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Original Article

Influence of Key Parameters on Parametric Fire Development: A Eurocode-Based Study

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Abstract *- Standard time–temperature curves are widely used in traditional structural fire safety designs. These curves make fire conditions easier to understand, but do not show how complicated true post-flashover fires are. To overcome these limitations, Eurocode EN 1991-1-2 introduced parametric fire models that consider factors such as ventilation, fire load density, wall material properties, and compartment geometry. This study investigated the impact of these key parameters on the development of parametric fire curves to support performance-based designs. Parametric analyses were performed on the baseline compartment while varying the number of openings, wall materials, building types, and compartment areas. The simulations used Eurocode-based formulations with realistic material and occupancy inputs. The results show that the opening factor significantly affects fire behaviour, where higher ventilation results in higher peak temperatures but shorter fire durations. The wall materials had minimal impact, although lightweight concrete showed slightly higher temperatures. The fire load density, based on building usage, influenced the duration of the heating phase, whereas larger compartments led to longer fire durations owing to increased thermal inertia. These findings highlight the importance of incorporating compartment-specific variables into fire scenarios and demonstrate that parametric fire curves offer a more accurate and reliable basis for structural fire safety in performance-based designs.*

Keywords *- Compartment fire modelling, Fire performance, Natural fire, Parametric fire, Performance-based design.*

1. Introduction

Fire is a critical hazard to building structures, posing a serious threat to both structural integrity and overall stability. Traditionally, structural fire design has been governed by prescriptive approaches, in which compliance with standardized fire resistance criteria is considered sufficient [1–3]. These criteria typically revolve around the fire resistance rating, which represents the duration a structural element can sustain its load-bearing function when subjected to a predefined heating curve, commonly the ISO 834 [4] or ASTM E119 [5] standard fire curves. Owing to their simplicity and consistency, these nominal time–temperature curves have been widely incorporated into design guidelines and building codes across various jurisdictions.

However, although standardized fire curves facilitate uniformity and ease of comparison, they fall short in representing the complexity of real post-flashover compartment fires [6]. These curves are fixed and do not consider important factors like fuel load, compartment geometry, ventilation conditions, or the thermal properties of the surrounding materials. They also leave out the decay and cooling stages of fire development, which limits their use in prescriptive design situations.

Performance-based approaches to Structural Fire Engineering (SFE) have been gaining attention recently [7–9] and attempt to create a more accurate reflection of how the structure will thermally interact with the environment. Eurocode EN 1991-1-2[10] defined fires' compartmented parametric curves and provided curves that represent the real representation. These curves consider essential physical parameters such as fire load density, ventilation characteristics (opening area and height), compartment volume, and the thermal inertia of the boundary materials, and these greatly affect how severe the fire will be and how long it will last [11]. This approach provides better outcomes in performance-based structural fire design and evaluation despite the shortcomings of prescriptive approaches.

In response to the limitations of standard fire curves, fire modelling techniques have evolved significantly over the past decades. These advancements have made it possible to simulate various realistic fire scenarios. This helps engineers identify and design for the most severe yet plausible thermal exposure. The parametric fire model, introduced by Wickström[12], provides a simple and effective way to represent compartment fire development. It uses a heat balance approach to describe fire progression based on key factors, including the opening factor, thermal inertia of the compartment boundaries, fire load density, and a correction factor known as the gamma factor. Magnusson and Thelandersson [13] experimentally validated these theoretical formulations, showing a strong link between their test data and the model's predictions. Because of its practical use and solid theoretical foundation, the parametric fire model was officially included in Eurocode EN 1991-1-2[10]. It now serves as a standardized method for modelling natural fires. This approach supports performance-based fire design that better captures the variability and complexity of real compartment fires compared to the oversimplified assumptions of nominal fire curves. Figure 1 shows a comparison between the parametric and standard fires.

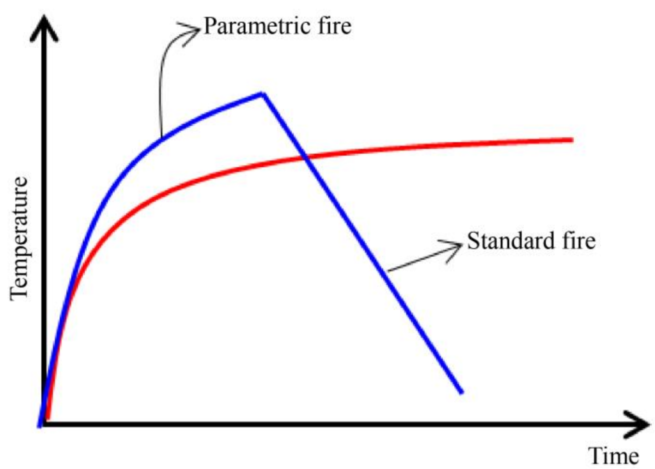

Fig. 1 Parametric fire vs Standard fire

Understanding the thermal environment during a fire is crucial for the safety and resilience of building structures. Traditional design methods based on standard fire curves often ignore the impact of specific features of a compartment. These features can significantly influence fire growth and intensity [14–16]. In contrast, parametric fire modelling allows for a more accurate and realistic assessment by incorporating critical factors, such as ventilation conditions, fire load density, thermal properties of construction materials, and compartment geometry. This modelling approach is particularly valuable for performance-based structural fire design, where the goal is to ensure structural integrity under credible fire scenarios rather than solely under standardized conditions. By reflecting the dynamic nature of real fires, including the heating and cooling phases, parametric fire curves provide engineers with a more reliable foundation for evaluating structural elements' load-bearing capacity and failure mechanism over time [17, 18]. This enhances not only occupant safety but also the robustness of fire protection strategies and overall building resilience.

Although parametric fire models are increasingly used in design, few studies have systematically explored how key compartment parameters, such as ventilation, wall materials, fire load, and area, affect the fire curve using Eurocode formulations. Previous studies have investigated the application of parametric fire models to assess the structural behaviour under natural fire conditions.

Howard et al.[19] developed closed-form expressions for I-girder bridges exposed to tanker fires, eliminating the need for complex CFD models. Abdallah et al. [20] examined the Eurocode parametric fire curves for large-scale compartment fires, focusing on key factors like opening factor and fuel load density.

However, many of these studies rely on numerical simulations or consider individual parameters in isolation, offering limited insight into the combined effects of multiple variables in a Eurocode-based analytical framework. This study addresses this gap by evaluating the influence of these factors on more realistic and performance-based fire design.

This study investigates how key compartment and material factors influence the development of parametric fire curves as defined in Eurocode EN 1991-1-2. Specifically, it focuses on the effects of ventilation conditions, compartment shape, wall material, and the type of building use. Through a series of parametric studies, this research aims to quantify how these variables impact the temperature-time profile of compartment fires.

The results should help engineers choose suitable fire scenarios for performance-based design and contribute to better decision-making in structural fire safety engineering.

2. Methodology

This study uses the parametric fire model from Eurocode EN 1991-1-2 to look at how compartment shape, ventilation, and material properties influence the time-temperature curves. It focuses on a standard compartment setup with specific thermal and geometric parameters. This allows for a detailed analysis of fire growth in real fire conditions.

A rectangular compartment has dimensions of 10 m × 10 m and a height of 4 m. It has four identical windows, each measuring 1.5 m × 4.0 m. These details are used to calculate the opening factor (O), defined as

$$O = \frac{A_v \sqrt{h_{eq}}}{A_t} \quad (1)$$

Where A_v is the total area of the vertical openings on all walls, h_{eq} is the weighted average of the window heights on the wall, and A_t is the total area of the enclosure.

To simulate the thermal behaviour of the compartment accurately, this study assigned different material properties to the floor, ceiling, and walls. The floor and ceiling were made from normal-weight concrete, which has a density of 2300 kg/m³, a specific heat capacity of 840 J/kgK, and thermal conductivity of 1.57 W/mK. These properties give a high thermal mass. This mass helps keep the temperature rise slower during heating and increases heat absorption during cooling. On the other hand, the walls were made from lightweight concrete, which has a much lower density of 500 kg/m³ but the same specific heat capacity of 840 J/kgK.

The thermal conductivity of the lightweight concrete is also much lower, at 0.22 W/mK, showing it has a reduced ability to conduct heat away from the fire compartment. The combined thermal behaviour of the enclosure is captured using the thermal absorptivity or thermal inertia (b), calculated as

$$b = \sqrt{\rho c \lambda} \tag{2}$$

Where ρ is the density, c is the specific heat, and λ is the thermal conductivity.

The parametric fire development is modelled in two phases—heating and cooling—as described in Eurocode EN 1991-1-2 Annexe A. The gas temperature (θ_g) in the heating phase is given by

$$\theta_g = 20 + 1325(1 - 0.324e^{-0.2t*} - 0.204e^{-1.7t*} - 0.472e^{-19t*}) \tag{3}$$

where $t*$ is the dimensionless time obtained by multiplying time t by a parameter Γ defined by

$$\Gamma = \frac{(O/b)^2}{(0.04/1160)^2} \tag{4}$$

The cooling phase begins at time $t*_{max}$, when the peak temperature T_{max} is reached. The cooling equations are as follows:

$t^*_{max} \leq 0.5h$

$$T_g = T_{max} - 625(t^* - t^*_{max}) \tag{5}$$

$0.5h < t^*_{max} < 2h$

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

$t^*_{max} \geq 2h$

$$T_g = T_{max} - 250(t^* - t^*_{max}) \tag{7}$$

The time to peak temperature, t*max, is obtained from:

$$t^*_{max} = (0.2 \times 10^{-3} \frac{q_{t,d}}{O})\Gamma \tag{8}$$

$$q_{f,d} = q_{f,d} A_f / A_t \tag{9}$$

Where $q_{f,k}$ is the fire load density, A_f is the floor area, and A_t is the total enclosed area. In this study, the design fire load density ($q_{f,k}$) was assumed to be 420 MJ/m², which corresponds to the typical values for office occupancies.

To achieve the objectives of this study and to systematically examine the influence of key factors on the development of parametric fire curves, a series of controlled variations was introduced into the baseline model. Each variation isolates a specific parameter, allowing for the assessment of its individual impact on fire development. The following four categories of variation were investigated:

1. Ventilation Conditions (Opening Factor)
   The number of window openings was varied while keeping the individual window size constant at 1.5 m × 4.0 m. Scenarios with 2, 4, and 8 windows were analyzed, corresponding to opening factors of 0.04, 0.08, and 0.16, respectively. This variation was designed to assess the impact of ventilation on the heating rate, peak temperature, and fire duration.
2. Wall Material Type
   The thermal properties of the compartment walls were varied to evaluate their influence on the thermal development of fire. Three commonly used construction materials were considered.
   - Lightweight concrete (ρ = 500 kg/m³, c = 840 J/kgK, λ = 0.22 W/mK),
   - Brick masonry (ρ = 1600 kg/m³, c = 840 J/kgK, λ = 0.69 W/mK),
   - Gypsum board (ρ = 1700 kg/m³, c = 1700 J/kgK, λ = 0.2 W/mK).
     Each material had distinct thermal inertia and conductivity properties, which were expected to affect both the heating and cooling phases of the parametric fire curve.
3. Building Use Type (Fire Load Density)
   Different building occupancies were modelled by assigning varying fire load densities based on Eurocode recommendations.
   - Office: 420 MJ/m²,
   - Dwelling: 780 MJ/m²,
   - School: 285 MJ/m².
     These values represent realistic fuel loads for the specific building types. They allow us to see how the type of usage affects fire severity and duration.
4. Compartment Size
   To explore the effect of the floor area while maintaining the same opening factor, three compartment sizes were analyzed.
   - 5 m × 5 m (25 m²),
   - 10 m × 10 m (100 m²),
   - 20 m × 20 m (400 m²).

In each case, this study adjusted the number and size of openings to keep a consistent opening factor. This helps us compare how the compartment area and volume affect the thermal response under similar ventilation conditions.

This study independently implemented and examined each variation using the fire modelling equations in Eurocode EN 1991-1-2. This study chose parameter ranges, like the number of openings, fire load densities, wall materials, and compartment sizes, based on typical values found in offices, homes, and schools. These scenarios reflect practical design cases important to performance-based fire safety engineering.

It is important to note that this analysis focuses only on thermal modelling and does not consider structural response or degradation over time. This study assumed the material properties were uniform and did not carry out probabilistic or uncertainty analyses. Still, the findings offer useful insights into how major compartment parameters influence fire development. They also provide a solid base for further studies on performance-based fire design.

3. Results and discussion

This section presents the results of the parametric fire simulations used to assess how important compartment parameters are in affecting the fire temperature and time development. The parameters studied included the opening factor, wall material, fire load density, and compartment area. Each of these varied in a systematic way while keeping the baseline conditions consistent. The analysis followed the guidelines in Eurocode EN 1991-1-2, which allows for a performance-based evaluation of thermal exposure during post-flashover fires. This study discusses the related temperature and time curves for each parameter, focusing on the heating and cooling phases, peak temperature, fire duration, and their impact on structural fire safety design.

3.1. Effect of Opening Factor on Temperature-Time Development

Figure 2 shows how different opening factors affect compartments with two, four, and eight windows in relation to parametric fire temperature and time curves. As expected, increasing the number of openings led to significant variations in both the peak temperature and duration of fire exposure. The compartment with eight windows, representing the highest opening factor (0.16), exhibited the most rapid temperature increase, reaching a peak of over 1100°C within approximately 20 min. However, this scenario also showed the shortest fire duration, with the temperature rapidly declining to near-ambient levels by 35 min. This behaviour is consistent with the physics of ventilation-controlled fires: the increased availability of oxygen accelerates combustion, resulting in higher peak temperatures, but faster fuel burnout.

In contrast, the case with two windows (opening factor of 0.04) showed a slower rate of temperature increase and a lower peak temperature, stabilizing at approximately 900°C. However, the decay phase was significantly prolonged, with elevated temperatures sustained for more than 100 min. This suggests that reduced ventilation limits the combustion rate, thereby extending the burning duration. The 4-window case (opening factor 0.08) represents a moderate condition, with a peak temperature slightly exceeding 1000°C and a fire duration that ends near 75 min. The shape of this curve reflects the balance between ventilation and fuel availability, highlighting the transition between the ventilation-controlled and fuel-controlled burning regimes.

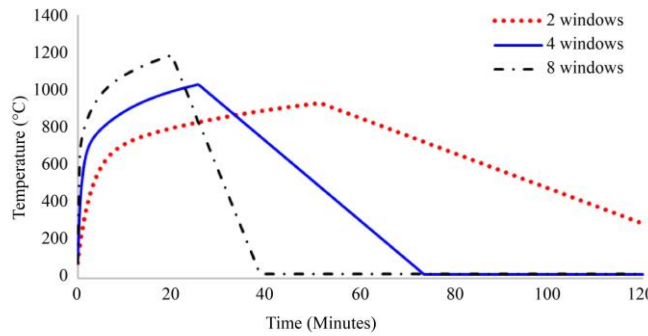

Fig. 2 Parametric fire temperature–time curves for different opening factors

These results underscore the importance of ventilation in determining fire dynamics. A higher opening factor enhances fire intensity but shortens its duration, which has direct implications for structural fire design. While higher peak temperatures may demand more robust fire resistance in the early stages of fire exposure, shorter durations may reduce the cumulative thermal load on the structural elements. Conversely, lower ventilation levels may result in less severe peak conditions, but pose a longer-term thermal threat, especially for thermally sensitive materials and protective coatings.

In summary, the opening factor was a critical determinant of both the severity and duration of compartment fires. Therefore, fire safety engineers must consider ventilation conditions when selecting design fire scenarios, particularly when applying parametric methods in performance-based structural fire design.

3.2. Effect of Wall Material on Temperature-Time Development

Figure 3 shows the results of the parametric fire simulations for compartments with varying wall materials: lightweight concrete, brick masonry, and gypsum boards. The thermal response curves reveal that while all scenarios follow a similar temperature–time trend, subtle differences in the peak temperature and cooling rate are observed owing to variations in thermal inertia. Among the three materials, lightweight concrete produced the highest peak temperature and the lowest cooling rate. This is attributed to its lower thermal conductivity and density, which results in a reduced heat absorption capacity, causing a greater proportion of heat to remain within the fire compartment. In contrast, brick and gypsum boards demonstrated slightly lower peak temperatures and faster cooling behaviour.

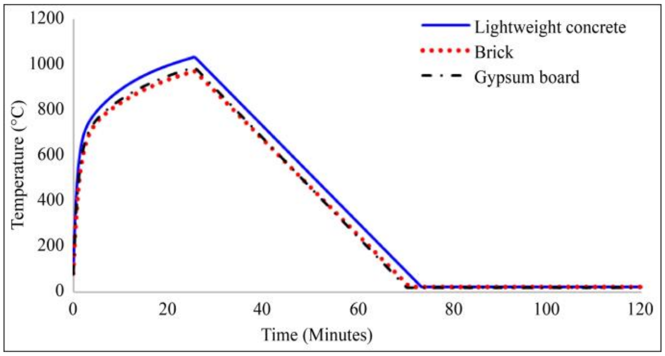

Fig. 3 Parametric fire temperature–time curves for different wall materials

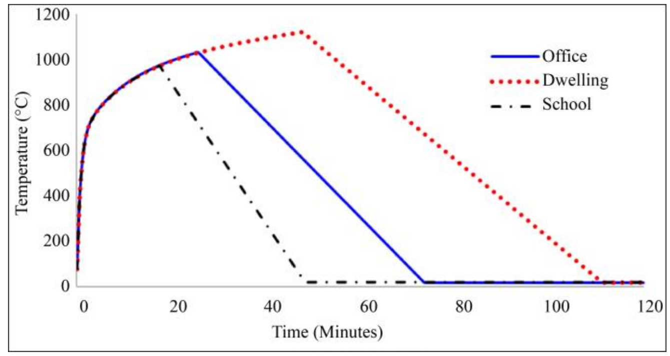

Fig. 4 Parametric fire temperature–time curves for different building use types

Notably, the curves for the brick and gypsum boards nearly overlap, indicating that their overall impact on the compartment thermal environment is quite similar within the context of the parametric fire model. Although bricks have a higher density and thermal conductivity than gypsum boards, their ability to moderate internal gas temperatures appears comparable, likely owing to the relatively short fire duration and limited enclosure thickness assumed in the model.

Despite the modest variations, these results emphasize that the thermal properties of compartment boundaries, particularly wall materials, exert an influence on fire development, albeit to a lesser extent than factors such as ventilation or fire load density. The findings suggest that although material selection affects the fire curve shape, its impact on structural performance may be more pronounced when interacting with other design variables, such as thermal protection systems and structural mass.

In summary, lighter and more insulating materials promote higher internal gas temperatures due to their limited heat dissipation capacity. However, in typical design scenarios, the influence of wall materials on the overall fire severity is relatively minor, and engineers may prioritize more dominant parameters, such as ventilation and fire load, when selecting critical fire design scenarios.

3.3. Effect of Building Use Type on Temperature-Time Development

Figure 4 shows the parametric fire temperature–time curves for three different building types: office (420 MJ/m²), dwelling (780 MJ/m²), and school (285 MJ/m²). These fire load densities are based on typical occupancy values, as specified in Eurocode EN 1991-1-2, and reflect the amount of combustible material per unit floor area. During the initial heating phase, the temperature curves for all three building types were nearly identical, indicating that the opening factor and thermal properties of the enclosure dominated the early development of the fire. This is expected because the rate of temperature rise is primarily governed by ventilation and compartment geometry, which are kept constant in these simulations.

However, distinct distinctions emerge during the peak and decay phases. The dwelling scenario, which had the highest fire load density (780 MJ/m²), exhibited the longest heating duration and sustained elevated temperatures for a significantly longer period, reaching a peak near 1100°C and gradually cooling for approximately 90 min. This prolonged thermal exposure is attributed to the larger quantity of combustible material, which extends fuel availability and delays the cooling phase.

In contrast, the school scenario, with the lowest fire load density (285 MJ/m²), reached a slightly lower peak temperature and began cooling as early as 30 min, with temperatures dropping to near-ambient values by 50 min. The office case, with an intermediate fire load (420 MJ/m²), follows a middle trajectory and is cooled to ambient temperature by 75 min.

These findings confirm that the fire load density directly influences the duration of fire exposure, even when the initial temperature increase is unaffected. In performance-based design, this highlights the importance of occupancy classification when selecting the critical fire scenarios. Although higher fire loads may not result in significantly higher peak temperatures, they produce longer thermal assaults on structural components, which can increase the risk of material degradation, creep, or loss of fire protection effectiveness over time.

3.4. Effect of Compartment Size on Temperature-Time Development

Figure 5 illustrates the parametric fire temperature–time curves for compartments of varying sizes: 5×5 m (25 m²), 10×10 m (100 m²), and 20×20 m (400 m²). In all cases, the opening factor was kept constant, ensuring that the ventilation conditions scaled proportionally with the surface area, allowing a focused investigation of the effect of compartment size alone.

The results revealed that larger compartments led to longer fire durations and slightly higher peak temperatures. The 20×20 m compartment showed the most extensive fire exposure, sustaining elevated temperatures for approximately 90 min. Conversely, the 5×5 m compartment reached its peak temperature quickly and entered the cooling phase much earlier, with temperatures returning to near-ambient levels by approximately 55 min.

This behaviour is primarily attributed to the compartment's thermal capacity and internal surface area. As the compartment area increases, so does the total surface area and air volume, which influence the rate of heat loss, fire load per unit surface, and thermal inertia effects. Although the opening factor was held constant, the larger compartments retained heat longer owing to their greater thermal mass and delayed heat dissipation, which extended the combustion period. Furthermore, although all configurations share a similar initial heating trend owing to identical ventilation scaling, the cooling phase notably diverges. Larger compartments sustain combustion for longer periods because of the greater fuel volume and increased thermal storage capacity, thus delaying the decay phase.

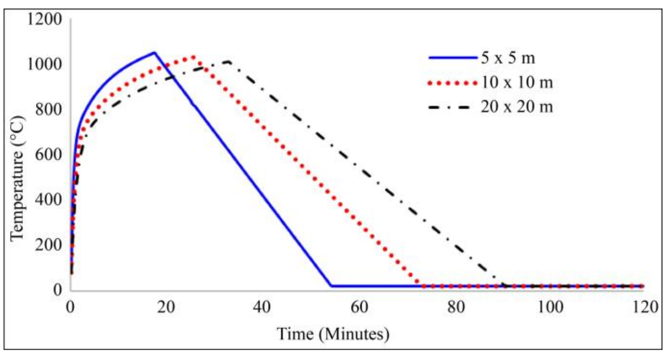

Fig. 5 Parametric fire temperature–time curves for different compartment sizes

These findings demonstrate that the compartment area, even under the same ventilation conditions, significantly affects the duration and decay characteristics of the fire. This has meaningful implications in fire-resistant design, as structural members in larger spaces may be subjected to elevated temperatures for extended durations, potentially increasing the risk of long-term thermal degradation, particularly for protective coatings and passive fire systems.

4. Conclusion

This study examined how important compartment factors influence the development of parametric fire curves based on Eurocode EN 1991-1-2. The factors included ventilation conditions, wall material properties, building usage type, and compartment area. The aim was to understand how these elements affected compartment fires' heating and cooling phases. This knowledge can help improve fire design strategies.

The results indicated that the opening factor had the greatest impact on fire behaviour. Increased ventilation leads to sharper temperature peaks, but shorter fire durations. On the other hand, reduced ventilation results in lower temperatures and longer exposure times. While wall material properties have a minor effect on the temperature profile, they still influence thermal inertia. Lightweight materials generally cool down more slowly.

The type of building use, which varies in fire load densities, is crucial in determining how long the heating phase lasts. Occupancies with higher fire loads, like residential buildings, lead to longer periods of high temperatures, even if their peak values are similar to those in offices or schools. Moreover, increasing the compartment area, even with constant ventilation, extends the fire exposure time due to the larger air volume and thermal mass available for combustion.

These findings stress the need to include realistic fire scenarios in structural design beyond standard fire curves. Parametric fire models provide a practical and scientifically sound way to reflect the actual thermal conditions of buildings during post-flashover fires. Structural engineers should consider ventilation, compartment shape, material properties, and occupancy type when defining design fires, especially for key load-bearing elements. The practical outcomes of this research involve better selection of fire scenarios for performance-based design, more accurate thermal demands on structural components, and potential material savings by avoiding overly cautious fire-resistance ratings. This study supports the Eurocode parametric method as a dependable tool in performance-based fire-safety design frameworks.

Unlike many previous studies focusing on numerical fire simulations or isolated parameters, this study systematically evaluates multiple compartment-level variables—opening factor, wall material, fire load density, and room size—using the parametric fire model defined in Eurocode EN 1991-1-2. This provides a practical analytical framework that is aligned with standard design methods. The results confirm and extend findings from prior studies [1, 7, 21] by demonstrating the dominant influence of ventilation and occupancy type on fire severity and duration. The inclusion of comparative parameter analysis offers a novel contribution to performance-based fire design practices.

In conclusion, the parametric fire approach supports a more robust and tailored fire safety design that ensures both safety and material efficiency. Future work may focus on coupling these thermal models with structural response simulations to assess actual member performance under time-dependent fire loading.

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Author Contribution

RS prepared the manuscript, IH reviewed it, and MS reviewed it.

Data availability

Data analysis https://zenodo.org/records/15495979

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