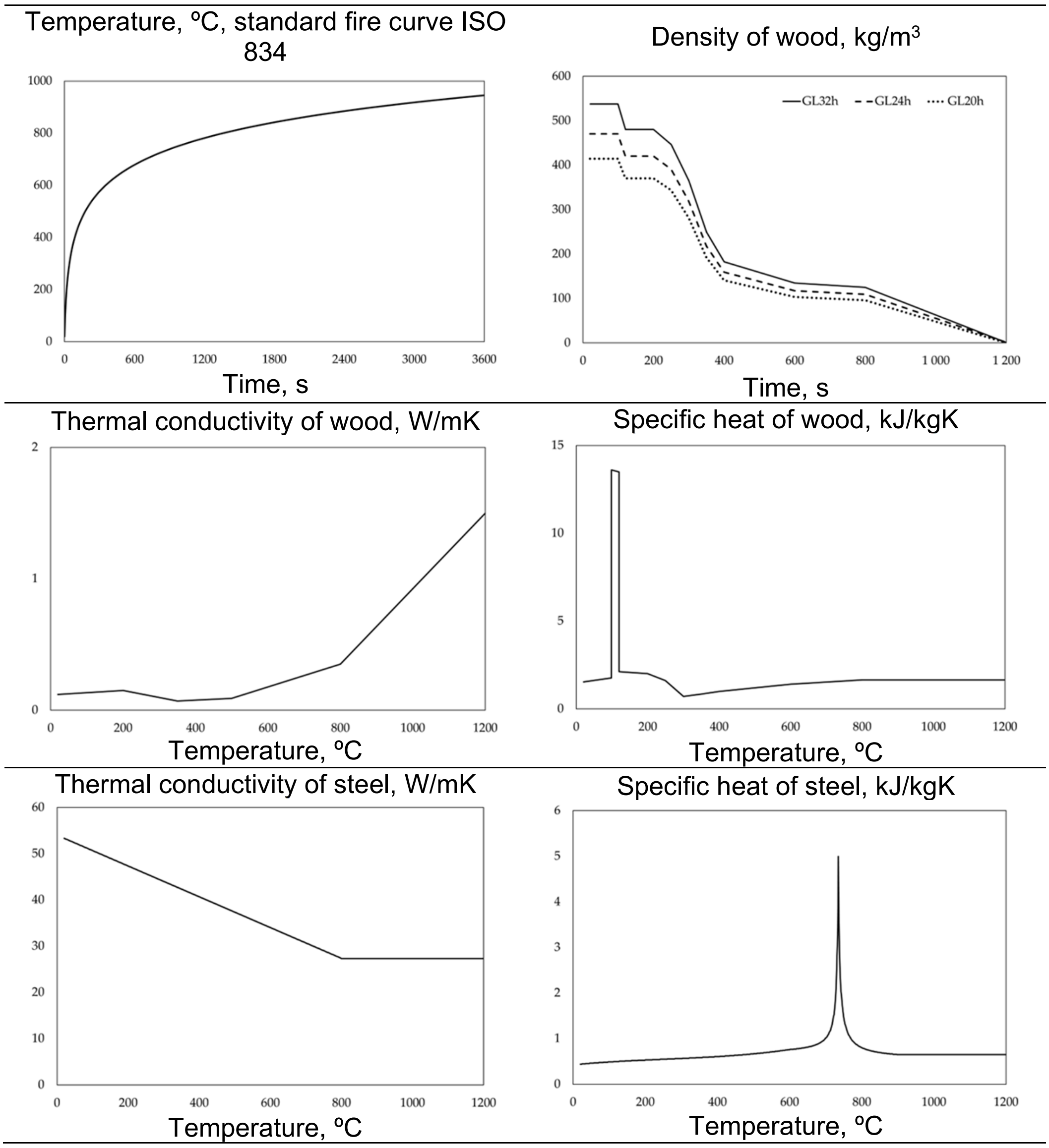


Figure 3: Time fire curve and thermal material properties of wood and steel.

For thermal analysis, heat transfer is governed by material density, thermal conductivity, and specific heat. The wood properties are temperature dependent, being defined by Eurocode 5, part 1-2 [2], presented in Figure 3. For steel, density is assumed to be constant for the entire range of temperatures produced during a fire, while thermal conductivity and specific heat are dependent, being the respective variation with temperature, Figure 3, Eurocode 3, part 1-2 [6].

The fire starts with a transient thermal analysis, resulting in the thermal response of the connection during the fire exposure. The nominal temperature-time standard curve ISO 834 will be allowed in the computational model because it has been used in fire tests to rate structural and separating elements [12], described by Equation (1) and in Figure 3.

$$\theta_{\infty} = 20 + 345\log_{10}(8t + 1) \qquad (1)$$

where *t* is the time in minutes and θ_{∞} is the temperature in the fire compartment in °C.

2.2 Analytical Methods

The presented analytical procedure follows the simplified equations of Eurocode 5 part 1-1 [9] to determine the dimensions of the connections. Eurocode 5 part 1-1 [9] provides easy equations to calculate the load-carrying capacity in various connection types. For the design of the connection, the aim is to determine the number of dowels and their dimensions. The equations presented in Table 2 are used for single shear connections [4, 5], where the main variables are as follows:

$F_{v,Rk}$ is the characteristic load-carrying capacity per shear plane per fastener (Table 2);
t_i represents the thickness of the wood member (*i*=1, 2), respectively, the smaller and the middle wood side member;
d is the dowel or fastener diameter;
β is the ratio between the embedment strength of the members, equal to 1;
$F_{\alpha x,Rk}$ represents the characteristic axial withdrawal capacity of the fastener;
$f_{u,k}$ is the material characteristic tensile strength.
ρ_k characteristic density of the wood;
$M_{y,Rk}$ is the characteristic fastener yield moment calculated according to the dowel diameter and the material strength, equation 2;
$f_{h,i,k}$ is the characteristic embedment strength in wood member (*i*=1, 2), equation 3.

$$M_{y,Rk} = 0{,}3\, f_{u,k}\, d^{2{,}6} \quad (2)$$

$$f_{h,1,k} = 0{,}082(1 - 0{,}01d)\rho_k \quad (3)$$

The design tensile strength along the grain $f_{t,0,d}$ must be equal to or higher than the design tensile stress along the grain. The tensile strength represents a reduced value of the characteristic tensile strength along the wood grain, due to the application of safety factors: the modification factor for load duration and moisture content k_{mod} is equal to 0.6 for permanent load action and the partial factor for material properties γ_M is 1.25, as the following expression 4:

$$f_{t,0,d} = \frac{k_{mod}\ \ f_{t,0,k}}{\gamma_M} \quad (4)$$

With the calculation $F_{v,Rk}$, from table 2, it is possible to obtain the number of bolts *N*, equation 6.

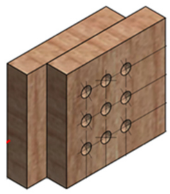
$$F_{v,Rd} = \frac{F_{v,Rk}\, k_{mod}}{\gamma_M} \quad (5)$$

$$N = \frac{E_d}{F_{v,Rd}} \quad (6)$$

Table 2 presents the characteristic load-carrying capacity per shear plane per fastener calculation and the respective failure modes that can appear. Mode I refers to an embedment failure of the connected materials without any yielding of the fastener, Mode II refers to a combination of embedment failure of the connected material and single yield failure per shear plane of the fastener, and Mode III refers to a combination of embedment failure of the connected material and multiple yield failures of the fastener [11]. Failure Modes II and III assume a ductile fastener that can form plastic hinges [11].

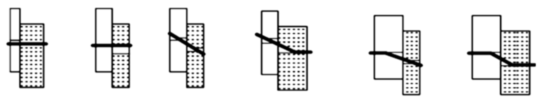
The results in Figure 4 represent the relationship between the number of dowels depending on the applied load, and the dowel diameter for each type of connection, using different variables. For wood-to-wood connections A, there is not a large variation in the number of dowels for connections with large diameters and any wood material density. But, when the use of dowels decreases in diameter, the variation in the number of dowels increases. For connections steel-to-wood with a thin steel plate B-i, and dowel diameters of 8 and 10 mm, the number of dowels is very close. The same behaviour is obtained when the steel plate is thick B-ii. For small dowel diameters, in these connections, a linear increase is verified, also in all different material densities used. In general, the density material does not affect the number of dowels so much when compared with the effect of dowel diameter. Nevertheless, the better the wood, the stronger and stiffer the connections. The increase in dowels is significantly pronounced in connections with small diameters. Comparing all types of connections, steel-to-wood with a thick steel plate B-ii needs a higher number of dowels for any type of wood density. For any connection, timber with high density combined with a higher dowel diameter needs fewer dowels.

Table 2. Simplified equations for fasteners in single shear.

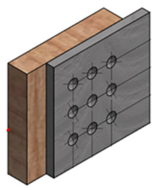


A-Wood-to-wood connection

$$F_{v,Rk} = \min \begin{cases} f_{h,1,k}\, t_1\, d \quad (a) \\ f_{h,2,k}\, t_2\, d \quad (b) \\ \dfrac{f_{h,1,k}\, t_1\, d}{1+\beta}\left[\sqrt{\beta + 2\beta^2\left[1+\dfrac{t_2}{t_1}+\left(\dfrac{t_2}{t_1}\right)^2\right]+\beta^3\left(\dfrac{t_2}{t_1}\right)^2} - \beta\left(1+\dfrac{t_2}{t_1}\right)\right] + \dfrac{F_{\alpha x,Rk}}{4} \quad (c) \\ 1.05\dfrac{f_{h,1,k}\, t_1\, d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\dfrac{4\beta(2+\beta)M_{y,Rk}}{f_{h,1,k}\, d\, {t_1}^2}} - \beta\right] + \dfrac{F_{\alpha x,Rk}}{4} \quad (d) \\ 1.05\dfrac{f_{h,1,k}\, t_2\, d}{1+2\beta}\left[\sqrt{2\beta^2(1+\beta)+\dfrac{4\beta(1+2\beta)M_{y,Rk}}{f_{h,1,k}\, d\, {t_2}^2}} - \beta\right] + \dfrac{F_{\alpha x,Rk}}{4} \quad (e) \\ 1.15\sqrt{\dfrac{2\,\beta}{1+\beta}}\sqrt{2\, M_{y,Rk}\, f_{h,1,k}\, d} + \dfrac{F_{\alpha x,Rk}}{4} \quad (f) \end{cases}$$



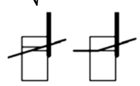
Modes: (a) I (b) I (c) II (d) II (e) II (f) III



B-Steel-to-wood connection

i) For a thin steel plate in single shear:

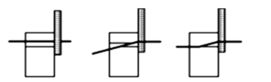
$$F_{v,Rk} = min \begin{cases} 0.4\, f_{h,1,k}\, t_1\, d \quad (a) \\ 1.15\sqrt{2\, M_{y,Rk}\, f_{h,1,k}\, d} + \dfrac{F_{\alpha x,Rk}}{4} \quad (b) \end{cases}$$



Modes: (a) II (b) II

ii) For a thick steel plate in single shear:

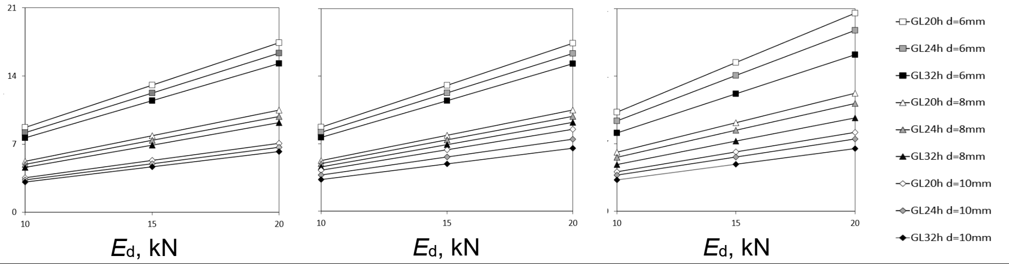
$$F_{v,Rk} = min \begin{cases} f_{h,1,k}\, d\left[\sqrt{2+\dfrac{4M_{y,Rk}}{f_{h,1,k}\, d\, {t_1}^2}} - 1\right] + \dfrac{F_{\alpha x,Rk}}{4} \quad (c) \\ 2.3\sqrt{M_{y,Rk}\, f_{h,1,k}\, d} + \dfrac{F_{\alpha x,Rk}}{4} \quad (d) \\ f_{h,1,k}\, t_1\, d \quad (e) \end{cases}$$



Modes: (a) I (b) II (c) II

The geometric model of the connections is calculated according to Eurocode 5, part 1-1 [9]. The main dimensions of the connection are the width (*L*), height (*H*), the depth (*W*) obtained by the thickness of the wood (t_1 or t_2) and steel plates (t_s), the minimum spacing, and edge/end distances between the dowels and the plates (a1, a2, a3,t and a4,c). Table 3 shows the equations that allow the calculation of these variables, depending on the angle α between the direction of the tensile load and the loaded edge (or end), represented in Figure 5.

Connection A	Connection B-i)	Connection B-ii
N dowels (0-21)	*N* dowels (0-21)	*N* dowels (0-21)



E_d, kN | E_d, kN | E_d, kN

Figure 4: Number of dowels for fasteners in single shear.

Table 3. Equations to determine the spacing or edge/end distance in connections.

Spacing or edge/end distance	Angle	Minimum spacing or edge/end distance
a1	0° ≤ α ≤ 360°	(3+2+|cos α|) *d*
a2	0° ≤ α ≤ 360°	*3d*
a3,t	-90° ≤ α ≤ 90°	Max (7*d;* 80 *mm*)
a4,c	180° ≤ α ≤ 360°	*3d*

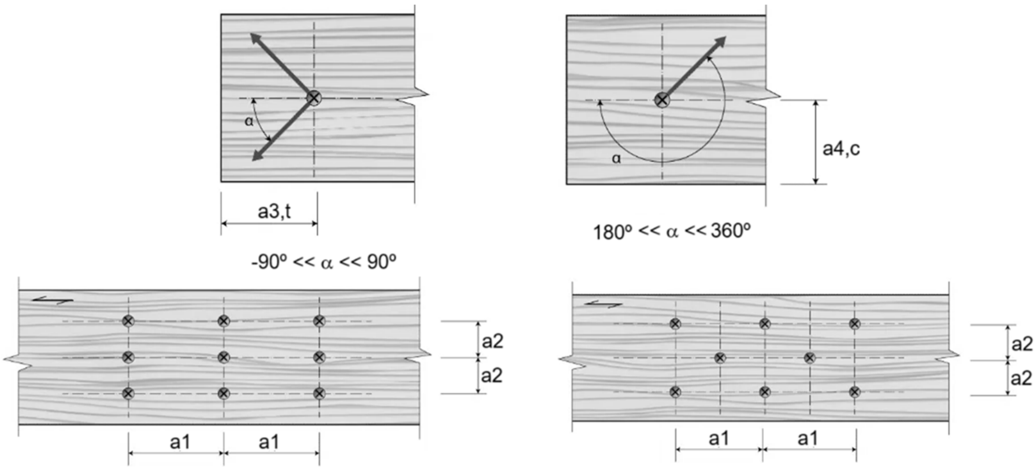


Figure 5: Spacing or edge/end distance between dowels in connections.

2.3 Computational Method

A three-dimensional numerical model was created using the ANSYS® program to carry out the thermal and transient analysis, considering the nonlinear properties of wood and steel materials. The boundary conditions are related to convection and radiation, according to the fire exposure following the standard fire curve ISO 834, equation 1. All sides of the connection will be exposed to fire. The initial temperature in the connection was considered equal to 20°C. The convection coefficient is 25 W/m^{2}K [12]. The emissivity of the flames is considered constant and equal to 1 [12]. For steel, the emissivity of the material is defined as equal to 0.7, Eurocode 3, part 1-2 [6]. The emissivity of wood is also defined as equal to 0.8, Eurocode 5, part 1-2 [2]. For this type of analysis, the software uses the Newton–Raphson method to determine the new equilibrium position in the transient process.

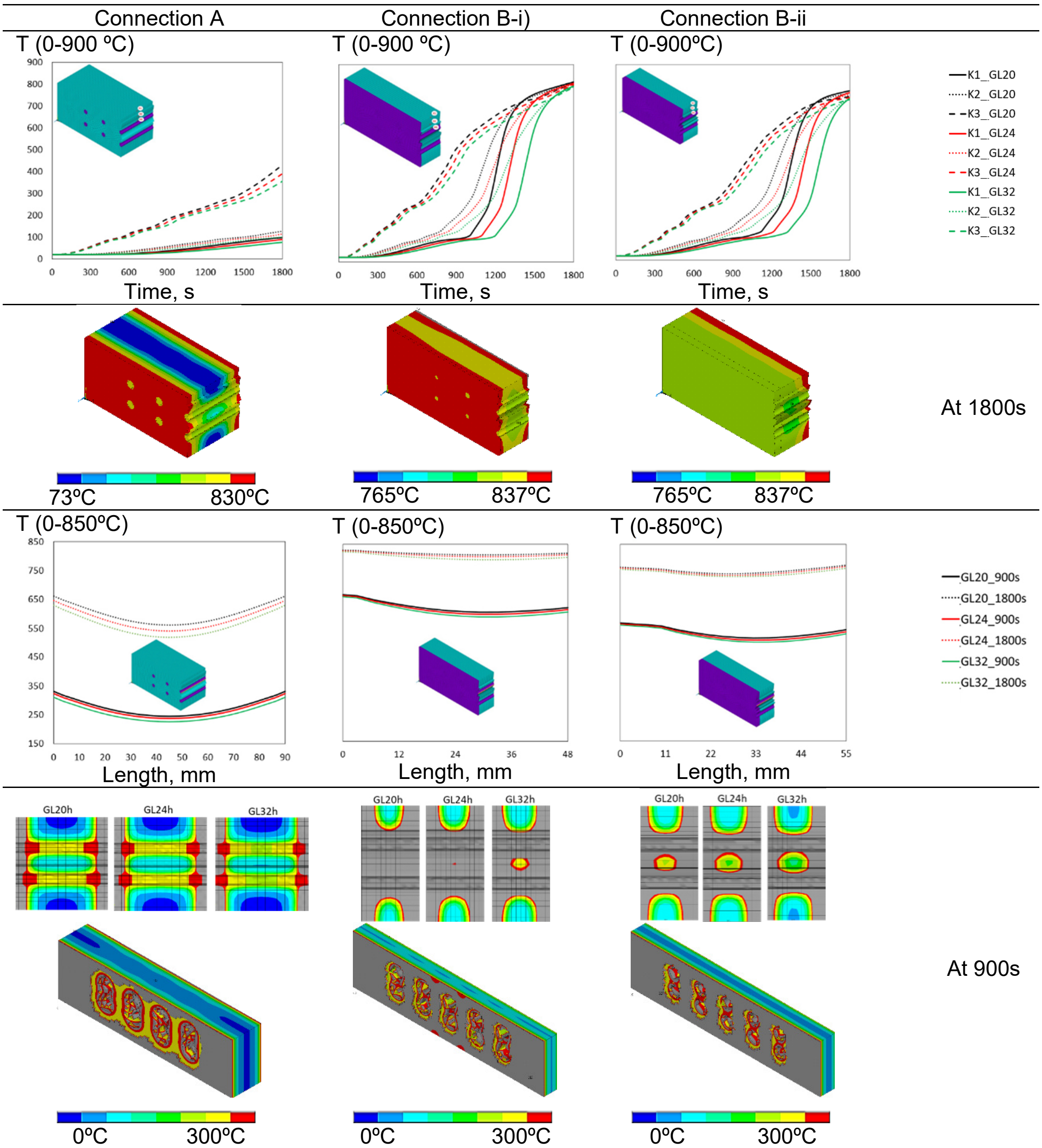


Figure 6: Results of the thermal analysis.

To represent the mesh, the finite element SOLID 278 with a 3-D thermal conduction capability was chosen. This element has 8 nodes with one degree of freedom, the temperature, for each node. Figure 6 presents the results and the mesh used. To obtain the results, different nodal points and the length of the dowel are considered for analysis, as well as post-processing for an imposed fire exposure time.

3. RESULTS AND DISCUSSION

A procedure with all analytical and simplified equations was presented to assess the dimensions of the connection cross-section for any applied tensile load. The number of fasteners increases with load, according to standards at room temperature. Lower dowel diameter has a higher pronounced effect on the number of fasteners. The mechanical effect due to the strength of the material is not significant, but the wood density variation affects the thermal behaviour. In addition, a numerical model, using the finite element method, was developed in order the obtain the temperature evolution and the wood char layer formation, as represented in the flowchart, Figure 7.

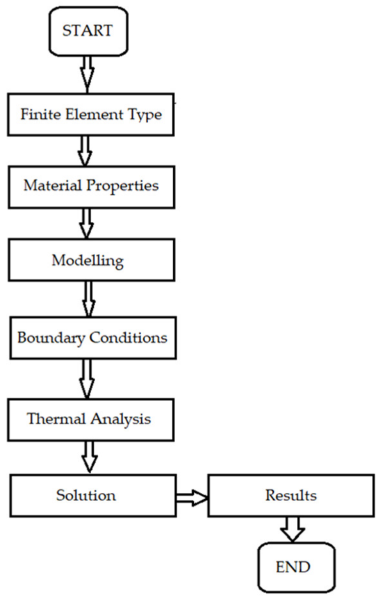


Figure 7: Thermal and transient analysis, flowchart.

These numerical models help to better understand the behaviour of the connection under fire exposure, in comparison to the simplified method. According to Eurocode 5, the charring rate is considered a standard and constant value; however, using the numerical results, the charring rate varies in the connection because of the steel and wood density. The wood charring rate is higher in the presence and in the vicinity of the dowels, being the worst situation between the dowels. It is important to point out that steel provides a heat flow to the inside of the connection, but the wood members give some insulation. This way, both materials participate in the char layer development in the connection. As a general conclusion, the combination of the largest wood density with the largest dowel diameter allows lower temperatures for the connection in a fire situation. In opposite, a lower wood density and a smaller dowel diameter led to a higher charring rate due to the greater number of connectors.

4. CONCLUSIONS

The main conclusions are listed as follows:
-The number of fasteners increases with load, and a lower dowel diameter has higher pronounced effect on the required number of fasteners.
-The mechanical effect due to the strength of the material and its density implies the verification that the better the wood, the stronger and stiffer the connections.
-A numerical method based on the finite element method was possible to apply, allowing the calculation of the temperature in connection subjected to a fire.

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SEGURANÇA 4.0

Fire Modelling

Best Practices Handbook

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Editor

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contents.

01.
introduction

1 introduction.

1.1 Scope

This manual is intended to provide a comprehensive and user-friendly overview of how to use fire modelling software in buildings. It is not (nor is it intended to be) a technical manual for using this type of tool, but rather a document to help the reader to understand the purpose of fire modelling software, to its advantages and limitations, and to help making decisions as to which calculation model to use in each situation. As it is also meant to provide methodologies and quality standards, it is called a best practices handbook.

1.2 What is fire modelling

Fire is a complex phenomenon, whose course depends on several factors, such as:

- Nature of the fire load (type of material, whether it is encapsulated or not, etc.)
- Fire load geometry
- Environmental conditions (temperature, humidity, pressure)
- Compartment characteristics (confined or unconfined, compartment geometry, thermal absorption of materials, etc.)
- Thermodynamics (fire-generated convection flows)
- Compartment fluid dynamics (smoke control systems, wind, etc.)
- Fire-fighting equipment available

The complexity of the phenomena and variables is such that it is hard to predict the course of a fire without software tools capable of processing all this information. Fire modelling software uses complex formulae to process the following types of information:

- Fire chemistry
- Fluid dynamics
- Thermodynamics
- Heat transfer

The calculations performed yield numerical information (tables) and graphical visualisations (2D and 3D images) of the development of the fire over time, to offer information such as:

- Height of smoke layer
- Temperature of smoke layer and smoke-free layer
- Optical density and visibility in smoke layer
- Chemical nature of gases in the compartment (oxygen content, carbon monoxide content, carbon dioxide and other reaction products) in both the smoke and smoke-free layer
- Gas flows through openings (air inlet and smoke outlet)
- Pressure gradients in the various compartments
- Temperature in compartment materials (walls, ceiling, floor)
- Radiation received at a specific point or surface

1.3 Purpose of fire modelling

Generally speaking, fire modelling is necessary whenever there is a need to predict how a fire will develop within a given compartment. Its applications are manifold:

- **Determine the fire resistance of structural elements**, allowing to predict the temperature to which they will be exposed and assess whether they will need passive protection, as well as the respective requirements
- **Check the tenability of the escape routes** over time (smoke height, temperature, toxicity, visibility, etc.); this is particularly useful in circumstances where the escape routes may be defective for some reason
- **Validate the effectiveness of the smoke control systems**; this is particularly relevant when the smoke control systems are not fully code compliant or where the characteristics of the compartment may cause the smoke control to be less effective, as in the case of particularly large or tall compartments
- **Analysis of fire and life safety design** whenever they do not fully comply with the regulatory requirements for any reason
- **Development of legislation**, allowing the legislator to validate whether the requirements it is providing for are efficient or excessive
- **Post-fire investigation** to model and understand what happened
- **Academic research**, which can be used to help interpreting the results of experimental work or to reduce the amount of experimental work required

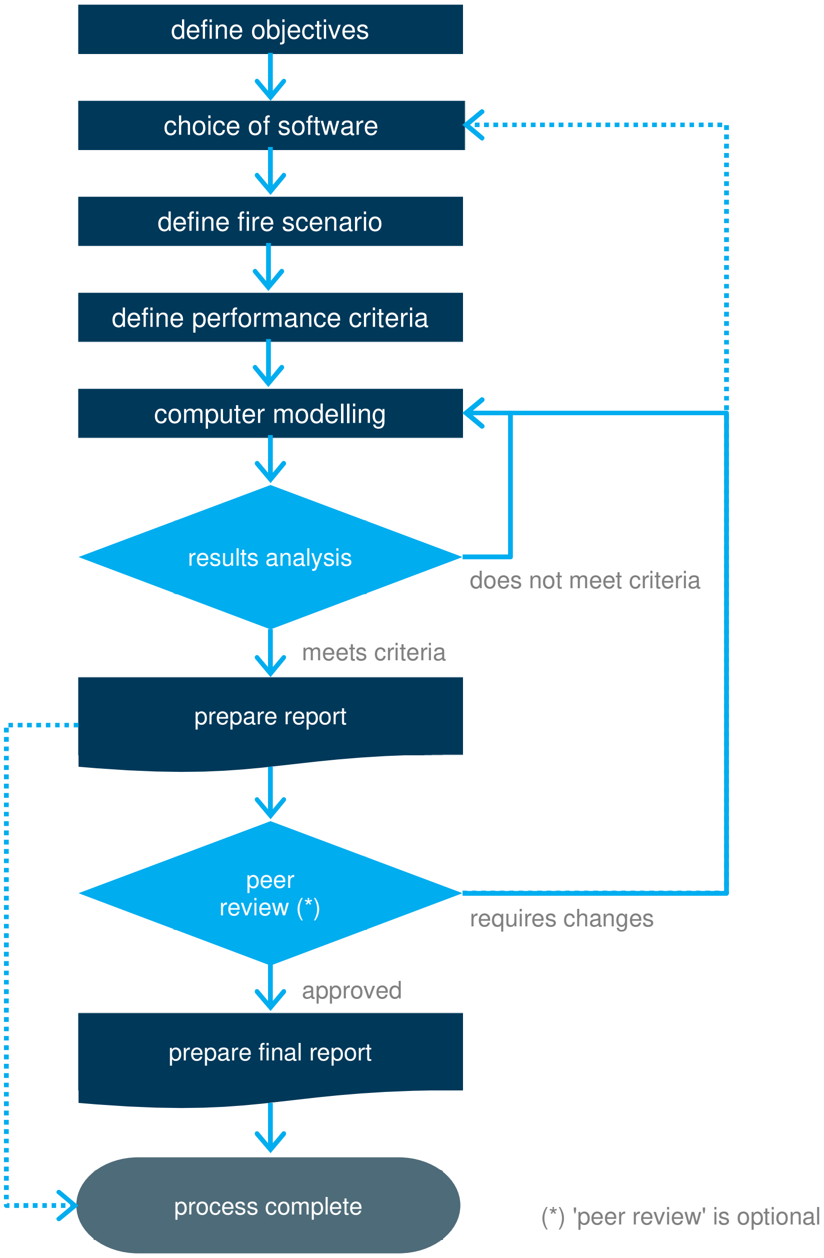
In a business environment, fire modelling can be used in the following contexts:

- Fire and life safety (F&LS) design
- Fire risk analysis
- Safety audits
- Safety management

02.
methodology

2 methodology.

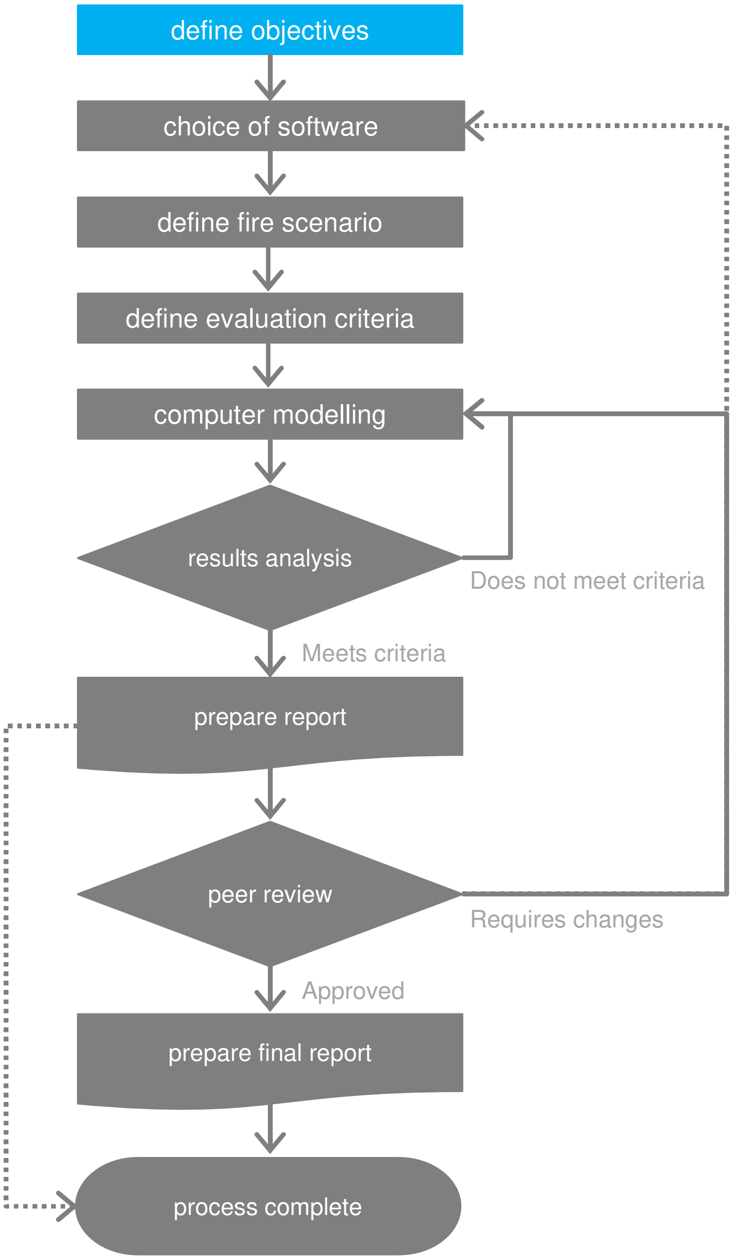
Like any other process, fire modelling must follow a certain procedure with several steps and tasks. The flow chart below depicts the usual procedure, and which needs to be adjusted on a case-by-case basis. Each of these steps will be described in a separate chapter in the following pages.



The methodology proposed above follows broadly the structure and rationale of ISO standard *23932:2009 Fire safety engineering - General principles*.

03.

modelling objectives


define objectives
choice of software
define fire scenario
define evaluation criteria
computer modelling
results analysis
Does not meet criteria
Meets criteria
prepare report
peer review
Requires changes
Approved
prepare final report
process complete

3 modelling objectives.

Defining the objective is the first step in the fire modelling process. As mentioned above, fire modelling can serve several purposes. Depending on the objective, there are different options as to the software, fire scenario and requirement criteria to be adopted.

Clearly defined objectives are of the essence to determine which resources will be needed, regardless of whether modelling is performed with internal company resources or using outside service providers. The tables below summarise the factors to take into consideration and provide a few examples.

Criterion	Example
Purpose	Determining the fire resistance of structural elements
Desired data	Temperatures in structural elements
Scope	Structural elements of a specific area
Addressee	Licensing authority / Contractor / Insurer
Peer review	No / University

Criterion	Example
Purpose	Check tenability of escape routes
Desired data	Smoke layer height and temperature, toxicity of gases, visibility
Scope	Categorisation of intended escape routes
Addressee	Licensing authority / Operating entity
Peer review	No

Criterion	Example
Purpose	Validate the effectiveness of smoke control systems in a car park
Desired data	Gas temperature at various heights, stream lines, visibility
Scope	Whole park, one floor only or one fire compartment only
Addressee	Licensing authority / Construction owner
Peer review	No / LNEC

Criterion	Example
Purpose	Post-fire investigation in case of fatalities
Desired data	Plume geometry, temperatures at specific (target) points, toxicity of gases
Scope	Compartments affected by fire and adjacent compartment that may bear an influence
Addressee	Insurance company / Legal entities
Peer review	No

The purpose, intended data and scope are important when choosing the calculation model to be used when defining the fire scenario, choosing the required performance criteria, and deciding on the duration of the modelling run time. Knowing who the addressee is helps choosing the type of presentation (report, slide show, 3D animations) and the type of language (everyday language, accessible to all or technical, which may be less readily understandable). Finally, knowing whether there will be peer review allows you to predict the time needed for interaction with the reviewer and possible required changes to the model, if any.

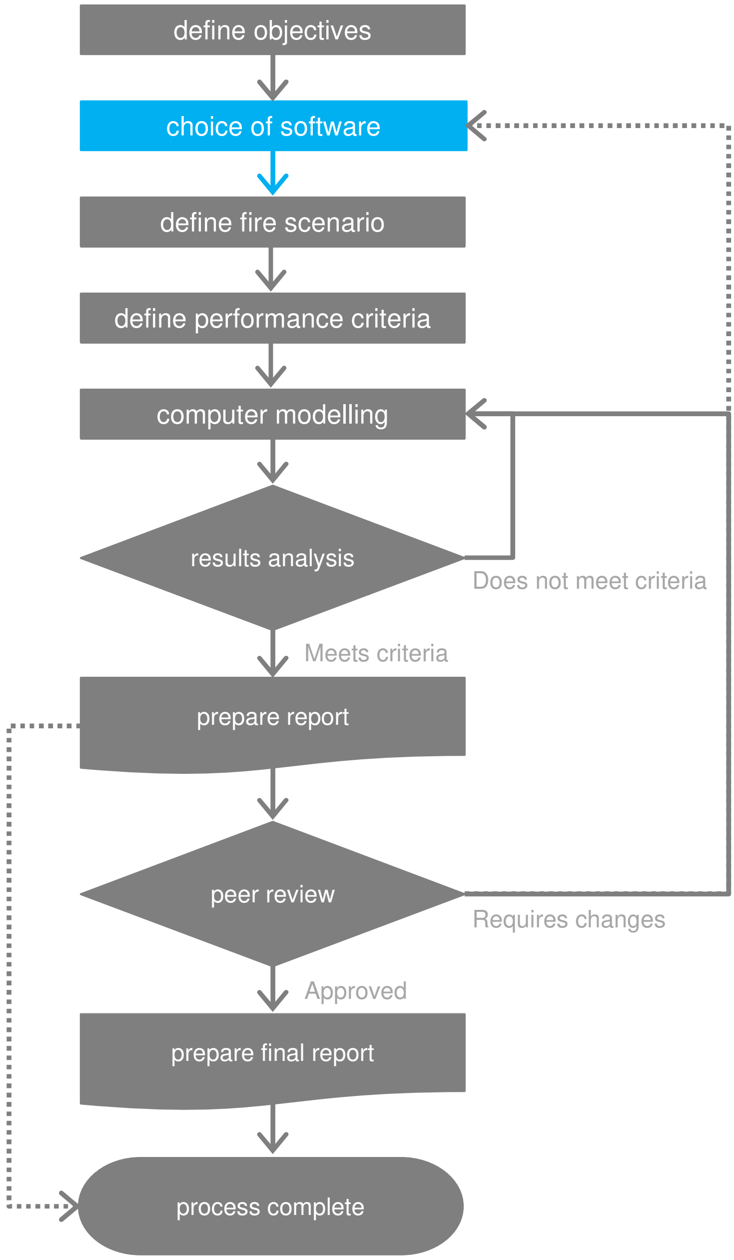
Naturally, if the modelling is carried out by an external service provider, additional information must be provided to allow for assessing the complexity of the work, namely:

- Building occupancy type
- In the case of a warehouse, the nature of the fire load
- In the case of a factory, specific features of the manufacturing process that may be relevant to the progress of a fire
- Floor and other plans

Ideally, the definition of objectives should be done in conversation - informal if required - with all stakeholders, namely:

- Who will elaborate the modelling
- Addressee, especially if it is an official body (licensing authority, insurer, legal entity)
- Who will perform the review, if any

04.
modelling software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process complete

4 modelling software.

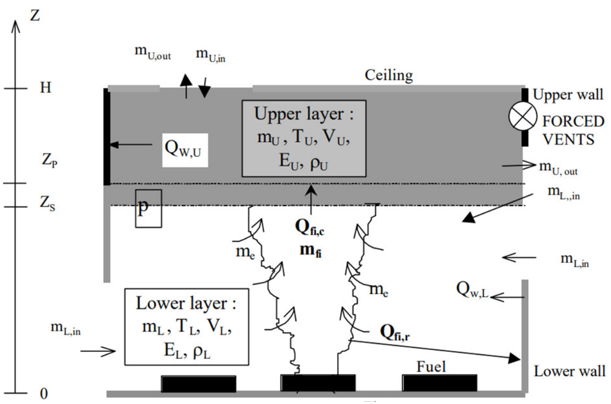
4.1 Software types

Several building fire modelling software are currently available on the market. Despite their diversity, they can be divided into two broad groups:

- Zone models
- Fluid dynamics models

Zone models

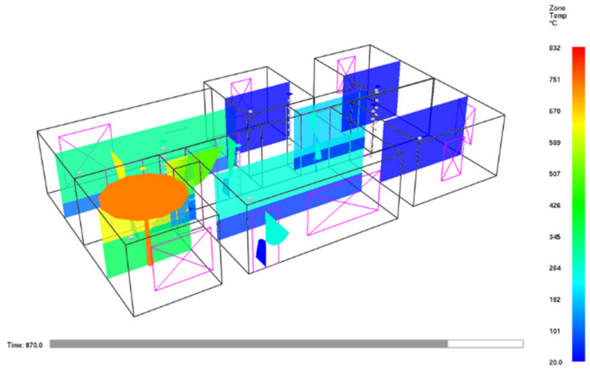
A zone model applies a simplified approach to the combustion phenomenology by considering that during a fire, gases stratify into two layers (or two zones), the upper one being the smoke layer (combustion gases) and the lower one the smoke-free layer (mainly air, but with other combustion gases). Although this approach is 'simplified', it is too complex for calculations to be done by hand or using spreadsheets. In fact, these models typically process eleven physical variables correlated via seven constraints and four differential equations continuously over time for both layers. These software allow to consider the exchange of gases through openings to the exterior or to other interior compartments, be they vertical (doors, windows) or horizontal (openings in slabs between floors or skylights). They also allow for contemplating mechanical ventilation devices for air supply and exhaust, thus enabling the modelling of smoke control systems.



Schematic section of a two-zone model and its various submodels. *Ozone, Université de Liège*

There are also simpler zone models, with only one zone for the total compartment volume, but as they are too rudimentary, they've mostly fallen out of use.

Software based on two zones allow for several volumes to be combined horizontally and vertically, which can form complex buildings with several hundred compartments and connections among them. Animated 3D visualisation of the model can be generated to show the evolution of the fire over time. They allow to visualise, for instance, the height of the various layers and their temperature and the flow of gases in the openings. It is also possible to consider multiple fire sources and include fire detectors, smoke control systems and, in some of the software, sprinklers. Command combinations can be created for triggering a succession of events, such as the activation of smoke control systems, or the opening and closing of doors and windows.

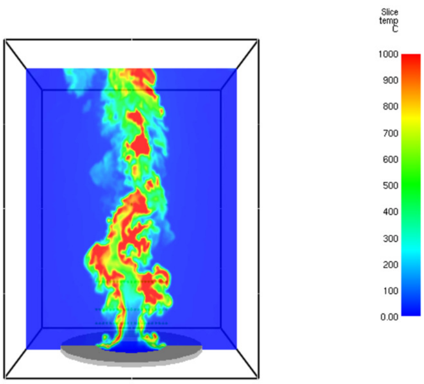


3D image of a three-bedroom flat. *CFast, Nist*

In addition to 3D visualisation, these software can export a number of types of physical and chemical data, such as temperatures, pressure, radiation, gas flow rates through openings, chemical composition of gases, optical density, fuel consumed, among others. This data can be extracted for each compartment and each opening, and several probes (targets) can be placed in the compartments to acquire data such as temperature, radiation, and pressure. Examples of zone model-based software are CFAST by NIST, and OZone, developed by the University of Liège.

Fluid dynamics models

Computational Fluid Dynamics (CFD) models are highly complex in mathematical and computational terms. The fire compartments are subdivided into small cells (finite element models) to create a fine mesh. The software processes gas interactions between these cells over time, allowing for a much more detailed analysis of what is happening in the compartment, namely the gas turbulence. Rather than being flat and perfectly stratified as in the zone model, the smoke layer has a three-dimensional geometry that varies in time and space.



3D image of a methane flame showing temperature variation along the flame. *FDS, NIST*

These software allow for extracting the same type of data as the zone models, but in much greater detail. In addition, they also provide information on gas turbulence, e.g., providing a visualisation of the particle transport in gases (streamlines).

Examples of software using fluid dynamics models are FDS (Fire Dynamic Simulator) by NIST, and FLUENT created by Ansys. As the FDS interface is not particularly user-friendly (data is entered numerically), graphical interface software are available to simplify the data entry process, such as PyroSim by Thunderhead Engineering.

4.2 Validation

It is of utmost importance that the software to be used, regardless of being a zone model or a fluid dynamics model, is duly validated by a third party. This validation is normally done via full-scale tests to allow for ongoing calibration and improvement of the software. When choosing a modelling software, you should therefore consult available reference literature to make sure the software has been duly validated for the scenario to be modelled. All software referred to in this document meet these criteria.

4.3 Applicability limits

All software have an applicability limit. This limit may be the maximum number of rooms, maximum building size or number of fires. It is therefore important to check these limits in the software reference manual. For instance, when modelling the performance of automatic suppression systems, some software performs more rigorous and complex calculations that include all factors, while others resort to simplification, usually resulting in more conservative results.

4.4 Criteria for selection

The choice of software to be used for a given modelling depends on the objectives that have been set. The table below summarises the advantages and disadvantages of the different types of software.

Type	Advantages	Disadvantages
Zone models	Simple and fast modelling Fast processing Allows for modelling several fire scenarios in a short period of time Efficient and reliable for laminar flow	Does not import 3D geometry from other software Does not allow for creating complex geometries Not suitable for turbulent flow Limited ability to model wind action
Fluid dynamics models	Allows for creating complex geometries More detailed data, namely flame geometry and smoke layer Models fire in turbulent flow Allows for modelling phenomena other than fire, such as gas leaks or pollution	Very complex modelling Requires large computing resources, cloud computing recommended Modelling can take several days to complete

Based on these parameters, below are some examples of software depending on the objective.

Compartment type	Objective	Type of software to use
Storage room or small warehouse, connected to a corridor	Determine if a fire in this warehouse would jeopardise evacuation of the compartments enclosing the corridor	Zone model
A building with several small or medium-sized rooms, such as a hotel, hospital or school	Modelling of various fire scenarios, for the purpose of modelling the escape route tenability conditions	Zone model
Atrium with several geometrically not too complex levels	Modelling for quick determination of how efficient different types of smoke control are	Zone model
Geometrically very complex large-volume atrium with organic forms and sloping surfaces	Modelling of smoke control systems by dilution, requires checking the smoke toxicity toxicity at several different heights	Fluid dynamics model
Open large-area covered car park	Understanding whether wind action alone is sufficient to adequately remove the carbon monoxide	Fluid dynamics model
Car park with jet fans	Check performance of the smoke control system and the location of possible vortices where smoke may accumulate	Fluid dynamics model

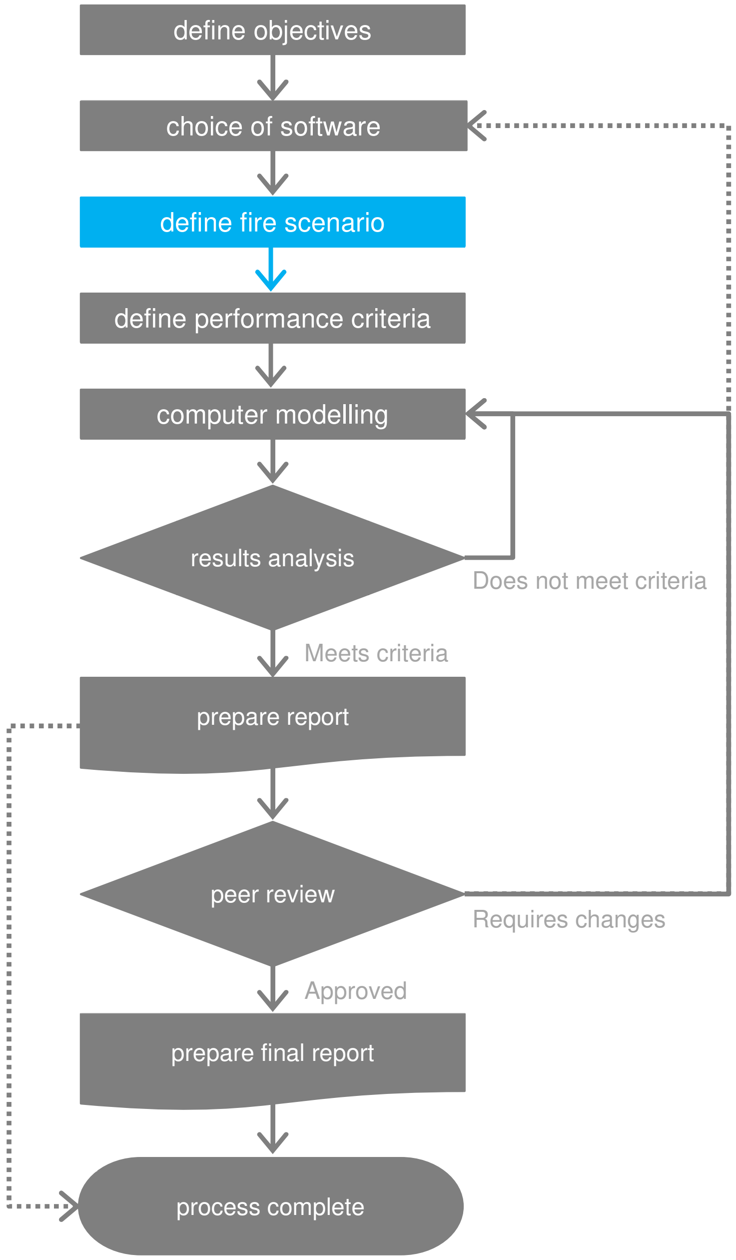
4.5 Interaction with other types of software

Another aspect that must be taken into consideration when choosing a software is a possible need for interaction with other types of software, whether for importing or exporting data, or for integrating data in real time.

For instance, when modelling a complex building that already exists as a three-dimensional BIM (Building Information Modeling) model, one would choose a software that can import that 3D geometry in a compatible format, the most common being IFC (International Foundation Class).

On the other hand, if for the building under study it is expected that it will be necessary to carry out fire and evacuation modelling to understand how the fire could affect the occupants, it is useful to choose a software that can integrate the result data of one model into the other. An example of this is PathFinder from Thunderhead Engineering, which allows the integration of FDS fire modelling results data.

05.
fire scenario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5 fire scenario.

5.1 What is a fire scenario and what is it used for

A fire scenario is a set of assumptions that are taken into account when modelling fire, including definitions such as the following:

- Fire location
- Duration
- Design fire
- Active fire protection systems to be deployed
- Specificities arising from the operation of the building

Computer-based fire modelling can be a time-consuming process, especially if fluid dynamics models are used. Depending on the type of software used and the complexity of the building, processing a fire may take hours, days or even weeks. As such, it may not be feasible to model several different scenarios, and the scenarios that may be most challenging for the building in question will need to be determined.

5.2 Location of the fire

The location of the fire comprises two aspects:

- Compartment in which it occurs
- Specific location of the fire within the compartment

The choice of compartment depends very much on the objective set for the modelling. Examples of common scenarios:

A. Room with highest occupancy load in the building (e.g., an auditorium)
B. Critical areas in the evacuation paths of the building (e.g., an entrance hall)
C. Tall high-volume compartment where smoke control may be less efficient due to its size
D. Compartment on a very high floor above the reach of the fire engine ladders
E. Compartment with highest fire load

Once the room where the fire will be modelled been determined, its location within that compartment needs to be defined. Bearing in mind that the scenario should be challenging, here are some possible locations for the examples above:

A. Near the main door of the auditorium
B. In a bottleneck area blocking the exit significantly
C. Near an air supply ventilation grille
D. Away from windows, so that they are not broken by the thermal action and do not ventilate the compartment
E. In the middle of the compartment to maximise progression

5.3 Duration

Modelling a fire requires defining the duration during which the fire will be modelled. The longer the duration, the more hours (or even days!) will be needed for the computer to process the modelling. In order to speed up the process, the shortest possible duration serving the purpose of the modelling should be used. Examples:

- To model the evacuation tenability conditions - 15 minutes (assuming that evacuation is completed before that; the fire modelling time should always be longer than the estimated evacuation time)
- To predict environmental conditions when the fire brigade arrives - 30 minutes (if their arrival is expected much earlier)
- To assess impact on structural elements - 60 minutes or more, depending on evolution of fire curve and regulatory requirements for the compartment under analysis

5.4 Design fire

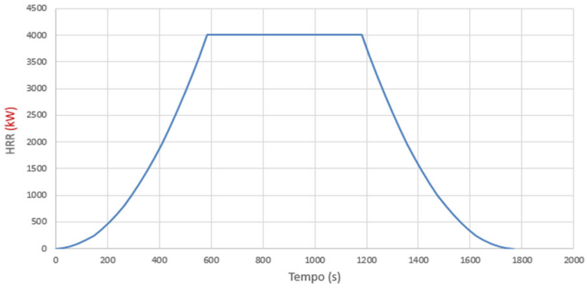
There are two possible methodologies for defining the design fire:

- If a given reference standard is to be followed, use the design fire specified in that standard
- Use a design fire matching the building's specificities

Standards usually typify situations, so a design fire may not be realistic for the compartment in question due to factors lacking or in excess. However, this approach is potentially more readily accepted by the licensing authorities.

The choice of a specific fire for the building may be a more appropriate solution, but it needs to be thoroughly substantiated via reference bibliography, and be reasonably conservative.

The graph below shows a sample fire curve, where the growth stage is a squared (αt^2) average growth reaching 1 MW at 300 seconds, as per Eurocode 1 - "Actions on structures", part 1-2 "General actions - Actions on structures exposed to fire" (EN 1991-1-2), followed by a steady burning stage of 4 MW, and finally a squared decay stage.



Fire growth and squared decay curve with a steady peak at 4 MW. *Bruno Lopes*

The definition of the design fire should cover several aspects. The most relevant ones are:

- Fire area
- Heat release rate

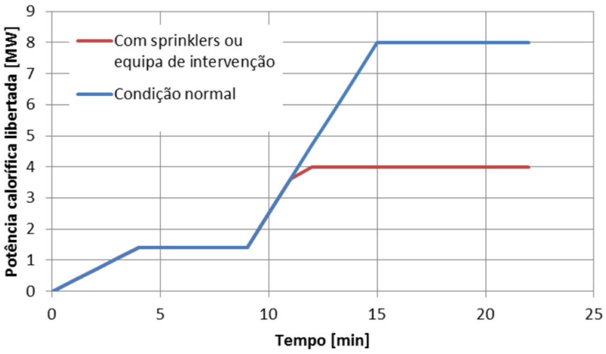
- Fire curve (development over time)
- Duration (which mayb be the result of combining the total energy released with the fire curve)
- Chemical composition of fire load
- Possibly relevant by-products, such as soot

The last two aspects are only really relevant if the modelling is for determining gas toxicity and visibility.

5.5 Active fire protection systems to be deployed

Active fire protection systems such as smoke control and automatic suppression systems have a significant impact on the fire that should be considered in the modelling. Most software allows for the model to be fitted with ventilation grilles, exhaust vents and mechanical ventilation or extraction devices. In fluid dynamics models, and unlike in in zone models, jet fans may be used.

The situation is somewhat more diverse when it comes to automatic suppression systems, where zone models are naturally more limited. However, even if the model does not have specific tools to handle suppression systems, their effect can be considered by using fire curves that already incorporate the heat release reduction resulting from their action. The graph below shows the example of a fire curve for cars, with and without sprinkler effect, as per Portuguese standard NP 4540:2015 '*Sistemas de ventilação de impulso em parques de estacionamento cobertos não compartimentados*' (Jet fans ventilation systems in non-compartmented covered car parks).



Car heat release rate fire curve, with or without sprinklers. *NP 4540:2015*

5.6 Specifics arising from the operation of the building

For the modelling to be realistic, its scenario should include any situation that could aggravate the fire and is considered very likely to occur.

For instance, when modelling a fire in a hotel room, it would not be logical to do it with the room door closed, as it would not significantly affect the corridor. Even if the room has fire resistant door with closer, the fire might occur while the room is being cleaned, with the door in an open position.

Another possible example is that of a fire in a nursery. The most critical moment for evacuation is probably during the children's nap time, when they are in their beds and caretakers are typically not in the room, but leave the door ajar. Modelling this scenario shows how the fire might affect the room where the children are sleeping if there is sufficient smoke in the corridor to spread into the room through the open door.

5.7 Opening of doors, windows, etc.

The opening of doors, windows, etc. , especially to the outside, may affect development of the fire greatly since it significantly changes the evacuation conditions. A fire scenario should therefore take into consideration the following:

- The opening of doors by the occupants during evacuation; if the doors are equipped with closers, the opening and subsequent closing of the doors should be considered; if evacuation modelling is done, these data should be considered (which doors are opened/closed and when) and incorporated into the fire model
- Any windows that may be open at the start of the fire
- The breaking of window panes resulting from heat

It might be difficult to estimate the moment when glass breaks. This moment depends on several factors, including:

- Temperature difference between inside and outside
- Temperature difference between different parts of the glass if the neutral plane is at window height, the upper part of the glass being exposed to the hot gases of the smoke layer and the lower part to ambient temperature
- Temperature difference between the edge of the glass, which extends into the frame, and the visible portion of the glass that is exposed to environmental conditions; in general, the more efficient the heat transfer from the frame to the glass (e.g., in the case of older iron frames), the more easily the glass will shutter
- Characteristics of the glass, namely thickness, type (for instance, whether it is tempered or not) and if it is plain, double or laminated glass; for example, plain 3 mm glass (harduly used anymore, but often found in older buildings) will break at temperature differences around 150ºC, while 6 mm or thicker double or laminated glass requires temperature differences of 650ºC or more to break

There are some specific software for calculating glass breakage. Most of them will only specify at what point the first cracks occur, but not when the glass collapses or what the open area of the window will be, as the collapse may be partial. The collapse of glass after breakage also depends on several factors:

- The way the glass is attached to the frame; glass extending into frames with silicone sealing on both sides is more unlikely to collapse or at least collapse completely
- Size of glass; the larger the glass, the more likely it is that parts of the glass will fall out, especially around its centre
- Type of glass; tempered glass will take longer to break, but once it does, it is likely to do so completely

- Whether the glass is plain, double or laminated; double glazing is naturally less prone to collapse when the window is fully opened, as the collapsed part of the internal glass pane is unlikely to fully coincide with the collapsed part of the external glass pane
- Pressure differential between inside and outside; fires generate positive pressure so that the pressure on the glass can accelerate its collapse after cracking; for instance, this may happen with laminated glass; it should be noted that the pressure effect is only relevant for the collapse of the first window of the room, since afterwards the pressure in the room is relieved

Given the degree of uncertainty regarding glass breakage and collapse, it may be prudent to perform several modelling runs with closed and open windows and doors, and verify which scenario is the best option for the modelling objective. Example of correlation between objectives scenario of opening doors and/or windows:

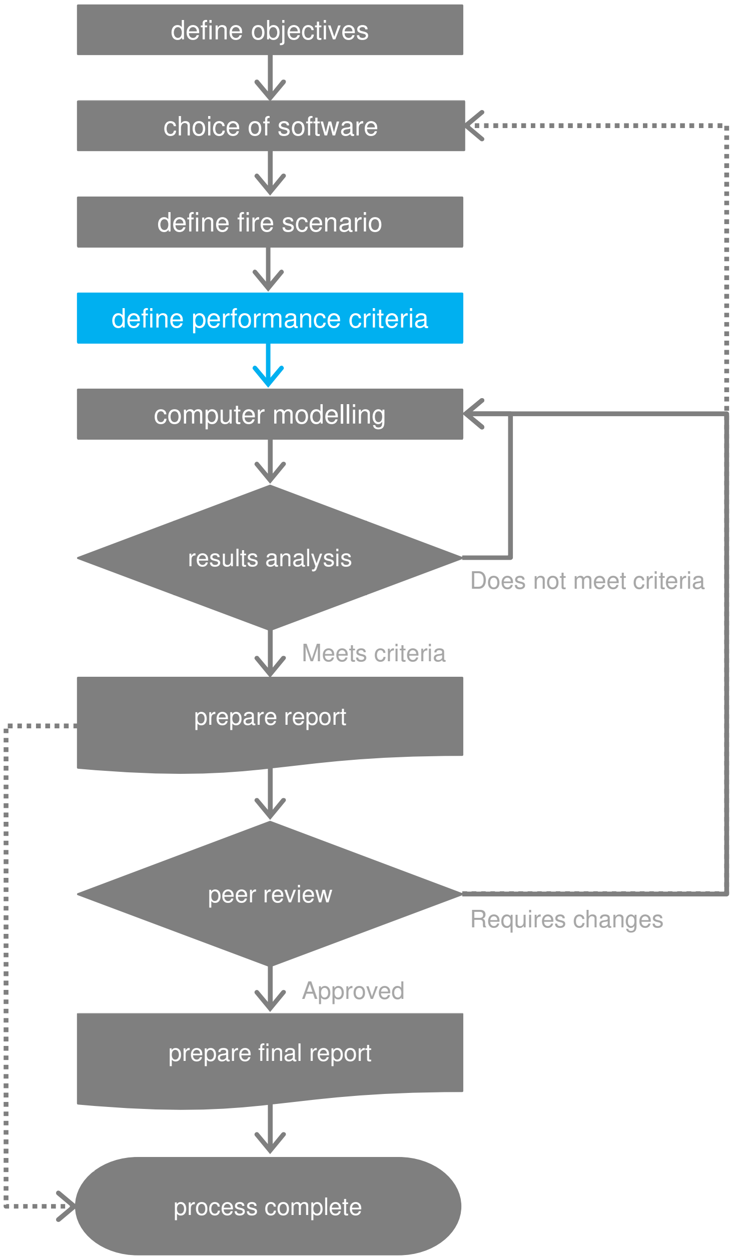
- If the objective is to model the fire resistance conditions of structural elements, a simulation considering all open doors/windows may be more challenging since oxygenation of the fire will give rise to much higher peak temperatures
- If the aim is to assess the evacuation conditions, a simulation with all windows to the outside closed and interior doors open (for instance, to the corridor) may be more suitable because while a fully developed fire will result in a lack of oxygen in the fire compartment, the temperature will be so high that pyrolysis will continue and a significant part of the combustion will occur when the gases reach the corridor rather than inside the compartment where the fire broke out; in this case, the fire temperature may be higher in the corridor (even when there is no fire load) than in the compartment where the fire broke out and where the fire load is located

5.8 Change of scenario

The fire scenario is chosen beforehand based on what is expected to be the most challenging case within the established objective. However, during the modelling process and according to the preliminary results, it may turn out that the scenario is less essential than initially expected, and that other situations may need to be examined. It may therefore be necessary to adjust or change the chosen scenario, something that should be considered as part of the normal process. Any changes to the fire scenario throughout the process should be referenced and duly justified in the modelling report.

06.

performance criteria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process complete

6 performance criteria.

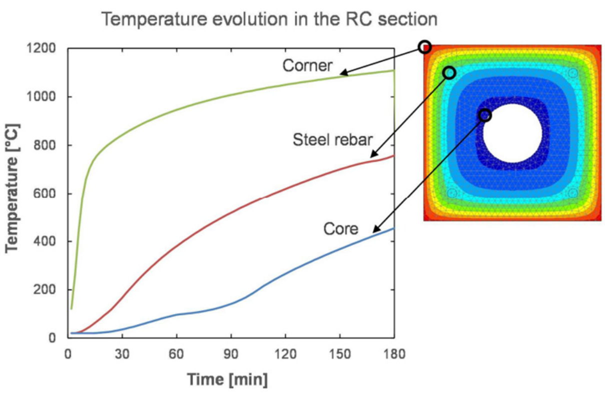
Determining the performance criteria is an important step in the process of computer-based fire modelling. These criteria must be chosen according to the objectives defined for the modelling and will subsequently determine the data to be extracted and analysed.

6.1 Fire behaviour of passive systems

If the objective is to model the performance of a passive system, the critical factor will be temperature. As such, the temperature that the structural element can withstand without collapsing needs to be known.

In the case of metallic elements, in which temperature distribution is reasonably uniform and without significant temperature gradients along their section, one speaks of 'critical temperature', given that thermal homogeneity across the section is assumed for reasons of simplification. However, for structural elements composed of various materials and with large sections, such as concrete structures, the temperature range along the section varies considerably, being higher at the edges and much lower in the central portion of the element, so that a critical temperature cannot be determined. In this case, the collapse will depend on the temperature reached in the rebar as well as on the number of rods that have reached a temperature at which they lose significant Loadbearing capacity.

It is important to understand that, up to the peak temperature of the fire, the gas temperature at the surface of structural elements is always considerably higher than the temperature of the structural elements themselves, i.e., the temperature of the structural element 'lags' behind the surrounding temperature. (Note: at an early stage in the temperature decrease of the fire, the temperature of the structural element exceeds the temperature of the gases around that element). The aforementioned lag is due to poor heat transfer between gases and solids, the higher or lower conductivity of the structural element material and the thermal inertia of the elements. As such, modelling the criteria considering only the temperature of the hot gases near the structural element is a rather conservative approach.



Temperature gradient in a concrete column and its evolution over time. *SAFIR Capabilities and examples of applications*

Finally, it should be noted that one of the possible approaches for modelling the structural fire resistance is to use a third-party structural fire modelling software such as SAFIR, developed by the University of Liège. Here, fire modelling is only used to generate temperature and radiation data for import into the structural modelling software.

6.2 Tenability of escape routes

If the modelling aim is to verify the tenability of escape routes, it is important to analyse the conditions to which the occupants will be exposed during evacuation. Conditions are influenced by several factors, such as:

- Gas temperature
- Gas composition, in particular oxygen content and toxic gases
- Amount of soot (to determine visibility)
- Radiation

These criteria should be based on legislation (no criteria are defined in Portugal), on reference standards or on specialised bibliography. Below you will find an example of the tenability criteria for healthy persons in Italian regulations (*Norme tecniche di prevenzione incendi*, 2011).

Tenability criteria	Applicable value for occupants
Height of smoke layer	≥ 2 m
Smoke layer temperature	≤ 200ºC
Temperature in smoke-free layer	≤ 60ºC
Radiant flux on occupants	≤ 2,500 W/m²
Visibility within ignition site	≥ 5 m (checked at height of 1.8 m)
Visibility on escape routes	≥ 10 m (checked at height of 1.8 m)

As noted, the above values are applicable to healthy people. If the building in question houses a significant number of people with some type of weakness, namely patients (hospitals and nursing homes) or for whom no consolidated data is available (e.g., children under three), more conservative values should be used.

6.3 Firefighting

The above criteria apply to persons without any protective gear whatsoever. If one of the objectives of the modelling is to verify the operational firefighting conditions, it should be considered that firefighters wear thermal protective clothing and a SCBA (self-contained breathing apparatus). The tenability criteria to be applied in this case should consider the protection provided by these equipment. The table below presents the tenability criteria for firefighters, again using Italian regulations as an example.

Tenability criteria	Value to be considered for fire fighters
Height of smoke layer	≥ 1.5 m
Smoke layer temperature	≤ 250ºC
Temperature in smoke-free layer	≤ 80ºC
Radiant flux on occupants	≤ 3,000 W/m^2
Visibility within ignition site	≥ 2.5 m (checked at height of 1.8 m)
Visibility on escape routes	≥ 5 m (checked at height of 1.8 m)

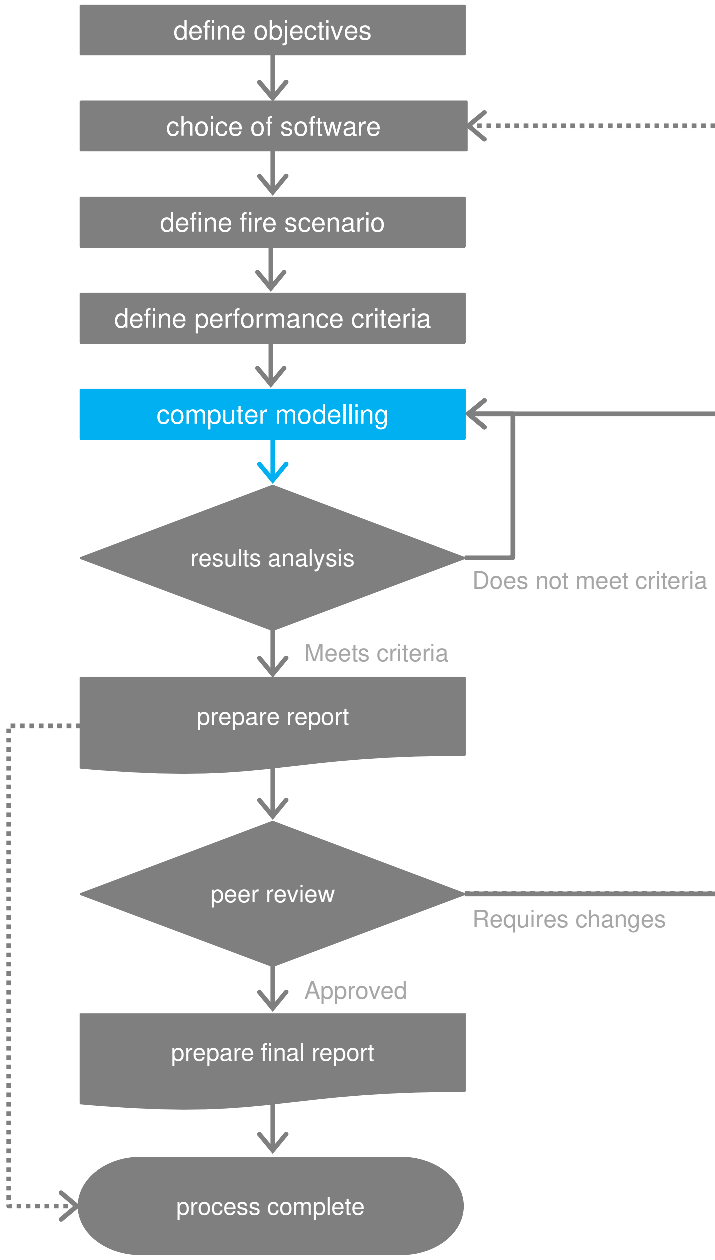
Of course, this cdoes not imply that firefighting is not possible under less favourable conditions or that firefighters are at risk if these values are exceeded. These values correspond to conditions allowing for firefighting to be carried out, and properly equipped firefighters can be exposed to them for periods of around 30 minutes.

6.4 Modelling with no defined criteria

In some particular cases, it may not be necessary to set performance criteria. Examples:

- Fire modelling intended to provide data for third-party software, as mentioned above for the fire behaviourial modelling software SAFIR
- Modelling performed to support post-fire investigation

07.
modelling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7 modelling.

7.1 GIGO

GIGO stands for Garbage In, Garbage Out. This expression is used widely in IT to alert to the risk that if input is unreliable or incorrect data, the output will be equally incorrect. This concept applies even more so for fire modelling. Users must have thorough knowledge of the software they are working so as not to make mistakes. A common mistake is not to confirm in advance what measurement units the software uses, i.e., whether they are metric or imperial units. Another possibly less serious one is not to configure the environment modelling conditions (ambient temperature, relative air humidity, altitude) to match the building being studied. Examples od other aspects in which greatest thoroughness is required:

- If you are using a design fire curve other than the software's, the definition of this new fire curve should consider both the heat release rate over time, and the characteristics of the fire load (chemical composition, soot production)
- The enclosure materials (walls and slabs)
- When not using wall or slab materials from the software library, definition of the thermal properties of the new material

7.2 Building the model

The methodology and care to be taken in building the model vary greatly depending on the type of software used. However, there are recommendations that are common to all types of software:

- The volumes of the compartments should be as close as possible to reality, whereas architectural elements that do not interfere with the fire behaviour, such as pillars, railings and furniture, can be neglected
- The openings between the various compartments, and between these and the outside should be modelled accurately and without any simplification, as they are of great relevance to the modelling; for instance, a ceiling with four 1 by 1 metre extractors must never be simplified down to a single 2 by 2 metre extractor, even though the area is exactly the same as regards aerodynamics, both cases behave differently, and a larger-area extractor may become less efficient due to a plug-hole effect (inverse eddying in the smoke layer causing the central part of the extractors to extract air from the smoke-free layer rather than smoke)
- Great care should be taken in the characterisation of the compartment materials, in particular walls and ceilings, since they can affect the temperatures reached

Zone models

In zone models, compartments are simplified into parallelepiped volumes. A compartment with a trapezoid floor plan can be simplified using a single volume of equal area and height (and as such the same volume) or by adjoining several connected volumes into a combined shape with an approximate equal volume. Here it is critical that the sum of the volumes is identical to the volume of the original compartment.

When a compartment has beams forming smoke reservoirs, multiple volumes need to be created, one for each reservoir for the modelling to consider the effect of the beams on smoke propagation along the ceiling. Similarly, if the compartment has varying heights in different parts, a volume needs to be created for each of these areas to link the various volumes together.

Most zone model software can also consider rooms with a tapering ceiling, i.e., that is narrower at the top than at the bottom (such as a dome or a vault), and a section that varies over its height can be defined.

Fluid dynamics models

Fluid dynamics software requires no significant volumetric simplifications, even in software where compartments are constructed according to a parallelipid mesh. A critical factor in the construction of the model is the definition of the mesh size. Typical values for mesh size range from 3 cm to 30 cm. While too fine a mesh provides more accurate results, processing time will increase signficantly as the calculations are performed volume by volume of the mesh. A 30 by 30 cm cube can fit 1,000 cubes of 3 by 3 cm, so a 3 by 3 cm mesh requires a thousand times more calculation than a 30 cm grid. The meshes can be variable, being thinner in the fire zone and widening as distance increases, but the different meshes must be multiples of each other.

Most fluid-dynamics based fire modelling software support import of 3D models from other software, namely from BIM (Building Information Modeling) software such as Autodesk Revit or others. Import is typically done using the interoperable IFC (Industry Foundation Classes) file format, which compatible with most software requiring 3D models. In addition to geometry, and if so configured, IFC can also export the physical properties of the materials (walls, slabs, openings), which can then be imported into the fire modelling software.

Importing the 3D model from other software can save many hours of modelling, but it is often not entirely straightforward, and some adjustments need to be made. For instance, in buildings with complex geometries, such as curved surfaces and numerous sloping planes, the conversion to software that work with a parallelepiped mesh can result in buildings with gaps in the walls, through which air can leak. A good way of detecting these types of faults is to pressurise the building and analyse the air flows to spot holes in the geometry. Another common problem is when the modelling software does not recognise openings, so some modelling work may be required in the fire modelling software.

Since exporting and subsequent importing are often slow and error-prone, especially for complex models, the 3D model should be simplified before exporting. When using BIM models, the best way is to export only the architectural geometry as well as possibly the structural geometry, but no furniture, hydraulics, electric systems, HVAC and so forth. If the fire scenario is in a localised area of the building (as happens most of the time), only the part of the geometry that will be used in the modelling software should be imported.

7.3 Implementating the fire scenario

Once the geometry of the building or part of the building under study has been created, the next steps of implementing the fire scenario in the model can be tackled. This includes in particular:

- Setting the environmental conditions (ambient temperature, relative humidity, altitude, wind outside, etc.) in case the software's default conditions are not used.
- Inserting the fire or fires to be used in the model as per the defined scenario
- Inserting the various active and passive systems of the scenario into the model, defining not only their properties (areas, flows, pressures, etc.), but also their trigger conditions (temperature, time, etc.)
- Inserting data acquisition points (targets) in the model if the modelling objective requires specific information, e.g., if the objective is to model structural resistance in a fire situation, temperature data on the surface of structural elements will need to be collected

7.4 Processing

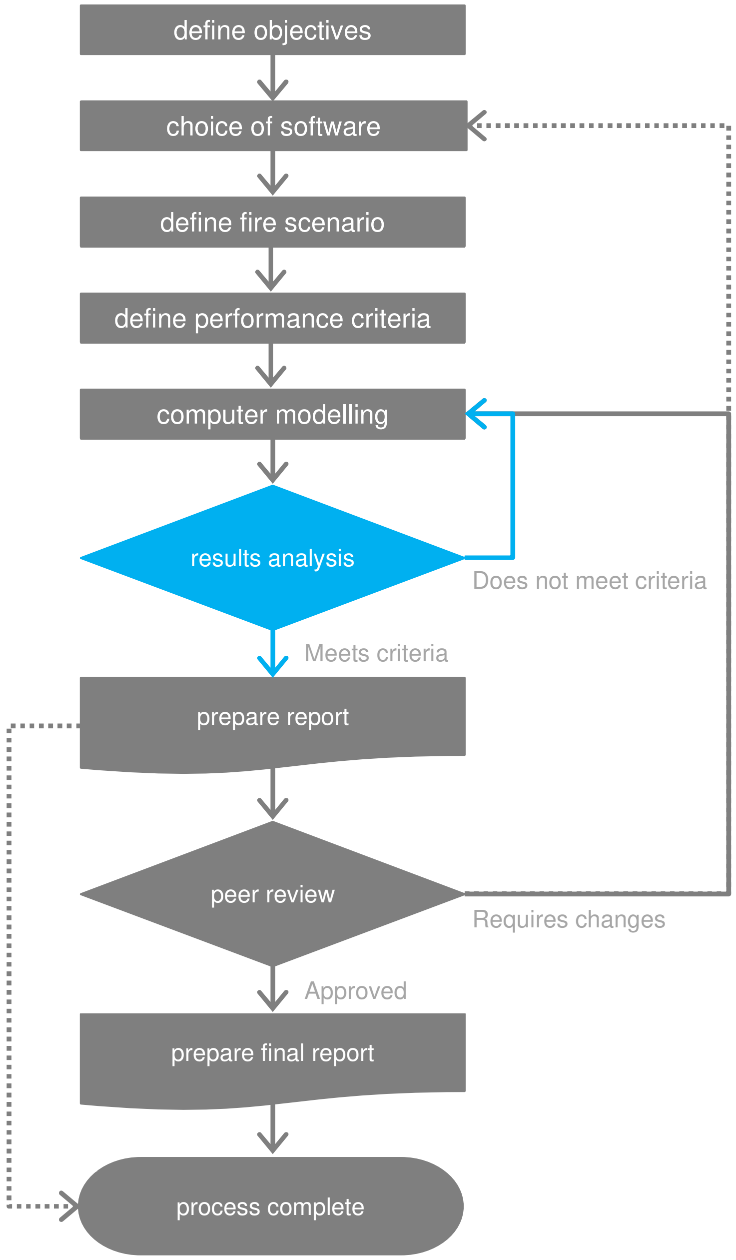
After completing the previous tasks, the actual modelling can now be run in the software. While processing in zone model software is usually done in a matter of minutes, fluid dynamics-based software it may take hours or even several days, depending on the complexity of the model.

To shorten modelling time, most fluid dynamics-based software can be run on multiple networked computers, and some companies provide cloud computing services, with processors being rented by the hour. The modelling process can also be split across multiple processor cores, ensuring that each part of the model has more or less the same number of finite elements. As processing needs to be done concurrently for all parts, if one part has many elements and another only a few, the larger part will be processed more slowly, thereby constraining processing of the other parts.

Model duration is equally critical in terms of processing time. As such, the duration chosen should be the shortest possible to allow for achieving the intended goal. Modelling evacuation tenability may only require 15 minutes, but modelling the fire behaviour of structural elements can take an hour or longer.

08.

results analysis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8 results analysis.

8.1 Data preparation

Modelling software generate a significant amount of data. Several types of data for each compartment (height of smoke layer, temperature in and below smoke layer, pressure, radiant flux over floor, etc.) are typically generated, and the same applies to openings (flow above and below neutral plane, velocity above and below neutral plane, pressure differences, etc.). All data is generated at short intervals over time (for instance, every 5 seconds). The information is usually provided in a CSV (comma-separated values) text file.

The data is normally processed and analysed in spreadsheet software such as Excel, which is capable of importing CSV files and organising the information into easy-to-read tables and graphs. Most modelling software splits the data into different files (e.g., one for compartment data, another one for fire data and yet another one for gas flows), and the information within each file is divided into groups (e.g., extractors, fans, etc.). The intended information must be selected bearing based on the objective of the modelling and the specified criteria, importing only what is needed for that objective, and deleting any data not deemed to be necessary. The data analysed will typically only be a small percentage (1% or less) of the data generated by the software.

The spreadsheets are used for analysing numerical information. However, an animated 3D visualisation of the results can only be produced in specialised software like NIST Smokeview, which allows for visualising both CFAST (zone) models and FDS (fluid dynamics) models. As mentioned above, modelling software generates a huge amount of data, enabling visualisation software to generate numerous different 3D views, such as smoke optical density, visibility, gas temperature, gas flows (including direction and velocity), etc. These software provide a quick and intuitive view of the results, and the visualisations can be exported to movie formats using an actual movie format such as MOV, or compiling sequential images (JPG or similar) into a movie using third-party video editing software.

8.2 Integration of information from other modelling software

Depending on the purpose of the modelling, data from other modelling software may also be included for combined analysis. This will be the case when the tenability of evacuation is to be verified by cross-checking fire modelling data against data generated by evacuation modelling software. Both software types generate CSV data and use the same time format, and all that needs to be done in both software (fire and evacuation) is to define the same time interval for the data export (e.g., 5 second intervals).

Data from both software can be combined in the same spreadsheet to be, for instance, displayed side by side or to visualise the evolution of the environmental conditions in a room and the number of people in a room within the same graph.

Finally, some software can also combine results from different software into a single visualisation. For instance, if the evacuation is modelled in PathFinder, a 3D animation visualisation can be created showing the people being evacuated, combined with information from the fire modelling in the FDS software.

3D visualisation of evacuation combined with fire. *Pathfinder Features*

8.3 Performance assessment

The modelling results should be compared with the performance criteria established initially. When the criteria are not met, the deviation should be analysed and possible strategies for amendment defined, namely modifying the planned passive and active resources. The solutions found should be validated through repeated modelling until the results meet the established criteria.

In some situations, it may happen that no viable solution can be found for the required criteria. In such circumstances, there are several possibilities:

- Re-evaluate if the fire scenario, namely the design fire, is not too conservative or excessive
- Revisit the performance criteria to make sure they are not too conservative or possibly excessive either; for instance, there are normative references for the height of the smoke layer referring to a height of 2.5 m (ISO TR 16738, Singapore regulation), others of 2.0 m (Italian regulation, Australian regulation), others of 1.5 m (NFPA 101) and others still, has a function of the compartment height, expressed by a formula such as *1.6 + 0.1 x h,* where *h is* the ceiling height (INSTA TS 950 standard, from Nordic countries). Whichever the case, only one reference must be chosen rather than multiple criteria from different sources
- Acknowledge that there is no feasible active or passive solution that can make the building meet the performance criteria, and a different approach must be made using measures other than active or passive, such as partial usage restriction

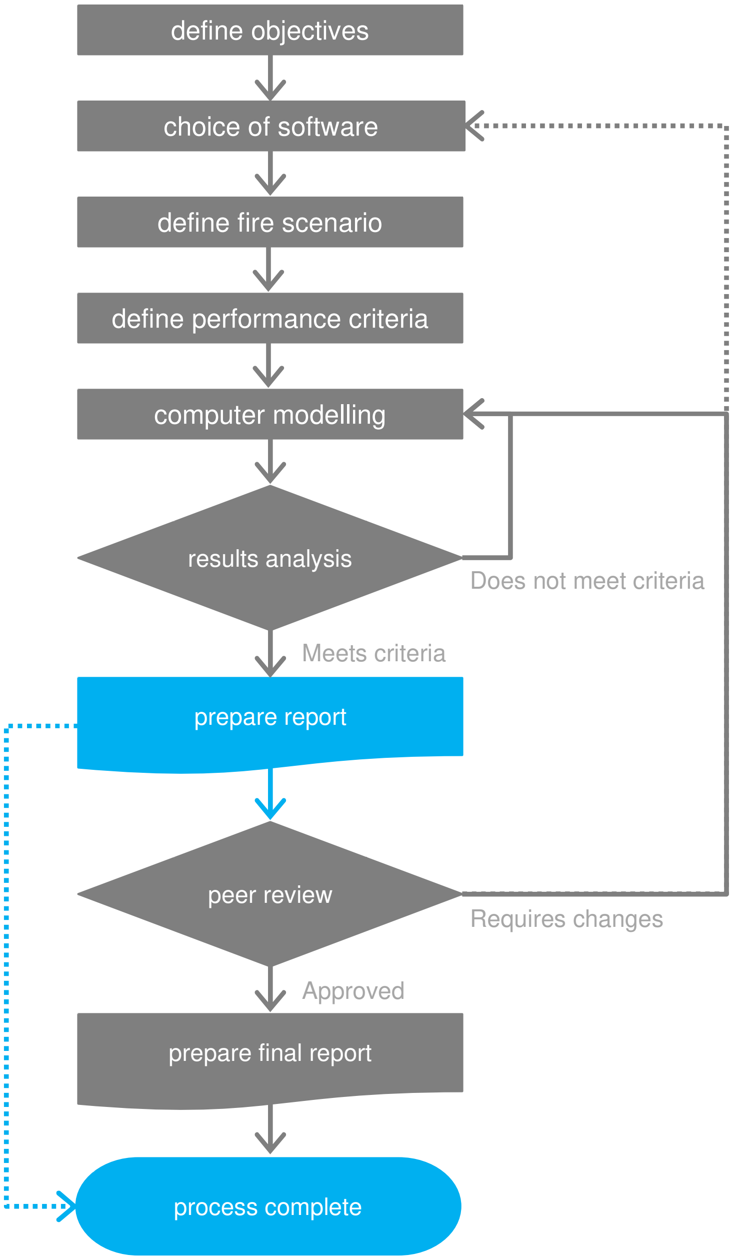
Any change in the scenario or performance criteria must be duly documented and justified in the report in a fully transparent manner.

8.4 Safety margin

All assessment needs to include a safety margin to minimize the risk related with uncertainties. This safety margin is sometimes defined in the fire codes (not covered in Portuguese regulations), and varies typically between 1.2 and 2.0 applied over the evacuation time. For instance, to verify the evacuation tenability conditions, the Available Safe Evacuation Time (ASET), in which conditions for evacuation are good (according to the chosen criteria) must be at least 1.2 times greater than the Required Safe Egress Time (RSET), that is the time actually needed for evacuation. The RSET should be determined by calculation or evacuation modelling.

The definition of the safety coefficient within the above-mentioned range needs to reflect the existing degree of uncertainty. Typically, a value of 1.2 will be used for fully compliant buildings or buildings with full sprinkler coverage (whether mandatory or not). If the building has major non-compliances or weaknesses, or if there are circumstances for which no consolidated technical and scientific knowledge is available (e.g., tenability criteria for the elderly), this value should be higher, up to 2.0. The coefficient used should be properly justified in the report.

09.
report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9 report.

The modelling report is an important part of any minimally formal modelling process. An example of this is the modelling of a car park fire with jet fans to be attached to the fire and life safety (F&LS) project or the specific smoke control project.

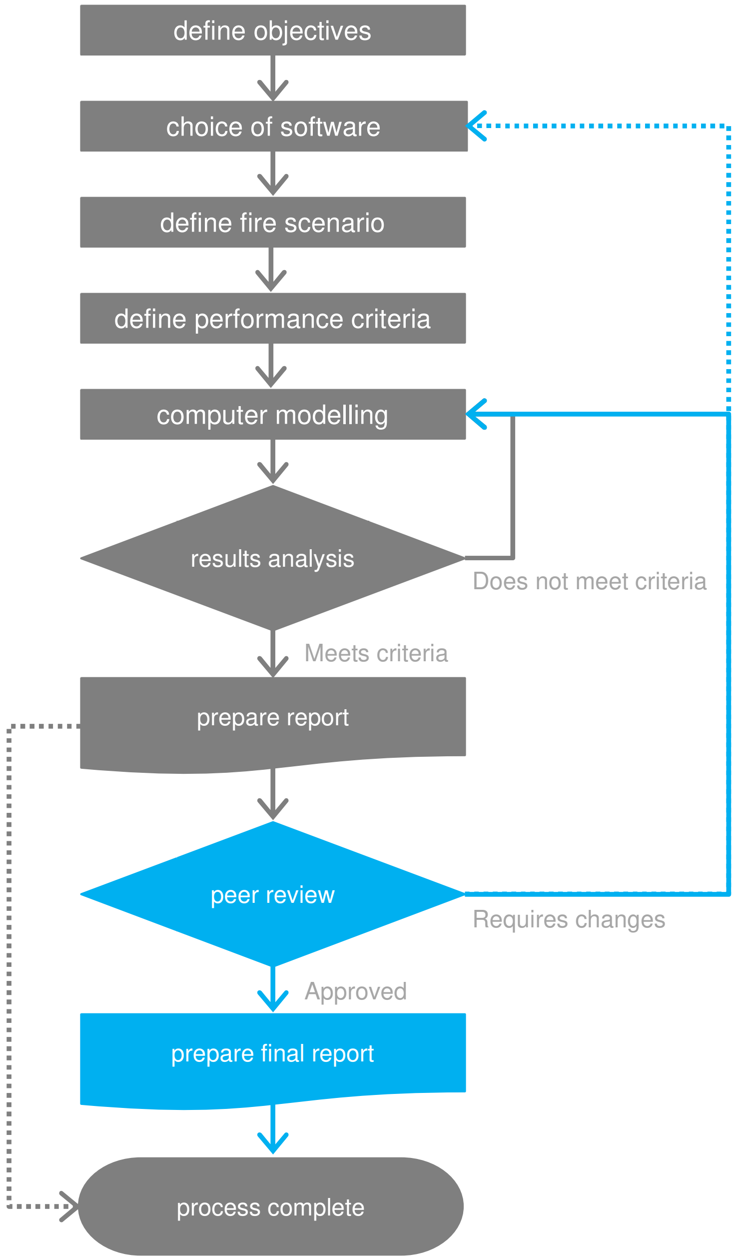
The report should be elaborated in the course of process detailing the different assumptions, decisions, results and conclusions reached. As such, the report should cover the following:

- Entity requesting the study
- Scope of study
- Name(s) of study author(s), including their specific training in the area to corroborate their technical competence to perform the required modelling
- If the study includes peer review, name(s) of reviewer(s) and information to corroborate their technical competence to review the work
- If third-party feedback (from project owner, designers, licensing bodies, insurers, installers, etc.) was obtained to perform modelling, specify these entities and their degree of involvement in the process
- Purpose of modelling
- Description of building
- Detailed description of the fire scenario, namely initial environmental conditions, location of fire and its properties, and passive and active resources that will be activated; the choice of the scenario over other possible ones needs to be properly justified
- Selected performance criteria, specifying their sources and why those criteria were chosen over others
- Software used and version
- Results in summarised form (only the most relevant ones) and analytical form (graphs comparing results with performance criteria)
- If the results did not meet the established criteria, suggest duly justified changes to the scenario or criteria
- Conclusions
- Reviewer comments (if required)
- Bibliography used as support, if applicable
- Useful attachments, such as 3D images over time and tables with more comprehensive results

The final report must be signed by the author(s) and reviewer(s).

10.

peer review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10 peer review.

Depending on the complexity or purpose of the modelling, peer review might be advised. A peer here is someone who has at least the same level of technical knowledge as the person performning the modelling.

Modelling can be complex and absorbing process, bringing with it a certain risk of 'tunnel vision', i.e., of being focused only on one aspect and accidentally neglecting others. It is therefore sensible to obtain an outside view to assure a critical look at the process.

Peer review may not be required for simple modelling processes. For a more complex modelling process, peer review is desirable and could conceivably be performed by a co-worker with the necessary technical skills. However, for modelling process of greater complexity and responsibility, the reviewer should ideally belong to a third-party entity other than the modelling authors.

It is important to make a clear distinction between the role of the author and that of the reviewer. The reviewer should not outweigh the author either. The role of the reviewer is to spot errors or omissions in the process rather than opine on it. The task at hand is of a technical, rational and impartial nature. Both the author and the reviewer are members of the same (extended) team working towards a common goal by performing distinct and complementary roles.

Reviewers should be involved in the process as early as possible, allowing them to work as the modelling process evolves. The analysis should not only be limited to the report, but the reviewer should also have access to the modelling templates in order to assess their accuracy against what is intended.

The reviewer should namely validate:

- Whether the fire scenario is the most appropriate for the specified objective
- Whether the performance criteria match the objectives correctly
- Whether the modelling software chosen is the most suitable for the purpose
- Whether the model has been constructed correctly, both from a geometrical point of view and from the point of view of the implementation of the scenario in all its aspects (environmental conditions, fire, passive and active resources triggered)
- Whether the results have been properly selected and interpreted, or whether additional data is missing

The review process needs to be interactive. The reviewer should analyse the model and the report, and provide feedback, giving the author of the model the opportunity to make corrections. However, the author does not necessarily have to agree with the reviewer or vice-versa, and there may be differing opinions on the same matter. If this occurs, it should be mentioned in the final report with fairness and transparency.

11.

who can do it

11 who can do it

There are no legal provisions as to who can develop this type of modelling or its review. However, some common-sense based considerations need to be taken into account:

- The author should have solid background knowledge, in particular of thermodynamics, combustion phenomenology and fire dynamics
- The author should have sound knowledge of the selected software, preferably having received specific training
- If the study is to be attached to a Fire & Life Safety (F&LS) project, the author should ideally have the same level of professional certification as the level required for the F&LS designer

It should also be kept in mind that fire modelling may be collective work involving several experts in a variety of different roles. Thus, the considerations above should be adapted on a case-by-case basis to each expert's role in the process. Naturally, requirements will be stricter for who signs the report than for someone who has collaborated on the 3D modelling. However, for all of them, thorough knowledge within the function they are performing is required.

12 bibliography.

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13 glossary.

Smoke layer

In laminar flow, layer of hot combustion gases that accumulate in the upper part of a compartment

Smoke-free layer

In laminar flow, lower layer of the compartment where the temperature and concentration of combustion products is considerably lower than in the smoke layer

Tenability criteria

Maximum value considered to be safe to which a building occupant can be exposed during a set period of time to the effects of fire, i.e., temperature, radiant flux, toxic gases, etc.

Temperature

Physical quantity measuring the degree of molecular activity of a material compared to a reference point. The measurement unit in this document is degrees Celsius, where 0ºC is the water phase change temperature from solid to liquid at a pressure of one atmosphere, and 100ºC the water phase change temperature from liquid to gaseous at a pressure of one atmosphere

Heat release rate

Heat released in the form of conduction, convection and radiation.

Radiant flux

Heat flow radiating a given area, expressed in kW/m^2

Zone model

Model where each compartment under study is subdivided into one or two zones calculated the energy and mass transfers across them and the compartment materials. The values calculated for each zone are average values

Finite element modelling

Model where the domain under analysis is divided into a mesh of smaller cells to calculate the energy and mass transfers across them and the compartment materials

Neutral plane

Plane in a compartment where the hydrostatic pressure matches the pressure outside the compartment

Laminar flow

Fire in which the smoke layer is clearly stratified, with a clear mostly horizontal separation between the smoke layer and the smoke-free layer

Turbulent flow

Fire in which the smoke layer is strongly turbulent, either due to high velocity air flows (for instance, jet fans), or because it is a large-scale and high-temperature fire, creating strong convection flows

Peer review

Review of process by a person or entity with at least the same technical knowledge as the author, with the aim of spotting errors or omissions

Critical temperature of a structural element

Temperature at which the collapse of the element occurs when subjected to the effects of fire; this only applies to structural elements with a uniform temperature field, such as metallic elements

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