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Original Article

Comparative Analysis of Steel Beam Fire Resistance Under Standard and Parametric Fire Scenarios

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Abstract *- Steel has a very good strength-to-weight ratio and flexibility, and therefore has a significant use in structural engineering. However, in high temperature situations, steel loses its strength and stiffness, which makes it very critical to consider in design. Conventional fire resistance evaluations use the standard ISO 834 fire. However, it does not consider compartment-specific elements such as compartment ventilation, the density of the fire load, and the thermal characteristics of the compartment boundaries. However, compartment fire ventilation, fire load density, and boundary thermal characteristics are incorporated into the Eurocode parametric fire model. This study, in consideration of both unprotected and passively protected conditions and standard and parametric fire scenarios, aimed to evaluate a supported steel beam's fire performance. For the analysis, the author used a modified formulation for the protected case that considers the insulation and a simplified energy balance approach for unprotected steel. The fire performance rating is the time it takes for the steel temperature to reach the limiting temperature, which is determined by the applied load ratio. The steel temperature evolution for each configuration was predicted by calculating the gas temperature–time histories using the ISO 834 and Eurocode fire curves. The findings indicate that, even with its cooling phase, parametric fires require less time to reach the limiting temperature—the unprotected beam reached 670 °C in less than 8 minutes as opposed to the standard fire's 14 minutes. By delaying the attainment of the critical temperature by roughly 24 minutes in a standard fire and 17 minutes in a parametric fire, passive fire protection significantly increased fire resistance. Because of its high peak temperature (~1050 °C) and quick heating rate, the parametric fire created more extreme thermal conditions in the early stages of exposure. The results show that, especially for unprotected members, parametric fires can pose a higher early-stage risk to steel structures than conventional fires. A more accurate evaluation of fire safety and more efficient specification of passive protection measures are made possible by integrating parametric fire scenarios into performance-based structural fire design.*

Keywords *- Steel Beam, Fire Resistance Rating, Standard Fire, Parametric Fire, Passive Fire Protection.*

1. Introduction

Steel is frequently used in structural engineering because of its high strength-to-weight ratio, adaptability, and simplicity. Its rapid loss of stiffness and strength in the presence of high temperatures is one of its primary drawbacks, though. Steel begins to lose strength at temperatures above about 400°C, and it can lose more than half its load-bearing capacity at temperatures above 600°C. Thus, assessing steel members' fire performance is crucial to preserving the structural integrity and safety during fires [1–4].

There are many difficulties in designing and evaluating structures in a fire environment. Numerous presumptions that hold at room temperature—like constant loading circumstances, predictable material behaviour, and fixed boundary constraints—do not hold here. Structural components experience uneven complex thermal actions at high temperatures due to the heat of hot gases and radiation. Consequently, the uneven heating and cooling of a member cross-section is practically unavoidable [5–7]. The mechanical properties of steel become less and less useful because of the high temperatures. Accompanied by a loss of thermal expansion control, the bowing and twisting due to the loss of strength and stiffness can generate large internal forces and considerable deflections. Alterations of load paths can occur with the loss of stiffness, leading to the deformation of a structure, which does not necessarily result in a collapse. These alterations point to a redistribution of internal and external stresses and the structure adapting to the new mechanical and thermal conditions [8–10].

Conventional assessments of fire resistance typically use standard fire curves as outlined in ISO 834 [11] or ASTM E119 [12]. These standards define a time-temperature relationship that increases steadily, with no consideration given to the specific features of the fire compartment. Though this is the most prevalent approach in building codes, simplifying the design and testing, it fails to account for the compartment shape, ventilation, enclosure thermal properties, and fire load density. Standard fire curves can impose unrealistically severe conditions. Some cases have overly conservative conditions, while others do not provide adequate protection.

In contrast, the parametric fire model in Eurocode EN 1991-1-2 [13] offers a more realistic view of how fire develops in a compartment. It looks at how fire growth, ventilation, and heat loss interact. This model generates a complete fire temperature-time history, including the heating, peak, and cooling phases. The heating phase is influenced by the fire load density (MJ/m^2 of floor area), the ventilation opening factor (size and height of windows), and the thermal inertia of compartment boundary walls. The cooling phase represents the natural fire dying down and exhausting fuel. Para-metric fire models allow structural elements to heat and cool over time—something standard fire curves ignore. This is why parametric fire models are more useful in performance-based design. They simulate scenarios for evaluating structural integrity and refining fire protection design [14–16].

There have been numerous studies on improving and assessing the development of fire-resistant steel structures. One of the most common techniques involves using passive fire protection systems, which prolong the heat transfer time and extend the fire resistance of steel. Insulating fire protection materials can be spray-applied fire-resistant, board-based insulating systems, or intumescent coatings. Each of these insulation systems possesses different thermal and mechanical performance characteristics[17–21]. Alongside experimental research, numerical modelling has gained traction in fire safety research. Using Finite Element Analysis (FEA) has become common in predicting the thermal and structural response of steel beams in real-time and parametric fires. Computer-aided methods enable researchers to perform parametric studies, assessing in scale insulation thickness and thermal conductivity, which would otherwise be costly and logistically problematic in full-scale fire modelling[22–24]. The predictive success of these computer models and software hinges on reliable experimental high-temperature material properties, realistic boundary conditions, and the proper capture of mechanical and thermal non-linearities.

Recent research has expanded our understanding of the fire resistance characteristics of steel beams with varying material attributes and protection coatings. Under combined static and fire loading, Dzolev et al.[25] Analysed IPE open-section profiles with water-based intumescent coatings. Their numerical simulations predicted fire resistance times between 24 and 53.5 minutes, indicating that even thin coatings provide significant thermal protection. Full-scale fire tests conducted by Jordão et al. [26] on beams made of conventional and fire-resistant steels showed that fire-resistant steels maintained better performance and had reduced deflection.

Likewise, Wang et al. [27] undertook full-scale studies on beams incorporating different fire protection systems and heating curves. They concluded that lateral torsional buckling was the principal failure mechanism, noting that high temperature would likely cause the fibre cement board protection to become brittle and spall off. The range of experimental and numerical methods aimed at understanding fire behaviour is apparent in these studies. They underline the material and protection combination's critical influence on beam performance.

This research provides valuable perspectives on the behaviour of steel members when subjected to heat and stress. However, most literature concentrates on the 'Standard Fire Exposure'. On the contrary, very few studies concentrate on 'natural fire' or 'changed fire' scenarios. Moreover, the few existing studies treat each fire model in isolation, without considering its impact on the fire resistance ratings of the same beam configurations. Specifically, comparisons on unprotected and passively protected steel members concerning the ISO 834 and EN 1991-1-2 fire curves are lacking. This is a considerable issue as fire resistance estimates could be overly conservative or overly permissive when only standard fire curves are used.

This study evaluates the subject of research by assessing the fire performance of a supported steel beam under ISO 834 standard fires and under EN 1991-1-2 standard flowers for both protected and unprotected scenarios. The novelty of the current study context is that it provides a direct comparison of the fire resistance ratings from each model. It clearly shows how passive fire protection affects performance under different heat levels. This study aimed to measure the differences in fire performance ratings, assess how conservative the two fire models are, and provide insights that aid in more reliable performance-based structural fire design.

2. Methodology

In this study, the fire performance of a supported steel beam was evaluated under standard and parametric fire exposure conditions. The selected beam configuration is shown in Figure 1. The beam, which spans between the two supports, represents a typical secondary floor beam in a residential building. The beam section adopted was a Universal Beam (UB) with dimensions of 356 × 171 × 45, and a nominal yield strength of 345 MPa.

The applied gravity loads consisted of a uniformly distributed dead load of 1.0 kN/m^2, representing the self-weight of the floor finishes and nonstructural components, and a live load of 2.0 kN/m^2, per the typical design requirements for residential occupancy. The combination of these loads provides the design loading condition used to determine the limiting steel temperature in the fire analysis.

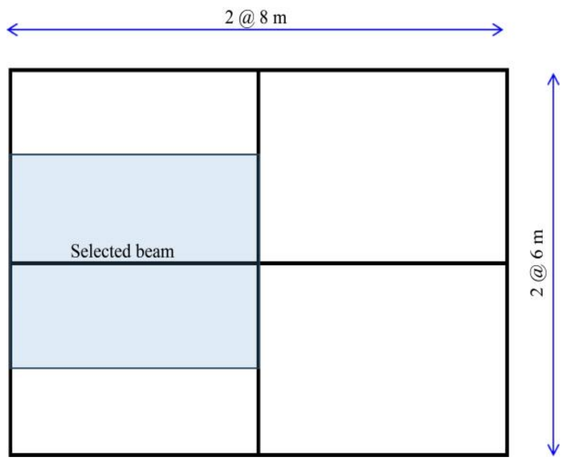

Fig. 1 Layout of the selected simply supported steel beam configuration

The beam was analysed under two fire exposure scenarios: ISO 834 standard fire [11] and Eurocode parametric fire [13]. The ISO 834 standard fire defines the gas temperature T_g as a function of time t in minutes, calculated as

$$T_g = 345\, log_{10}(8t + 1) + T_0 \tag{1}$$

Where T_0 is the ambient temperature (ºC). This curve represents a continuously increasing temperature with no cooling phase, independent of the compartment characteristics.

A compartment fire parametric fire model was built, which incorporated fire load density and the compartment boundary and enclosure ventilation. This model was designed for the heating and cooling cycles of the compartment. During the heating phase, the gas temperature is given by

$$T_g = 20 + 1325(1 - 0.324e^{-0.2t*} - 0.204e^{-1.7t*} - 0.472e^{-19t*}) \tag{2}$$

Where t^* is the dimensionless time obtained by multiplying the physical time t by a parameter Γ defined as

$$\Gamma = \frac{(O/B)^2}{(0.04/1160)^2} \tag{3}$$

Where O is the opening factor and B is the thermal absorptivity of the enclosure boundaries. The opening factor is given by

$$O = \frac{A_v\sqrt{h_{eq}}}{A_t} \tag{4}$$

$$b = \sqrt{\rho c \lambda} \tag{5}$$

Where A_v is the total area of vertical openings on all walls, h_{eq} is the weighted average height of the openings, A_t is the total internal surface area of the enclosure, ρ is the material density, c is the specific heat capacity, and λ is the thermal conductivity

The cooling phase was determined as follows.

$$T_g = T_{max} - 250(3 - t^*_{max})(t^* - t^*_{max}) \tag{6}$$

Where T_{max} is the maximum gas temperature reached at t_{max^*} during the heating phase. This value is obtained from

$$t^*_{max} = (0.2 \times 10^{-3} q_{t,d}/O)\Gamma \tag{7}$$

$$q_{t,d} = q_{f,d} A_f / A_t \tag{8}$$

Where $q_{f,d}$ is the designed fire-load density, A_f is the floor area, and A_t is the total internal surface area.

In this study, a parametric fire curve was developed using a designed fire load density of 511 MJ/m^2, thermal absorptivity of 1470 Ws$^{0.5}$/m^{2}K, and an opening factor of 0.1. These parameters represent a compartment with limited ventilation and moderate heat storage capacity, which is typical of enclosed residential spaces. Figure 2 illustrates the temperature–time relationships for the standard and parametric fires used in this study.

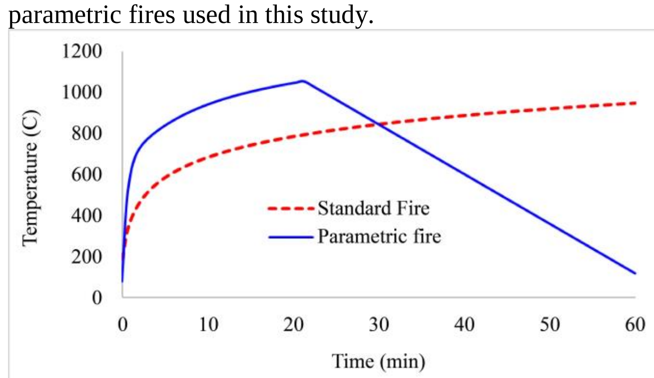

Fig. 2 Comparison of the standard fire curve and parametric fire curve

Two steel beam conditions were considered in the analysis: unprotected and protected steel beams. In the unprotected case, the steel section was directly exposed to fire without any insulating layer, allowing for rapid heat transfer from the surrounding hot gases to the steel surface.

The steel temperature increase was determined using a simplified energy-balance method, which assumes that the steel cross-section is uniformly heated (lumped capacitance assumption), that the material properties of steel remain constant within the considered temperature range, and that heat transfer is governed only by convection and radiation from the surrounding hot gases. The formulation is expressed as follows:

$$\Delta T_s = F/V \frac{1}{\rho_s c_s}\left[h_c\left(T_g - T_s\right) + \sigma\varepsilon\left(T_g^4 - T_s^4\right)\right]\Delta t \quad (9)$$

Where h_c is the convective heat transfer coefficient, σ is the Stefan-Boltzmann constant taken as 56.7x10^{-12} kW/m^{2}K^4, ε is the resultant emissivity, and T_s is the steel temperature. *F/V* is the section factor, ρ_s is the density of the steel, and c_s is the specific heat capacity of the steel.

In the case of beam protections, the beam was entirely protected and was assumed to be encased by a passively protected fire layer which offered additional thermal resistance. The insulation has thermal conductivity (k_i) 0.2 W/mK, density (ρ_i) 0.300 kg/m^3, and thickness (d_i) 20 mm. The insulation layer increases the temperature of the steel by absorbing and slowing down the incoming heat, reducing conduction, and absorbing heat during the upward convection. The net estimation of temperature increase of steel for this case was calculated using the modified energy balance equation.

$$\Delta T_s = F/V\left(\frac{k_i}{d_i \rho_s c_s}\right)\left(\frac{\rho_s c_s}{\rho_s c_s + (F/V) d_i \rho_i c_i/2}\right)\Delta t \quad (10)$$

Where d_i indicates insulation thickness and c_i indicates the specific heat capacity of the insulation. This formulation considers the thermal storage capacity of both the steel and the insulation, leading to a better estimation of the temperature changes that will occur in the configuration going forward.

The fire resistance rating of the steel beam included in this study was the duration it took for the beam to attain a specific limiting temperature (T_{lim}). Once this temperature was reached, its ability to bear loads was deemed insufficient. The limiting temperature was calculated using the European Commission for Constructional Steelwork (ECCS) [28].

$$T_{lim} = 905 - 460 r_{load} \quad (11)$$

Where r_{load} is the load ratio, which is determined as

$$r_{load} = \frac{M_{fire}}{M_n} \quad (12)$$

Where M_{fire} represents the bending moment in the beam under fire loading, and M_n is the bending resistance of the beam at ambient temperature. Thus, the load ratio reflects the proportion of the ambient temperature capacity of the beam that must be sustained during fire exposure. A higher load ratio results in a lower limiting temperature, indicating reduced fire endurance under higher applied loads

Once the limiting temperature was determined, it was compared with the predicted temperature–time curves obtained from both standard and parametric fire scenarios. The time at which the steel temperature curve intersects the limiting temperature, referred to in this study as the critical temperature attainment, defines the fire resistance rating for each case. This parameter represents the point at which the beam is deemed unable to sustain its load-bearing function, enabling a direct comparison between the unprotected and protected configurations under both fire scenarios.

3. Results and Discussion

Figure 3 presents the temperature–time histories for the gas phase, unprotected steel, and protected steel subjected to the ISO 834 standard fire, together with the calculated limiting temperature. The gas temperature followed the characteristic logarithmic increase of the standard fire curve, reaching approximately 900°C at 60 min.

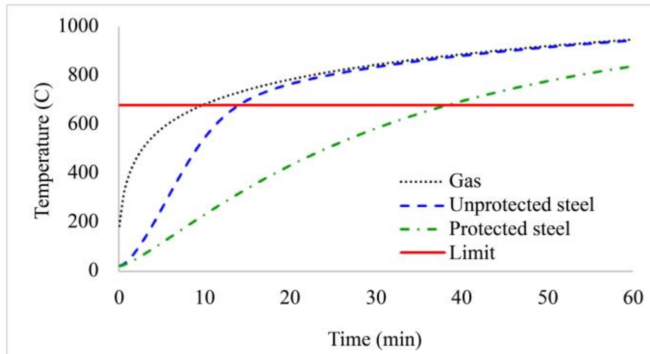

Fig. 3 Steel temperature development under the standard fire

For the unprotected steel beam, the temperature increase was rapid owing to direct exposure to hot gases, with steel temperatures exceeding 600°C in less than 10 min. The limiting temperature, calculated as 670°C for a given load ratio, was reached after approximately 14 min of exposure. Beyond this point, the load-bearing capacity of the beam was assumed to be insufficient under the applied fire loading. In contrast, the protected steel beam showed a significantly slower temperature rise, highlighting the insulating effect of the passive fire protection layer. For the first 30 minutes of the fire exposure, the protected steel temperature remained below 600°C, and the steel frame reached the limiting temperature after approximately 38 minutes of exposure. This extended duration demonstrates the effectiveness of the insulation in protecting the steel section from heat damage.

The results indicate that with the ISO 834 standard fire, the fire resistance rating of the protected beam is over twice that of the unshielded beam under the same loading conditions. This is consistent with previous studies demonstrating that insulation with low thermal conductivity greatly reduces the heat transfer to a steel member. This added insulation increases the available time for evacuation and firefighting. Unshielded beams under standard fire exposure, having short fire resistance, highlight the inadequacy of protective measures and the rapid loss of structural integrity that steel fire protection needs to provide.

Figure 4 shows the temperature and time histories for the gas phase, unprotected steel, and protected steel under the parametric fire, along with the calculated limiting temperature. Unlike the steadily increasing profile of the ISO 834 standard fire, the parametric fire curve displayed a quick heating phase followed by a cooling phase once the fuel load was used up. In this study, the gas temperature reached about 1050 °C at around 22 minutes before gradually dropping.

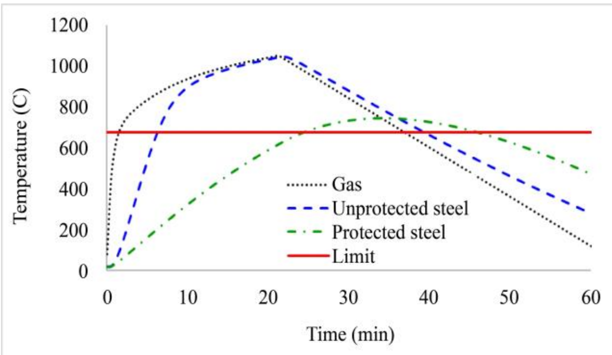

Fig. 4 Steel temperature development under the parametric fire

For the unprotected steel beam, the temperature rise closely matched the gas temperature during heating, surpassing the limiting temperature of 670°C in under 8 minutes. The highest steel temperature happened shortly after the peak gas temperature, showing the brief thermal delay between the surrounding air and the steel section. When the steel reached the cooling phase, its temperature did drop, but remained above the critical threshold for an extended period. This indicates that the structural capacity would still be weakened, even in the period of declining gas temperatures.

Because of the insulating layer, the protected steel beam had a slower heat transfer, which resulted in a slower temperature rise and lower peak temperature than the unprotected case. The temperature peak was reached around 25 minutes, while the steel temperature remained lower than the peak value of the unprotected case during the fire exposure. Even during the beginning of the cooling phase, the insulated steel's temperature response to heat was controlled. It delayed the temperature drop, and the withdrawal of heated steel remained more than the critical strength loss buffer.

The data from both fire scenarios indicate the difference in the fire resistance rating values and behaviour of the steel beams when exposed to fire. In the case of ISO 834 standard fire, the unprotected steel beam takes 14 minutes to reach a limiting temperature of 670°C. In the case of the protected beam, it takes 38 minutes to reach the same temperature. A standard fire curve provides a prolonged heating phase, which allows time for the insulation to exhibit its full potential intervals in a temperature rise to the zone surrounding the steel beam. In contrast, the Eurocode parametric fire curve provides minimal time for the initial heating phase. For that reason, both beams reach the limiting temperature much earlier. In the case of the unprotected beam, it takes less than 8 minutes to surpass the 670°C threshold; in the case of the protected beam, it takes around 25 minutes to reach the limit. This behaviour indicates the intense heating that occurs during the growth phase of the parametric fire, influenced by the opening factor, fire load density, and thermal inertia of the compartment. The absence of fire load is important for the duration of the heating period, resulting in the overall duration of the cooling phase being shorter. Despite this, the parametric fires created a more severe thermal environment as a result of the much shorter duration of the initial exposure phase.

Table 1 demonstrates how a protection system continued to improve fire resistance in both cases under side-by-side analysis. It delayed reaching the limiting temperature in the standard fire by 24 minutes and in the parametric configuration by 17 minutes. The relative benefit of protection, however, was less in the parametric case because of the quick early temperature rise. Also, the strong protection measures necessary for cases of rapid fire growth are reflected in the parametric curve's peak gas temperature of 1050°C compared to the standard fire's peak of 900°C.

Table 1. Fire resistance ratings

Fire scenario	Unprotected	Protected
Standard fire	14 min	38 min
Parametric fire	8 min	25 min

An analysis of the effect of temperature increase on parametric fires reveals a concern from a structural safety perspective. Since steel members limit temperature in a shorter time frame, evacuation, firefighting, and structural stability time are all reduced compared to what standard fires predict. In this context, "time to reach the limiting temperature" is a key measure in determining the fire resistance rating. It reveals the duration the member can carry its loads before its strength and stiffness fall to dangerous levels. This also links the thermal response of steel to its load-bearing capacity. This also reiterates the necessity of performance-based fire engineering approaches that consider realistic compartment fire development.

The considerations from these studies go beyond thermal observations. For fire safety design, the implications of these findings are considerable. The explanation for lower fire resistance under certain conditions points to the need for more prudent use of prescriptive fire curves in isolation. These may underestimate the severity of building early-stage heating in actual situations. As noted, passive fire protection did appreciably increase resistance, but its benefits were lesser under rapid heating conditions. This emphasizes the need for appropriate material selection, detailed scenario insulating, and careful scenario assessment. From a structural safety point of view, the value added in this work is in assessing the protection systems for different fire models and the interactivity value. This informs safer design, enhances evacuation routing and planning, and facilitates a more user-oriented approach in contemporary fire engineering.

Practically, these findings lead to three recommendations regarding design strategies. First, in situations that require performance-based assessments, fire engineers need to pair ISO 834 with parametric fire models. This is of particular relevance in compartments with dense fire-loads and those with restricted ventilation. Second, when designing passive fire protection, one must consider scenarios that involve rapid heating. This may involve specifying thicker insulation or insulation materials that are more thermally stable. Third, the time to reach the limiting temperature can be considered a proper design parameter. This relates the thermal response to the structural performance, offering greater reliability and clarity in evaluating the overall fire resistance.

This study also makes several advancements over the previous research. While prior studies concentrated on conditional protections, specifically on ISO 834, or separately investigated Individual Protection Systems, this study, for the first time, juxtaposed standard and parametric fires within one framework and assessed unprotected and protected beams in the same scenario. This singular approach starkly illustrates the impact of the rapid heating effect in parametric fires on unprotected beams. It also illustrates insulation's effectiveness in varied fire scenarios and identifies limiting temperature attainment as a plausible practical performance indicator. Such insights extend beyond the coverage of most cited works and bridge the gap between theoretical fire models and performance-based design.

In this regard, the results imply that performance delivered based on standard fire metrics may not provide an accurate depiction of performance in a real compartment fire scenario. This is not surprising as the research also concluded that parametric fires, especially on unprotected steel members, are more intense immediately after ignition and drastically reduce the time available for evacuation and intervention. This highlights the need for performance-based fire engineering to involve both models to encompass the full structural and thermal response.

4. Conclusion

This study analysed the behaviour of a simply supported steel beam experiencing fire under the ISO 834 standard fire and the Eurocode parametric fire scenarios. It included setups with and without passive fire protection. The time taken to reach the calculated limit temperature of the steel, as determined by the load ratio, serves as the basis for determining steel protection. The main findings are as follows.

1. The difference in the thermal response of the fire models is substantial. The ISO 834 standard fire has temperatures that increase steadily and continuously. In contrast, the parametric fire experiences a quick heating phase, followed by a cooling phase once the fuel is consumed.
2. The time to limiting temperature is shorter under parametric fire
   For the unprotected beam, the limiting temperature of 670 °C was reached in less than 8 minutes under parametric fire conditions. This happened in about 14 minutes under standard fire conditions. For the protected beam, the times were around 25 and 38 minutes. The shorter times in the parametric scenario were due to the sharper initial temperature rise.
3. Passive fire protection significantly improves fire resistance
   The use of insulation delayed reaching the limiting temperature by about 24 minutes in the standard fire and 17 minutes in the parametric fire. This shows how well it reduces the rate at which the steel temperature rises.
4. Early stages of parametric fires may pose more extreme conditions.
   The decreased cooling phase of the parametric fire and its rapid initial heating significantly worsened thermal conditions during the early stages relative to the standard fire, primarily due to the significant elevation of peak gas temperatures (about 1050 °C). This greatly reduced the time available for evacuation and intervention, particularly for unprotected occupants.
5. Design implications
   Depending solely on standard fire curves will overestimate fire resistance times in regions that are subject to rapid fire growth. Including parametric fire assessments in performance-based designs gives fire-protecting structures a more realistic account of the safety of the structures and enhances fire-protecting systems. The outcomes also reveal that although complementing passive protection will always be of value, the protection will be of decreasing value in the case of rapid heating. This also provides a real-world reminder that insulation design needs to be more thoughtful.

In relation to the findings, it is important to value the interconnection of prescriptive and performance-based fire scenarios in the design of structural fires. This study has downsides, including a single beam configuration, standard high-temperature material data, and a simplified energy balance method.

Those elements are likely to miss system-level consequences and the arbitrary nature of fire scenarios. Subsequent research will need to include more robust simulations, broader parametric studies, and experimental confirmation to improve the relevance of the findings.

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Author Contribution

RS prepared the manuscript, MS reviewed the manuscript, and RH reviewed the manuscript.

Data availability

Data analysis https://zenodo.org/records/16810711

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