The Journal of Engineering and Exact Sciences – jCEC, Vol. 10 N. 08 (2024)
journal homepage: https://periodicos.ufv.br/jcec
eISSN: 2527-1075
ISSN: 2446-9416

Assessing Delayed Collapse Risks in Load-Bearing Reinforced Concrete Walls Exposed to Parametric Fires: A Numerical Investigation

Article Info:
Article history: Received 2024-05-05 / Accepted 2024-08-04/ Available online 2024-08-06
doi: 10.18540/jcecvl10iss8pp19442

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Abstract
This study delves into the thermo-mechanical analysis of structures exposed to fire, focusing on the evolution of gas temperatures, thermal distribution in structural members, and mechanical behavior during fire scenarios. Traditional prescriptive approaches assume a monotonically increasing temperature, while contemporary performance-based designs incorporate both heating and cooling phases for a more realistic fire resistance assessment. The critical aspect of this research is the modeling of the fire's cooling phase, which, though not commonly practiced in design offices, is essential for evaluating the risk of delayed structural collapse. Utilizing the finite element program SAFIR, numerical simulations were conducted on reinforced concrete walls to investigate their behavior during and post-cooling phase. The findings indicate potential failure not only during the cooling phase but also after the fire has subsided and temperatures have returned to ambient levels. This highlights delayed temperature increases in the core of the element and the consequent loss of concrete strength during cooling as key mechanisms of failure. A parametric study was undertaken, examining various fire scenarios, wall geometries, load levels, wall heights, adjacency, and boundary conditions. The results underscore that short-duration fires pose the most significant risk for delayed failure, particularly for simply supported walls. Additionally, the study scrutinizes the mechanical properties of materials across the heating and cooling phases. This investigation underscores the necessity of incorporating cooling phase analyses in fire resistance evaluations to mitigate the risk of delayed collapses. The insights gained aim to inform safer structural designs and

enhance fire safety protocols, emphasizing the importance of realistic fire modeling in performance-based design methodologies.

Keywords: Concrete wall. Parametric fire. Residual strength. Delayed failure.

1. Introduction

Fire represents a formidable threat, capable of inflicting significant damage to property and endangering human lives. Despite our best efforts, fires can occur unexpectedly, particularly in buildings where adequate precautions have not been taken. In Algeria, more than 90% of buildings stand as reinforced concrete (RC) structures, making their fire safety a matter of paramount concern. The fire resistance of RC structures primarily hinges on the thermal conductivity and fire resistance of their loadbearing elements, namely, walls, columns, and beams.

Among these loadbearing elements, walls stand particularly vulnerable due to their expansive surface area exposed to fire (Ni *et al.*, 2018). Additionally, the performance of walls during a fire event can be significantly influenced by their boundary conditions. Horizontal elements adjacent to walls, such as slabs and beams, when subjected to fire, exert horizontal forces perpendicular to the wall. These forces induce substantial stresses within the wall's cross-section, further compounded by the structural elements restraining its thermal elongation.

Given these considerations, comprehending the behavior of reinforced concrete (RC) structures under fire conditions is paramount. This study integrates thermal and structural analyses to characterize the behavior of concrete walls during natural fires, including the cooling phase, which is governed by the properties of concrete and steel at elevated temperatures. Concrete and steel undergo significant changes in strength, stiffness, and other physical properties when exposed to fire, with varying rates of decrease during a fire. Notably, the modulus of elasticity decreases as temperature rises (Gruz, 1966; Ni *et al.*, 2018; Krishna *et al.*, 2019; Hamda *et al.*, 2023). Several studies have explored the effects of fire on concrete (Kim and Lee, 2015; Ni *et al.*, 2018; Onundi *et al.*, 2019) and steel (Wang *et al.*, 2008; Yang *et al.*, 2020), emphasizing the dynamic nature of material behavior under fire conditions.

In the prescriptive approach, time-temperature curves are typically derived from design codes such as Eurocode ISO834 (ISO834, 1999) or ASTM E119 standard fire. These standard fire curves feature continuously increasing temperatures, which lead to a gradual reduction in the structure's load-bearing capacity. Therefore, verifying the structure's integrity for the required fire duration ensures that it remains stable at any point during the fire.

Recent research aimed at enhancing fire safety through alternative, cost-effective solutions has spurred an increased adoption of performance-based approaches in fire safety design (Craig and Naser, 2023; Gernay, 2023). In such approaches, the behavior of structures or structural elements is evaluated within a performance-based framework, allowing for a more realistic representation of fires that includes both the heating and cooling phases, where the fire temperature returns to ambient levels. In scenarios reflecting real fires, the necessary duration for structural stability may extend beyond the heating phase, possibly requiring structures to endure the entire fire until it burns out completely (Ni and Gernay, 2020; Gernay *et al.*, 2023).

However, verifying the structure's load-bearing capacity only at the peak gas temperature does not ensure protection against collapse later on. The structure’s load-bearing capacity continues to diminish after reaching the peak gas temperature, potentially reaching a minimum value before partially or completely recovering as temperatures return to ambient levels. Therefore, designers must use a step-by-step iterative method for time-domain verification.

The ongoing degradation of load-bearing capacity after the peak gas temperature is primarily due to two factors: structural temperatures may continue to rise while gas temperatures decline. In concrete structures, regions near the surface may cool shortly after gas temperatures drop, but central zones, especially in massive sections, may experience prolonged temperature increase. Heat penetration into the cross-section persists during the cooling phase, resulting in thermal stresses and cracks, a process that can last for hours and reverse during cooling, potentially widening micro cracks due to chemical reactions like the reformation of calcium hydroxide (Klingsch *et al.*, 2009;

Hiroshi *et al.,* 2019). The combination of these factors can significantly reduce concrete's compressive strength after a fire, with investigations indicating that minimum strength occurs after the concrete has returned to normal temperature (Felicetti *et al.*, 2009; Rossino *et al*., 2041).

Secondly, material behavior plays a crucial role. While steel can regain strength and stiffness upon temperature decrease, the extent of recovery depends on the steel type and maximum temperature reached (Smith *et al.,* 1981; Sha *et al.,* 2001). In contrast, concrete remains severely damaged after cooling. Concrete not only fails to recover its strength but also exhibits indications suggesting additional strength loss during cooling from peak temperature to ambient levels (Hsu and Lin, 2008; Cheng *et al*., 2022).

The delayed increase in temperature within the structure, coupled with the irreparable damage sustained by heated concrete and the additional loss of concrete strength during cooling, presents a potential risk of delayed collapse for concrete structures exposed to natural fires. Although significant research has been conducted on the residual mechanical properties of concrete (Nassif, 2006; Abdulkareem and Izzet, 2021), reinforcement (Tao, 2015; Neves *et al.,* 2021), and the concrete-rebar interface after exposure to high temperatures (Chiang and Tsai, 2003), there has been limited focus, to the authors' knowledge, on the risk of collapse during the cooling phase of a fire.

While some studies have explored the residual load-bearing capacity of structural elements after fire exposure-such as Yu *et al.* (2021) for reinforced concrete beams, Lie and Kodur (1996) for reinforced columns, and Chen *et al.* (2022) for eccentric RC columns-there remains a gap in understanding the risk of collapse during the cooling phase.

A structural failure occurring during this phase, when compartment temperatures return to ambient levels, presents an even greater threat as it coincides with initial inspections, potentially by both fire brigades and other individuals. Notable incidents, such as a full-scale fire test in the Czech Republic in 2008 (Wald *et al.,* 2009; Rush and Lange, 2017) and a tragic event in Switzerland in 2004 where seven firefighters lost their lives due to a sudden collapse in an underground car park after successfully extinguishing a fire, highlight the need for detailed studies on the risk of delayed collapse in natural fire scenarios. Such analyses require access to data on the evolution of material properties during the cooling phase.

2. Objective of the Research

The objective of this research was to conduct numerical analyses on reinforced concrete walls exposed to natural fires to assess whether the risk of structural failure during or after the cooling phase is real, and to identify the parameters and conditions most likely to lead to such undesirable outcomes.

Reinforced concrete elements were selected for study because they are particularly susceptible to ongoing reductions in load-bearing capacity and stiffness after reaching peak gas temperatures, a phenomenon less common in steel structures. In reinforced and prestressed concrete subjected to flexure, the performance is primarily influenced by the behavior of the reinforcing steel. This principle is less directly applicable to reinforced concrete columns, where fire performance is governed by both the concrete's and the reinforcement's responses, as noted by Liu *et al.* (2021). The research utilized the general constitutive models for steel and concrete as outlined in the Eurocode, due to their broad acceptance within the scientific community and common application in structural analysis. Specifically, the Eurocode's concrete constitutive model (Eurocodes 2; 2004) incorporates the effects of transient creep within the mechanical strain term, allowing for a comprehensive analysis of the material's behavior under fire conditions.

3. Material Models

3.1 Thermal Models

The thermal properties of steel and concrete during the heating phase were obtained from Eurocode 2 (2004). For this study, siliceous concrete was selected, featuring a density of 2400 kg/m³ and a water content of 46 kg/m³. The material's emissivity was assumed to be 0.7, and the convective heat transfer coefficient was set at 35 W/m²K. The thermal properties of steel were treated as entirely reversible upon cooling. The thermal properties that are necessary to calculate the heat transfer and temperature distributions in structures are the thermal conductivity and the specific heat, which are considered non-linear. Another critical physical property for structural analysis is thermal elongation.

It was assumed that the specific mass of concrete, which typically decreases during heating due to water loss, remains constant during cooling, retaining the value at the peak temperature. As the temperature within the concrete rises, its thermal conductivity tends to decrease, a change considered irreversible for the purposes of this research. Therefore, during the cooling phase, the concrete's thermal conductivity is maintained at the level corresponding to the highest temperature reached, as per the guidelines of Eurocode 4 (2005). This approach ensures a consistent framework for analyzing the thermal behavior of concrete and steel structures under fire conditions, taking into account the significant aspects of material properties and their variations with temperature.

3.2 Mechanical Models

The mechanical models for the steel reinforcing bars and concrete used in this study are based on the assumption that steel regains its initial stiffness and strength upon cooling, with no residual thermal expansion once it returns to ambient temperature. Specifically, during heating, steel exhibits a thermal elongation plateau around 800°C with an expansion coefficient of 11 x 10^{-3}, which shifts to slightly lower temperatures (around 700°C) and reduces to 9 x 10^{-3} during cooling. This reflects the reversible nature of steel's mechanical properties under thermal cycling.

Conversely, concrete is treated with an inherent residual thermal expansion or shrinkage once it cools down to ambient temperature, dependent on the maximum temperature reached during heating. This residual effect is quantified based on experimental findings by Schneider (1988), and it does not consider spalling. Importantly, the compressive strength of concrete does not return to its initial value upon cooling. According to Eurocode 2 (2004), an additional 10% loss in strength is expected during the cooling phase. For example, if the compressive strength of concrete is reduced to half its original value at a certain temperature, it will further decrease to 45% of its original value when cooled back to ambient conditions. This critical assumption underpins the predictions made in the study and, consequently, the reliability of its conclusions.

Recent research by Hai and Franssen (2011) and Kim *et al.* (2014) suggests that the reduction in concrete's strength during cooling could be even more significant than the 10% decrease stipulated by Eurocode 4 (2005). based on an extensive analysis of experimental data from the literature. The stress-strain relationship for concrete during cooling was assumed to retain the strain level corresponding to peak stress, fixed at the value achieved at the maximum temperature, as supported by Felicetti *et al.* (2002) and Arano *et al.* (2021) and reflected in Figure C.2 of Eurocode 4 (2005). This assumption plays a vital role in understanding and modeling the mechanical behavior of concrete under fire and cooling conditions

For steel within the context of fire analysis, the total strain comprises three components: thermal strain, instantaneous stress-related strain, and creep strain. However, by applying anisothermal temperature-modified strengths, the need to account for the creep strain explicitly can be circumvented. This simplification acknowledges that, under varying temperature conditions, the material properties of steel can be adjusted in a way that inherently considers the effects of creep without needing a separate term.

In contrast, the total strain calculation for concrete is more complex due to an additional component known as transient creep strain. This strain is specific to concrete and arises from changes in its chemical composition when subjected to heating for the first time. Transient creep strain is a critical factor in the analysis of concrete under fire conditions, as it develops irreversibly during the initial heating phase if the concrete is under load, distinct from the behavior observed when concrete is loaded at an elevated temperature without prior heating (Li and Purkiss, 2005; Fan *et al.,* 2019). This phenomenon, highlighted by research from Anderberg and Thelandersson (1976), Khoury *et al.* (1985) and further supported by Wei *et al.* (2017) and Fan *et al.* (2019) is essential to consider in any fire analysis involving concrete in compression.

The significance of transient creep strain extends to the predictive accuracy of structural behavior under fire conditions. For instance, neglecting this strain component in stress-strain models can lead to unsafe predictions, particularly for columns heated on three sides that experience induced thermal moments. Such scenarios demonstrate not only the mechanical impact of fire on structural elements but also how thermal gradients and moment gradients can exacerbate the effects, as noted by Purkiss (1996).

Constitutive models for concrete have been developed to address this complexity, with some proposing explicit terms for transient creep in their strain decomposition. Models by Anderberg and Thelandersson (1976), Schneider (1988) and Terro (1998) are notable examples of this explicit approach. Conversely, the Eurocode concrete model (2004) adopts an implicit strategy, incorporating the effects of transient creep within the mechanical strain term. This distinction between models underscores the varied approaches to capturing the nuanced behavior of concrete under fire load conditions, emphasizing the importance of selecting an appropriate model for accurate analysis and safety assessment.

4 Analyses for Reinforced Concrete Walls

The analysis of reinforced concrete walls under natural fire conditions utilized the time-temperature fire curves derived from the parametric fire model described in Annex A of Eurocode1 Gulvanessian (2001). A key aspect of this model is the use of the factor Γ in Equation (A.2a), which was set to 1.0 for this study. Setting Γ to 1.0 aligns the heating phase of the natural fire model's time-temperature curve closely with the ISO834 standard fire curve, providing a standardized basis for comparison and analysis. Figure 1, would illustrate the variety of fire curves utilized in the analysis, characterized by differing durations of the heating phase, ranging from 43 to 143 minutes.

To clarify the discussion of the results, three distinct phases of the fire scenario are identified:
Phase 1 (Heating Phase): This phase encompasses the period during which the gas temperature increases from an ambient temperature of 20°C to its maximum value. The duration of this phase is denoted as Tpeak, marking the time it takes for the temperature to reach its peak value.
Phase 2 (Cooling Phase): Following the heating phase, Phase 2 describes the period during which the gas temperature decreases back down to 20°C. The conclusion of this phase is identified by the time 20, indicating when the temperature has cooled to the endpoint of 20°C.
Phase 3 (Post-Fire Phase): This final phase occurs after the fire has been extinguished, and the gas temperature has stabilized back at 20°C. Phase 3 represents the period for assessing the aftermath and residual effects on the structural integrity of the concrete walls.
This structured approach to analyzing the fire scenario allows for a detailed examination of the reinforced concrete walls' response to the dynamic thermal conditions imposed by a natural fire, spanning from the initial heating through the cooling and the post-fire recovery phases.

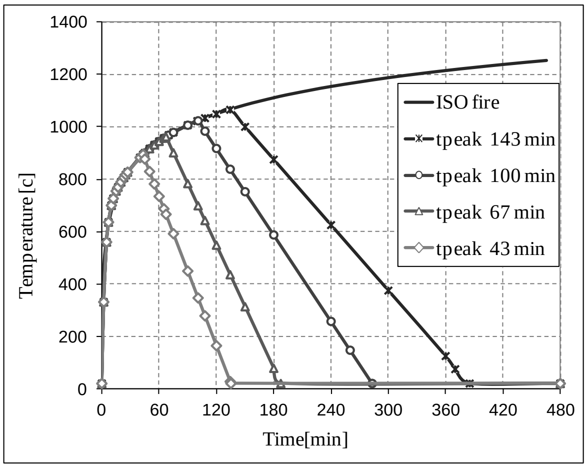


Figure 1 – The time-temperature curves used in the study exhibit varying durations of the heating Phase

The analysis focused on reinforced concrete walls subjected to fire on one side, while the opposite side remained at room temperature. This scenario was explored using SAFIR, a nonlinear finite element software developed by Franssen (2005), renowned for its capability to simulate the behavior of structures under fire. The temperature distribution within the wall sections was determined through 2D nonlinear transient analyses, a sophisticated approach that captures the complexity of thermal gradients during fire exposure.

To facilitate the structural analysis, the walls were discretized longitudinally using Bernoulli beam-type elements. The cross-sections of these beam elements were further divided into fibers, aligning with the 2D elements used in the thermal analysis (see Fig. 2). This methodological choice ensures a detailed and accurate representation of the temperature distribution and its impact on the structural integrity of the walls.

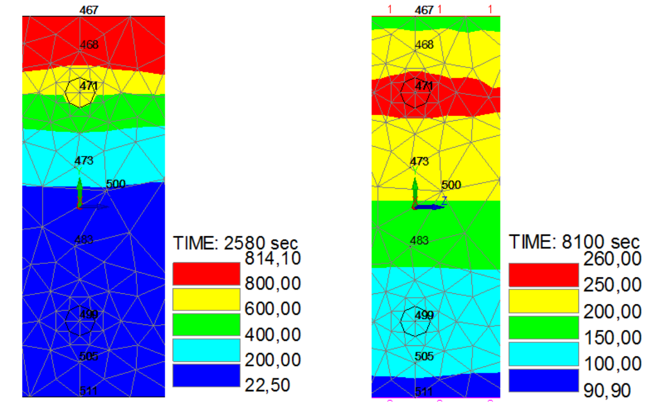
The basic case considered for analysis features a wall section with a thickness of 15 cm, reinforced with two layers of nine bars, each 12 mm in diameter, and a concrete cover of 25 mm. The wall, spanning 3 meters in length, is simply supported at both ends. To account for potential imperfections and the influence of the thermal gradient, a sinusoidal imperfection with a maximum amplitude of L/300 was introduced.

The study aimed to shed light on the factors that contribute to the risk of delayed collapse under fire conditions. Key parameters examined included:

- *Duration of the Heating Phase:* Understanding how the length of time the wall is exposed to elevated temperatures affects its structural integrity.
- *Effective Length of the Wall:* Investigating how the length of the wall influences its behavior and potential for failure under fire exposure.
- *Section of the Wall:* Analyzing how the cross-sectional dimensions and reinforcement layout impact the wall's response to fire.

Additionally, the effect of the concrete material model on the simulation outcomes was considered. The simulations employed the Eurocode 2 (2004) concrete model, a choice reflective of the study's commitment to leveraging widely recognized and accepted standards for analyzing concrete's behavior under fire conditions.

This comprehensive approach, integrating detailed modeling of thermal and structural responses, provides valuable insights into the resilience of reinforced concrete walls under fire conditions and identifies critical factors that influence their risk of delayed collapse.



t_{peak} = 43min t_{20}=135min

Figure 2 – Isotherms after 43 minutes in a section heated on 1 side

5. Results

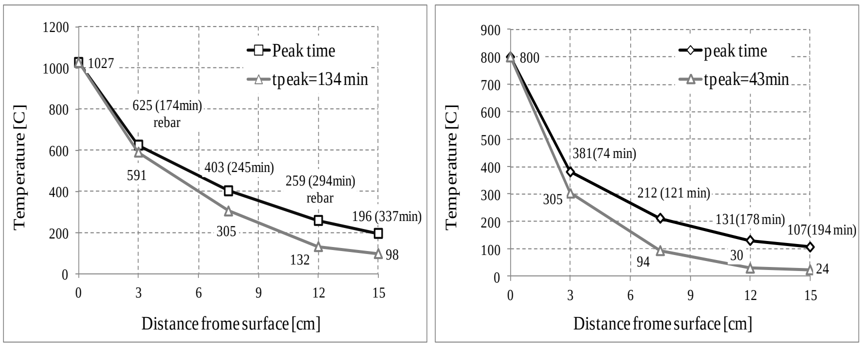
5.1 Peak Temperature Distribution

The results concerning peak temperature distribution offer significant insights into the thermal behavior of RC walls subjected to parametric fires of varying durations. Figure 3 evidently illustrates how the peak temperatures within the concrete and reinforcing bars (rebar) vary across different depths of the cross-section in response to fire exposures lasting between 43 and 143 minutes.

Key observations from the data include:

- *Temperature Gradient with Depth:* There's a clear indication that the deeper layers of concrete experience greater temperature increases both during and after the cooling phase. Specifically, the temperature at the center of the wall increases by approximately 118°C for a 43-minute fire exposure (tpeak) and by about 60°C for a 143-minute exposure during the cooling phase. This behavior underscores the insulating properties of concrete, which cause a time delay in thermal penetration and result in higher internal temperatures that persist or even increase during cooling.
- *Time Delay in Peak Temperature:* The data also reveals that the time taken to reach peak temperatures increases with depth, highlighting the thermal inertia of concrete. This delay is more pronounced in walls exposed to longer fire durations, reflecting the gradual heat transfer process through the material.
- *Protection by Concrete Cover*: The concrete cover, with a thickness of 2.5 cm, plays a crucial role in insulating the reinforcing bars from direct fire exposure. This cover not only slows down the increase in rebar temperatures but also provides a minimum level of heat insulation deemed necessary for structural integrity. The peak temperatures measured for rebar near the exposed surface were significantly lower than those at the wall's surface, approximately 300°C for the 43-minute exposure and 590°C for the 143-minute exposure. Interestingly, on the side opposite the fire exposure, rebar temperatures peaked during the cooling phase, emphasizing the dynamic and complex nature of thermal gradients in such scenarios.
- *Efficacy of Concrete Cover:* The results highlight the effectiveness of the 2.5 cm concrete cover in reducing rebar temperatures, with a reduction of at least 400°C compared to the wall surface temperature during fire exposure. This finding validates the importance of concrete cover in protecting the structural reinforcement and ensuring the overall thermal resilience of reinforced concrete walls under fire conditions.

These observations are critical for understanding the thermal performance of reinforced concrete structures during and after fire exposure. They underscore the need for strategic design considerations, such as the thickness of the concrete cover, to enhance the fire resistance of structural elements.



(a) (b)

Figure 3 – Concrete and rebar temperatures at the end of the heating phase and maximum values at various depths: (a) t_{pak} 143min and (b) t_{peak} 43min

5.2 Possibility of delayed collapse

The summarized results in Figure 4 delve into the analysis of the basic case under varying durations of natural fire exposure, focusing on the evolution of the wall's load-bearing capacity over time. This analysis is instrumental in understanding the potential for delayed collapse of reinforced concrete walls under fire conditions.

Key insights from the analysis include:

- *Initial Load-Bearing Capacity:* At the onset (t = 0), the wall's load-bearing capacity is quantified at 2616 kN. Through a series of simulations that progressively reduce the load, a curve is generated that outlines how the fire resistance time extends as the applied load decreases. This curve effectively maps the dynamic change in load-bearing capacity throughout the fire event.
- *Critical Load Points:* For a fire with a peak heating phase of 43 minutes (tpeak), the critical load corresponding to this heating duration is identified as 810 kN. At loads exceeding 810 kN, the wall is prone to failure during the heating phase itself. Conversely, if the load on the wall is below 810 kN but above 650 kN (marked as t20 on the curve), failure is anticipated throughout the cooling phase of the fire.
- *Delayed Collapse Potential:* The analysis identifies a nuanced behavior where, for loads under 650 kN, collapse might not occur until Phase 3 of the fire, when the gas temperature has returned to ambient levels. Notably, a load of 168 kN is highlighted as capable of causing collapse more than 30 minutes after the conclusion of the heating phase, but any load below this threshold does not result in the wall's collapse, indicating a horizontal asymptote on the curve.
- *Load Range for Collapse:* The findings underscore a significant span of loads that can precipitate the wall's collapse during the cooling phase, demonstrating the critical nature of load management and fire safety design in mitigating the risk of delayed structural failure.
- *Duration of Fire vs. Critical Load Range:* An important observation is that the range of loads leading to failure during Phase 2 (the cooling phase) is wider for shorter-duration fires and becomes narrower as the fire duration increases. This suggests that the vulnerability of the wall to collapse under lower loads increases with shorter fire exposures, potentially due to less time for heat to thoroughly penetrate and weaken deeper sections of the wall.

This analysis sheds light on the intricate relationship between applied load, fire duration, and the timing of potential structural failure, offering crucial insights for the design and assessment of reinforced concrete structures in fire conditions. It underscores the importance of considering not just the immediate impact of fire but also the post-heating phase in structural fire safety planning.

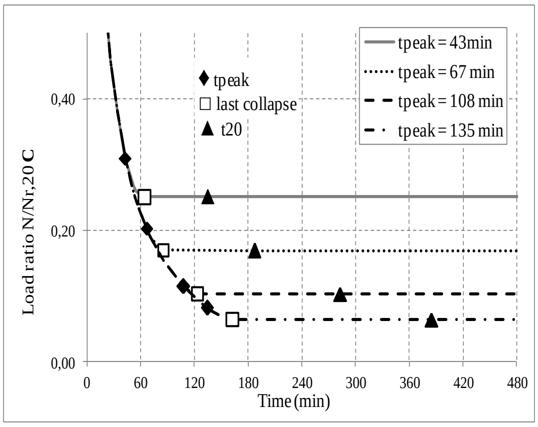


Figure 4 – Evolution of the load bearing capacity for a column subjected to natural fires of different duration of heating phase

The insights from Figure 5, which offers an alternative visualization of the results discussed in Figure 4, highlight the impact of the heating phase duration on the structural integrity of a wall exposed to fire.

The insights derived from Figure 5, which represents a different visualization of the results previously discussed in the context of Figure 4, focus on the influence of the duration of the heating phase on the structural integrity of a wall exposed to fire. The described structure allows us to conceptualize how the applied load ratio (relative to the initial load-bearing capacity of 2616 kN at time t = 0) correlates with the duration of the fire's heating phase and the resulting collapse phase.

Conceptual Overview of Figure 5:

Horizontal Axis: Represents the duration of the fire's heating phase, measured in minutes.

Vertical Axis: Displays the applied load ratio, which is the load on the wall expressed as a percentage of its initial load-bearing capacity at room temperature (2616 kN).

Each bar in Figure 5 corresponds to a specific scenario from Figure 4, segmented into up to four parts based on the collapse phase:

- *Collapse Phase I:* This segment shows the range of load ratios leading to collapse during the heating phase. For instance, a fire lasting 67 minutes could result in collapse for load ratios between 80% and 100% of the initial capacity (530 kN to 2616 kN), indicating a very high susceptibility to immediate failure under substantial loads during the heating phase.
- *Collapse Phase II:* This portion of the bar represents the load ratios at which collapse occurs during the cooling phase, highlighting the critical period after the peak temperature has been reached and temperatures begin to decline.
- *No Collapse:* This signifies the spectrum of load ratios that do not lead to the wall's collapse under the given conditions, emphasizing scenarios where the structure maintains its integrity despite the thermal stress.
- *Collapse Phase III:* This segment, present only for fires of shorter durations, marks the dangerous load ratios that could lead to collapse in Phase 3, after the compartment returns to ambient conditions. Notably, this segment disappears for fires with longer heating durations, suggesting that extended exposure to heat fundamentally alters the risk profile of the structure.

The distribution of these segments across different fire durations reveals critical insights:

The risk of collapse during the heating phase is significantly higher under heavier loads, especially for fires of moderate duration.

The possibility of collapse extends into the cooling phase and, in some cases, even into the post-fire phase, though this risk diminishes with longer fires.

The narrow "collapse phase III" segment illustrates the relatively low incidence of post-fire collapses compared to total building collapses, underscoring the specific conditions under which such outcomes occur.

This nuanced representation underscores the complexity of assessing fire impact on structural integrity, emphasizing that both the magnitude of the applied load and the duration of fire exposure critically influence the risk of collapse. It also highlights the importance of understanding these dynamics to mitigate risks effectively, especially in the design and fire safety planning of buildings.

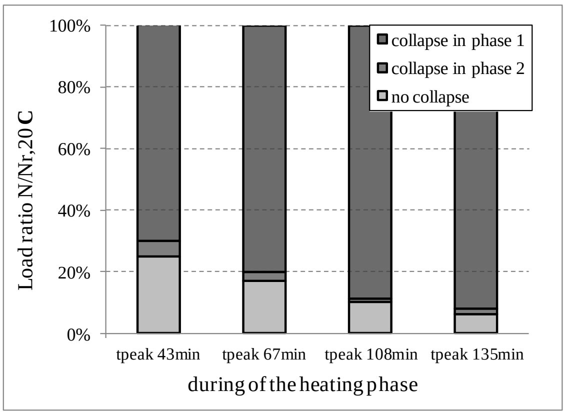


Figure 5 – Influence of the duration of the heating phase on the possibility of delayed collapse

The phenomenon of delayed collapse being more prevalent in scenarios involving shorter-duration fires compared to those with prolonged heating phases is intriguing and counterintuitive at first glance. However, this observation can be elucidated through a deeper understanding of the thermal behavior of concrete sections and steel reinforcement bars during and after fire exposure, as detailed in the temperature evolution analysis.

Temperature Evolution in Concrete and Steel Bars:

Delayed Heating in Concrete: The analysis highlighted in Section 5.2 reveals that deeper parts of the concrete section continue to experience temperature increases even after the external gas temperature has reached its peak. This is because concrete has a high thermal mass, which causes it to absorb and retain heat for extended periods. Consequently, the core or inner layers of concrete can still be heating up while the surface begins to cool, creating a thermal lag.

Continued Temperature Rise in Steel Bars: Similarly, steel reinforcement bars, especially those located further from the heated surfaces, exhibit a continued rise in temperature for a significant duration post-peak external gas temperature. Dimia *et al.* (2011) and Guergah *et al*. (2018) noted that this temperature increase could persist for at least 30 minutes and, in some cases, for more than an hour after the fire has ended. This sustained increase in temperature within the steel reinforcement contributes to further stress and potential degradation of the structural integrity.

Effect on the Compressive Strength of Concrete: The ongoing rise in internal temperatures, coupled with the inherent 10% reduction in compressive strength of concrete as it cools back to ambient temperatures, forms a critical factor in explaining delayed failures. The cooling phase does not merely represent a return to pre-fire conditions but involves a complex interplay of thermal and structural responses that can exacerbate vulnerabilities in the concrete and steel components.

Implications for Delayed Collapse:

The interrelated thermal behaviors of concrete and steel reinforcement under fire exposure provide a comprehensive explanation for the higher occurrence of delayed collapses in cases of shorter fires. Shorter-duration fires lead to rapid heating followed by a swift transition to the cooling phase, allowing less time for the heat to distribute evenly throughout the structure. This uneven thermal distribution results in significant internal stresses as different parts of the structure expand, contract, and weaken at different rates during the cooling phase.

Moreover, the additional decrease in concrete's compressive strength during cooling further diminishes the structural capacity to bear loads, making it more susceptible to collapse even after the fire has been extinguished.

Understanding these dynamics is crucial for fire safety engineering and emphasizes the need for designs that consider the post-fire behavior of materials to mitigate the risk of delayed collapse

5.4 Influence of the adjacent building's floor

In the initial scenario, the wall is constructed with its base built-in and its top free. Simulations were conducted to determine the load-bearing capacity, with Figure 7 summarizing the analysis to investigate the effect of support and the length of the heating phase on the likelihood of short fire incidents. Each curve in Figure 5 corresponds to a specific fire scenario, with tpeak values of 15 minutes and 43 minutes, respectively. These curves facilitate the identification of potentially hazardous load ranges that might lead to structural collapse either during the heating phase or afterward. Whether a delayed collapse occurs is contingent upon the actual load exerted on the wall.

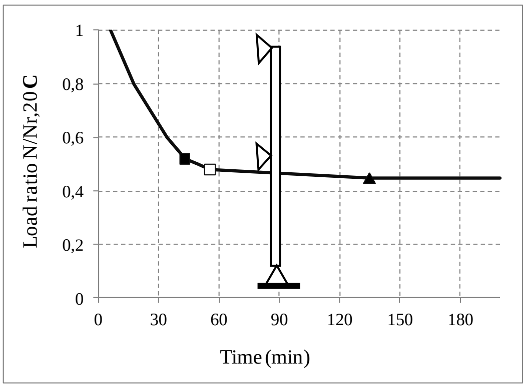


Figure 6 – Wall built in at the base with two adjacent floors

For instance, according to the curve labeled "tpeak 15 min", a wall subjected to a 198 kN load will fail 42 minutes into the event, marking a collapse during the cooling phase. In the case of a fire with a 43-minute heating phase, any load exceeding 109 kN will result in a collapse within the heating phase itself. Loads ranging between 133 and 108 kN lead to collapse during the cooling phase. Conversely, loads below 108 kN do not precipitate wall collapse, thereby ensuring infinite stability; such fire durations preclude the possibility of post-cooling phase collapse.

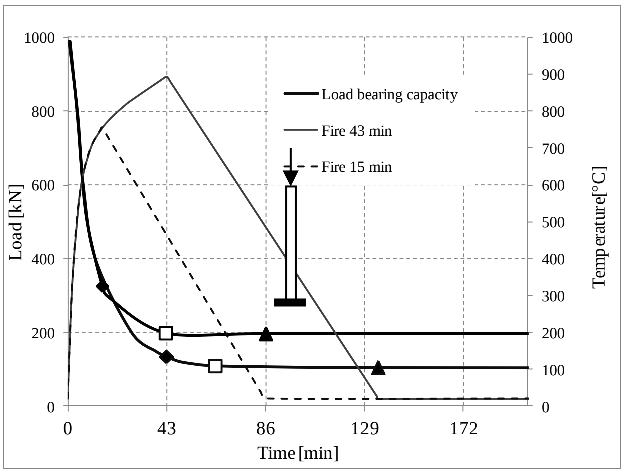


Figure 7 – Influence of the support on the possibility of delayed collapse

Figure 7 underscores the potential for structural collapse post-heating, demonstrating that even short heating phases can lead to significant structural failures.

In a more complex scenario, the analysis extends to a wall akin to the one described but incorporated within adjacent building floors. This wall is supported at both the top and midway up its height, aligning with the floor levels. As depicted in Figure 7, collapse tends to occur during the fire's cooling phase. The bending moment's evolution within the wall, as illustrated in Figure 8, indicates a critical shift in the bending moment at the intermediate support during the cooling phase. This phenomenon must be taken into account when determining the constructional approach.

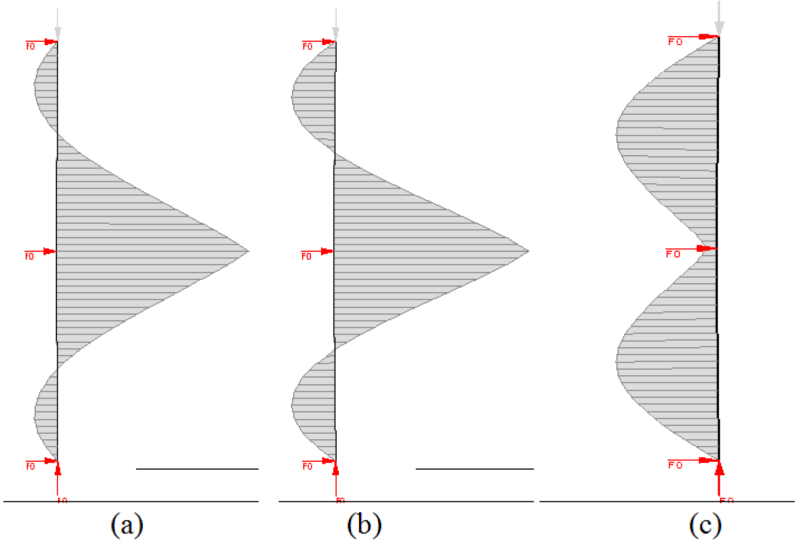


Figure 8 – Evolution of bending moment at (a) tpeak , (b) t collapse and (c) t20

6. CONCLUSIONS

The comprehensive numerical analysis presented in this work scrutinizes the structural behavior of concrete walls under the duress of natural fires, emphasizing the pivotal role of accurate constitutive models for both steel and concrete materials. Despite the widespread adoption and acceptance of the Eurocode mechanical model for concrete in prescriptive design, its application in capturing the nuanced behavior of concrete during the cooling phase of a fire raises pertinent questions. This is primarily due to the implicit incorporation of transient creep effects within the mechanical strain term of the model, a method that may not fully encapsulate the complexities observed in real-world scenarios.

A critical examination of experimental data suggests that while the Eurocode model is competent in delineating the behavior of concrete structural elements during the cooling phase, there is a pressing need for the development of an explicit model. Such a model would enhance the predictability of structural behavior under fire conditions, offering a more nuanced understanding of the material responses during both the heating and cooling phases.

The investigations carried out on concentrically loaded, simply supported concrete walls, subjected to unilateral heating, unequivocally demonstrate the potential for structural failure during the cooling phase of a fire. Alarmingly, it is posited that the structure remains vulnerable to failure even after the fire has been extinguished sometimes hours after the fire compartment has returned to tenable conditions and preliminary inspections might be initiated.

The underlying mechanisms for these delayed failures stem from two critical phenomena: the continued increase in temperatures within the central zones of the element post the ambient temperature normalization, and the additional strength loss experienced by concrete during the cooling phase relative to its strength at the peak temperature. The findings highlight that the risk of delayed failure is particularly acute for short-duration fires and in structures that are either simply supported or interconnected with adjacent elements.

In conclusion, this work underscores the necessity for ongoing development and refinement of constitutive models that can accurately represent the behavior of concrete and steel under fire conditions. Acknowledging and addressing the potential for delayed structural failure is paramount to enhancing the fire safety design and assessment of buildings, thereby ensuring greater resilience and safety for structures exposed to fire hazards.

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