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Abstract

This study focuses on the fire behavior of structural members considering their response until the end of the fire event. The study reviews and discusses a framework for determining the burnout resistance (B) of structural members through the Duration of the Heating Phase concept (DHP). This framework complements the fire resistance rating (FRR) system by providing a rating that captures the sensitivity to delayed structural failure during the cooling phase. The report describes experimental and numerical studies on concrete, timber, and steel members, highlighting substantial differences between their fire resistance rating, based on evaluation during the heating phase, and their burnout resistance, based on evaluation under the heating and cooling phases. With the burnout resistance as a complementary rating to fire resistance, a more holistic characterization of the safety and robustness of different structural solutions can be evaluated.

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Summary

This report describes a framework for determining the burnout resistance (B) of structural members exposed to fire through the Duration of the Heating Phase concept (DHP). The latest advancements in applying this concept to diverse materials and elements are outlined, offering insights into the current state of the art and a roadmap for further development. The key conclusions can be synthesized into these main points:

Behaviour of Structural Members under Fires with Decay Phase: Structural members are vulnerable to failure during or after the cooling phase of a fire. Indeed, heating of the core of the members' sections continue even after the fire has peaked, resulting in continued reduction in loadbearing capacity. This behavior is not merely due to the fact that the members receive an additional amount of energy from their environment during the cooling phase; it is in fact mostly due to the effects of thermal inertia of the structure, i.e., the heat penetrating the outer layers of the cross section are redistributed to the inner part with a delay. Delayed failure may occur in all types of members and materials, and this has been shown through experiments and numerical simulations. Other factors either material- (e.g., smouldering) or structural-dependent (e.g., force redistribution in frames) also play a role. Such delayed failures pose specific threats to fire service and building occupants, yet are not examined through the standard fire resistance framework.

Burnout Resistance Definition (B): The conceptualization of burnout resistance (B) as the longest DHP in a 'standardized natural fire' complements traditional fire resistance ratings. It provides an indicator for assessing elements before final utilization that captures the sensitivity to a prescribed cooling phase that is not present in the traditional fire resistance rating.

Application of B – DHP concepts: The concepts of DHP, and the associated B rating, have been applied in both experimental and numerical studies. These studies have shown that this framework can be systematically applied to quantify and compare the performance of structural members under fires including cooling phase. Agreement between numerical and experimental studies provided proof of concept.

Considerations on Experimental Determination: To become standardized and repeatable between laboratories, the experimental determination of burnout resistance requires complementary definitions. Redefined performance limits for cooling phases in fire resistance furnaces, along with suggestions for standardized frameworks, are important steps towards practical application. Suggestions for these performance limits are given in the report. In a regulatory context, the burnout requirement may be to prove that a member meets the minimum required burnout resistance, which can be achieved with a single test. If the member maintains its function until full burnout under the minimum required fire with cooling phase, the test is passed, and the member obtains the required rating.

Termination Criteria: Defining termination time of a test or calculation during cooling is important. Two proposed approaches include time-based termination, linked to the heating phase, and temperature-based termination, setting thresholds for specimen temperatures. Striking a balance between comprehensive testing effectively capturing the effects until burnout, and cost-effectiveness, is key for promoting a wider use of the concept.

Numerical Modelling: Advanced numerical modelling, particularly using the Finite Element Method (FEM), emerges as a key component for determining burnout resistance, offering a cost-effective

alternative to furnace testing. Studies highlight promise, but further efforts are needed in some cases regarding validation, material models and material properties in the cooling phase.

Structural Assemblies and Buildings: The definition of a Burnout resistance rating is envisioned at the level of an individual member, similar to the standard fire resistance. However, specific effects develop during the cooling phase in structural assemblies and entire buildings, such as variations of thermally-induced forces. The techniques developed within the DHP concept can be applied to study structural assemblies and provide insights into the ability of entire structures to resist fire exposure until full burnout. This refined perspective equips structural fire safety engineers with enhanced tools for developing practical, performance-based solutions, fostering both safety and efficient material utilization in construction.

Sammanfattning (in Swedish)

Denna rapport beskriver ett ramverk för att kunna utvärdera brandmotståndet (den lastbärande förmågan) hos konstruktioner när man inkluderar omfördelningen av värme under avsvalningsfasen. Vid vanlig brandmotståndsprovning utvärderas byggnadselement genom att utsättas för en kontinuerligt växande temperaturexponering enligt standardbrandkurvan. När sedan uppställda kriterier bryts får konstruktionen sitt brandmotstånd definierat i minuter. Vid denna sorts provning ingår igen avsvalningsfas. Det har visat sig att olika konstruktioner som har samma brandmotstånd enligt det standardiserade systemet kan ha mycket olika brandmotstånd om man inkluderar att elementet också ska kunna bära en last under en avsvalningsfas. När man utvärderar enligt det traditionella systemet missar man alltså att riktiga bränder har en avsvalningsfas vilket leder till en mindre robust design.

Projektrapporten innehåller en sammanställning av relevant litteratur inom området samt en diskussion och plan framåt för att introducera konceptet på en bredare front. Detta hoppas vi i förlängningen kan leda till framtagandet av en internationell standard inom området. Dock finns det inget om hindrar brandkonsulter att redan nu börjar använda konceptet för att jämföra hur robusta olika konstruktionslösningar är. Vidare ser vi också detta som ett koncept som kan användas vid diskussioner krig robust brandmotstånd inom räddningstjänsten och när myndigheter tar fram nya regelverk.

Sammanfattning av några punkter från rapporten:

- **Definition av ”Burnout resistance”**: En konstruktions burnout resistance, vilket i denna rapport kallas B, definieras som den längsta upphettningsfas i minuter som en konstruktion kan vidmakthålla sin lastbärande förmåga om den också måste uppfylla sin funktion under den efterföljande avsvalningsfasen. Inom detta koncept följer både upphettingsfasen och avsvalningsfasen definitionen som finns i Eurokoden för en brand som i upphettningsfasen liknar standardbranden. Detta koncept fungerar som ett komplement till brandmotståndsklassificeringen och används för att bedöma brandmotståndet hos ett element innan men vet var det ska användas. Vi tror inte att detta nya koncept med en ny B klass kan ersätta den nuvarande brandmotståndsklasserna, men det kan fungera som ett viktigt extra robusthetsmått för nyckelelement i konstruktioner. Införandet av detta koncept leder till säkrare konstruktioner ur ett räddningstjänstperspektiv och ur ett försäkringsperspektiv samt i förlängningen till en bättre avvägd nivå på brandskyddet vid dimensionering.
- **Kompletterande definitioner vid ungsprovning**: Vid experimentell bestämning av den nya klassen måste brandmotståndsstandarden kompletteras. Detta då brandmotståndsugnar nästan uteslutande används för upphettningsförlopp utan avsvalning. Tillåtna avvikelser under avsvalning måste då också definieras, både för individuella plattermoelement och tillåten avvikelse för arean under medeltemperaturen i ugnen. Rapporten innehåller förslag tillåtna nivåer på dessa avvikelser.
- **Avslutningskriterium**: Både vid experimentella studier och beräkningar för att ta fram B måste ett avslutningskriterium definieras. Vid genomförda experimentella studier har man sett att kollaps av element kan ske efter flera timmars avsvalning. Detta ska avvägas mot att metoden inte får vara för komplicerad för att kunna slå igenom på en bredare front. Här följer resonemang kring två olika vägar att hantera frågan:

  - **Avslutning efter en viss tid**: Ett tidsbaserat kriterium kan vara en förbestämd varaktighet av provet. Denna varaktighet kan vara ett konstant värde eller kopplat till hur lång upphettningsfasen är. Dock vet vi att olika konstruktioner är olika känsliga för kollaps i avsvalningsfasen vilket gör att ett tidskriterium inte nödvändigtvis fångar hela avsvalningsförloppet. Detta koncept bör utredas mer i detalj men det är inte vår prioriterade väg framåt.
  - **Avslutning vid en viss temperatur**: Alternativt kan avslutningskriteriet baseras på en temperatur i objektet som testas (eller beräknas). Då man provar konstruktioner med olika geometrier och material bör man ange ett kriterium både för yttemperaturen och temperaturen i centrum av tvärsnittet. T ex skulle ett kriterium kunna vara att temperaturen ska vara under 50°C på båda ställen. Detta är dock något som måste utredas mer i detalj eftersom låga temperaturer kan leda till mycket långa provningar och centrum av objektet kanske inte har nåtts av värmevågen.
- **Numeriska modeller:** I rapporten visas exempel på inledande studier av numeriska modeller för att teoretiskt beräkna konstruktionselements burnout resistance, B. Dessa studier ser lovande ut men mer insatser behövs kring materialmodeller, materialegenskaper och valideringsstudier.
- **Ramverk och hela byggnader:** Konceptet kan lyftas från elementnivå till hela ramverk eller byggnader där olika sorters tvångskrafter även utvecklas under avsvalningsförloppen. Detta skulle kunna vara utgångspunkten för mer detaljerade studier för att se hur hela system fungerar.

Preface

The present study has three main goals:

i) summarizing the studies performed using the DHP concept,
ii) review a broader literature on the effects of the cooling phase, and
iii) to specify a roadmap for future studies needed for developing our knowledge and introduce the DHP concept for a wider, more diverse audience.

The first and third objectives are particularly centred around consolidating the existing DHP studies into a singular publication, thereby enabling a more efficient and widespread dissemination of the underlying message.

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1 Introduction

1.1 Background

The standard fire resistance classification is a system for grading elements or structures based on the hypothesis that a higher fire resistance time will perform better in a real fire. In this standard classification system only the heating phase is evaluated, however, this approach does not provide a refined enough picture given that all real fires include a cooling phase during which heat is redistributed in the cross section of the structural element. Previous studies and experience from fires have shown that when including the cooling phase in the evaluation we see substantial differences regarding performance of common structural elements with similar standard fire resistance. An important conclusion from this is that the level of safety in real fire scenarios is very widespread despite the same fire resistance classification. The consequence is that some elements may have an unacceptable level of performance while other elements may be overdesigned. The Duration of Heating Phase (DHP) concept has been suggested as a method to include in a pragmatic manner the importance of the cooling phase of structural elements in fire safety engineering (Gernay and Franssen, 2015). This concept is a complementary measure to the standard fire resistance where elements are classified based on testing according to fire resistance standards. Introducing the complementary DHP concept provides an additional tool to be used for fire design of structures in support of the overall goal to provide consistent safety levels and avoid resource-inefficient designs.

Reports of structural collapses following fires have highlighted a critical concern. In 2004, a twelve-story RC building in Cairo collapsed after surviving a fire, resulting in 15 fatalities and 45 injuries (Mostafaei et al., 2004). Similarly, in Switzerland in 2004, an underground car park failed after a fire had been extinguished, causing the tragic death of seven rescue service members due to structural vulnerabilities (Hody, 2004) (Annerel et al., 2004). More recently, on June 19, 2022, a firefighter lost his life in Philadelphia when a three-story masonry building collapsed post-fire (CNN, 2022). These incidents underscore the necessity of comprehending structural behavior during the various fire phases.

It is also noteworthy that the general objectives of fire protection are to limit risks with respect to the individual and society, neighboring property, and where required, environment or directly exposed property, in the case of fire. Essential requirements for the limitation of fire risks are spelled out in building codes and standards such as the Eurocodes (“Eurocodes: Building the future”, 2022). The latter are based on the 1988 Construction Product Directive (“The Construction Products Regulations 1991”, 1991) requirements that “the construction works must be designed and built in such a way, that in the event of an outbreak of fire, (i) the load bearing resistance of the construction can be assumed for a specified period of time, (ii) the generation and spread of fire and smoke within the works are limited, (iii) the spread of fire to neighboring construction works is limited, (iv) the occupants can leave the works or can be rescued by other means, (v) the safety of the rescue service is taken into consideration”. In some buildings, firefighting and delayed evacuation may be necessary (depending on national regulations and fire strategies), requiring structural elements to remain stable beyond the fire's heating period.

Furthermore, evolving performance expectations for the built environment extend beyond the safety of occupants and first responders to encompass resilience. Society may in some situations demand structures that can remain intact and even be reoccupied following extreme events. Consequently, there is a need for methods to assess structures throughout the fire including stability until burnout and post-fire condition. The traditional fire resistance framework, reliant on standard time-temperature exposure, fails to address structural integrity during and after the fire's decay phases, rendering it inadequate.

In response to this need for better assessment methods, researchers started investigating the issue of structural stability during a fire's cooling phase. The aim was to develop understanding into the behavior of structural members during the decay and cooling phase of a fire until burnout, to develop methods for assessing loadbearing capacity throughout these different fire stages, and ultimately to design structures capable of withstanding fires until burn out.

The knowledge development regarding natural fires beyond the defined standard fire exposure used in fire resistance testing started with the fundamental studies by Kawagoe in the 1950s when he described the coupling between the burning rate of the fuel and the shape and size of the openings (Kawagoe, 1958). This knowledge was extended in the early 1960s to more advanced descriptions of room fires including the heat losses to the walls of the enclosure and out through the openings by radiation and convection (Ödeen, 1963). And in the late 1960s the present knowledge were used in calculations of the “Swedish fire curves” describing under ventilated fully developed fires dependent on the opening factor, thermal properties of the room and available fuel (Magnusson and Thelandersson, 1970). These curves (which initially were only drawings) were later parametrised to a set of equations by Wickström (Wickström, 1985) and adopted as the basis for the parametric temperature time curves in the Eurocode (EN 1991-1-2 (2002)). These parametric fire curves including a cooling phase are often used when describing fully developed fires in enclosures, even though the cooling phase is not directly coupled to the physics, it is based on the ISO 834:1975 fire resistance standard.

In 2011, Dimia et al. used numerical analysis to reveal that reinforced concrete columns could fail during the cooling phase of a fire due to delayed temperature increases in central zones (Dimia et al., 2011). Further numerical studies analyzed the vulnerability of concrete columns to failure during and after the cooling phase as a function of parameters including the fire duration, column slenderness and section size (Gernay and Dimia, 2013). Similar delayed failures were observed in prestressed concrete beams (Bamonte et al., 2018). In 2020, Wang et al. (2020) studied continuous RC slabs under fires with cooling phases, revealing increased reaction forces at supports due to thermally induced restraint forces. In 2022, Gernay et al. conducted tests on loaded RC columns subjected to controlled heating and cooling, showing failure in the decay phase that confirmed prior numerical analyses (Gernay et al., 2022).

The issue of structural stability until the end of a fire is especially pertinent for loadbearing timber structures, which have seen significant growth due to decarbonization policies. Timber elements pose an added risk during fire cooling due to permanent loss of mechanical properties at temperatures as low as 65°C (Dietenberger and Hasburgh, 2016). According to Eurocode 5 fire regulations (EN 1995-1-2, 2004), at 100°C, timber loses most of its compressive strength (75% loss) and modulus (65% loss). At 300°C, the mechanical strength and elastic modulus drop to zero. Under a standard fire, heat penetration beyond the charred depth is about 40 mm (Schmid et al., 2015), but in compartment fires, where duration and severity vary, this depth can be much greater. Recent research has shown delayed failures in cross-laminated timber (CLT) members, occurring up to 29 hours after a fire (Mindeguia et al., 2021). The experiments involved loaded CLT slabs subjected to natural fires, representing dwellings. Delayed failures of elements in high-rise buildings with exposed CLT may have severe consequences.

Wiesner et al. calculated the crushing capacity of glulam columns exposed to standard fires for 90 minutes (Wiesner et al., 2022). After cooling, the columns retained only 13% of their capacity, attributed to continued heat penetration. Another study tested load-bearing CLT walls exposed to heating from one side, observing some failures during forced cooling (Wiesner et al, 2019). The continuous loss of strength and stiffness from thermal and moisture penetration and loading eccentricities during heating contributed to these failures. Experimental tests in Japan on glued laminated timber beams (Kinjo et al., 2018) and columns (Hirashima et al, 2020) demonstrated gradual temperature increases in the cross-section after heating phases, leading to additional deflections and, in some cases, failure during cooling. In 2023, Gernay et al. tested two loaded glulam columns subjected to 15 min of ISO 834 heating followed by controlled cooling; the columns failed during the cooling phase, respectively after 98 and 153 minutes (Gernay et al., 2023).

Overall, these prior studies highlight the need for extensive research to understand structural stability during the fire decay phase and thereafter, as well as the development of appropriate design methods.

1.2 Introduction to studies on DHP

In 2015, a systematic method to measure structural members' ability to endure fire exposure until burnout was introduced by Gernay and Franssen (Gernay and Franssen, 2015). The method introduced an indicator, called DHP (for Duration of Heating Phase), to quantify a component vulnerability to delayed failure. More information on the concept and method is presented in Section 2. This new indicator carries additional and significant information compared with the standard fire resistance for classifying structural systems in terms of their fire performance and propensity to delayed failure. Gernay applied this method numerically to a dataset of 74 reinforced concrete columns, which revealed that columns failed during the cooling phase when exposed to standard fire for over 70% of their standard fire resistance time (Gernay, 2019). In 2021, a similar study was conducted on timber columns (Gernay, 2021). These numerical studies were complemented, and verified, by experimental tests on concrete columns at University of Liege (Gernay et al., 2022) and on timber columns at Braunschweig (Gernay et al., 2023).

Since its introduction in 2015, other researchers have adopted the concept of DHP to quantify the performance of structures until full burnout of a fire, including:

- Binh (Chu, T. B., & Truong, Q. V. (2018). Numerical studies of composite steel-concrete columns under fire conditions including cooling phase. In Proceedings of the 4th Congrès International de Géotechnique-Ouvrages-Structures: CIGOS 2017, 26-27 October, Ho Chi Minh City, Vietnam 4 (pp. 213-223). Springer Singapore.)
- Truong (Truong, Q. V., Pham, T. H., & Chu, T. B. (2018). Failure of building structural members during the cooling phase of a fire. In Proceedings of the International Conference on Advances in Computational Mechanics 2017: ACOME 2017, 2 to 4 August 2017, Phu Quoc Island, Vietnam (pp. 65-77). Springer Singapore.)
- Thienpont (Thienpont, T., Van Coile, R., Caspeele, R., & De Corte, W. (2019). Comparison of fire resistance and burnout resistance of simply supported reinforced concrete slabs exposed to parametric fires. In 3rd International Conference on Structural Safety under Fire and Blast Loading.)
- Thienpont (Thienpont, T., Van Coile, R., Caspeele, R., & De Corte, W. (2021). Burnout resistance of concrete slabs: Probabilistic assessment and global resistance factor calibration. Fire Safety Journal, 119, 103242.)
- Molkens (Molkens, T. (2022). The cooling phase, a key factor in the post-fire performance of RC columns. Fire Safety Journal, 128, 103535.)

- Hebbar (Amar Hebbar, V. P., Sachin, V., & Suresh, N. (2022, August). Analytical Studies on the Fire Resistance of Reinforced Concrete Beams Exposed to Parametric Time–Temperature Curve. In International Conference on Trends and Recent Advances in Civil Engineering (pp. 309-323). Singapore: Springer Nature Singapore.)

This method has also been incorporated in the *fib* bulletin 108 from the International Federation for Structural Concrete on Performance-Based Fire Design of Concrete Structures (fib, 2023).

2 Previous studies

2.1 Concept

2.1.1 Effects of cooling on structural fire response

Fire resistance refers to the ability of an element or a structure to withstand a fire exposure without compromising the structural integrity. Most common criteria/classes used for assessing the fire resistance is the loadbearing capacity R, integrity E and thermal insulation I. This system is mainly based on results from standardized fire resistance tests where single elements are exposed to the standard time-temperature curve created in a special purpose furnace. When assessing these classes, the basic principle is to fire up the furnace and follow the continuous growing standard fire curve until one or several of the criteria, R, E or I is broken. An example is that if a single surface thermocouple on the cold side of a fire exposed wall rises in temperature more than 180°C then the wall is no longer fulfilling the insulation criteria and the element will be classified to the nearest standard time before this event, i.e., 30, 60, 90 minutes etc. This type of testing and classification of building elements is based on a growing thermal exposure and no cooling phase is included in the assessment. Although this single thermal exposure scenario that the standard time-temperature fire curve represents is not representative of all possible real fires, the use of the standard fire exposure allows for fire resistance rating of building elements independent of their final use in a building (McNamee, 2022). So, fire resistance base on standardized testing is a grading of elements or structures based on the hypothesis that a higher fire resistance time will perform better in a real fire. But what about real fires since these always include a cooling phase? This is not covered by the present fire resistance concept.

Fully developed natural fires can in a simplistic way be represented by the parametric fires defined in the Eurocode. In this representation the temperature development depends on the fuel content, opening factor and the thermal properties of the surrounding enclosure. In figure 1 the temperature development of a parametric fire exposure including the decay phase is shown. The figure also includes the delayed temperature development inside a reinforced concrete column. The consequence of the delayed heat penetration, which will depend on parameters such as the loading applied on the column, is shown in figure 2 showing the deflection and collapse scenarios during the cooling phase.

Beyond this delayed temperature increase in the section, other important phenomena may take place during the cooling phase. The properties of materials keep changing, and in some cases (e.g., concrete) the strength reduces even further during cooling compared to the value at the maximum reached temperature. Changes in thermal gradients and reversal in thermal strains may generate stresses in the members. Combustible materials (e.g., timber) may experience continued combustion or smouldering. As these many effects of cooling on the structural response are significant, complex, and vary between members and materials, a framework is needed to systematically capture them.

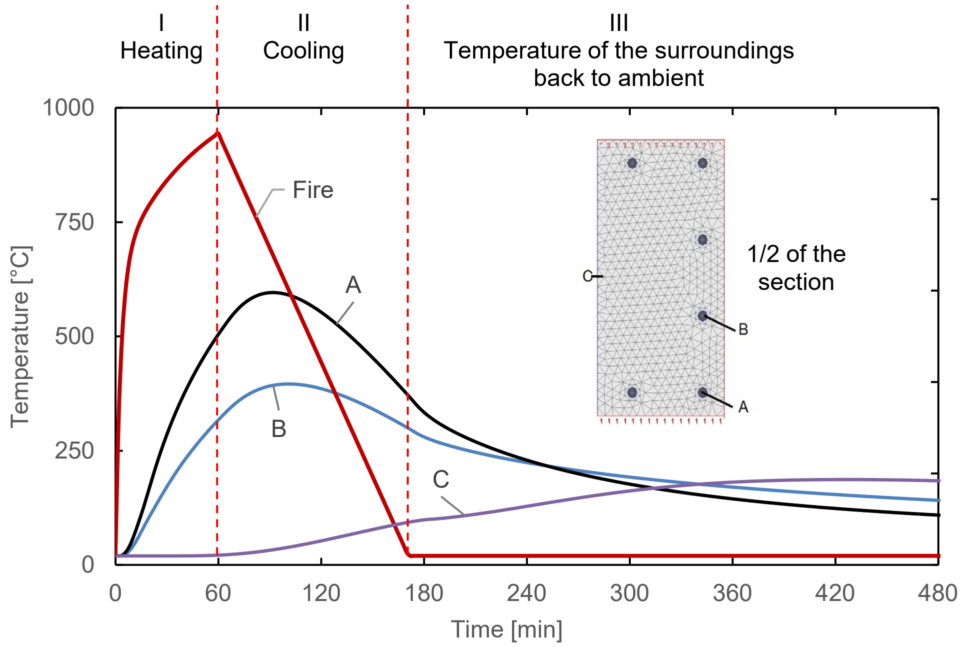

Fig 1. Evolution of temperature in the section of a reinforced concrete column exposed to a 60-minutes heating phase natural fire (Gernay and Franssen, 2015).

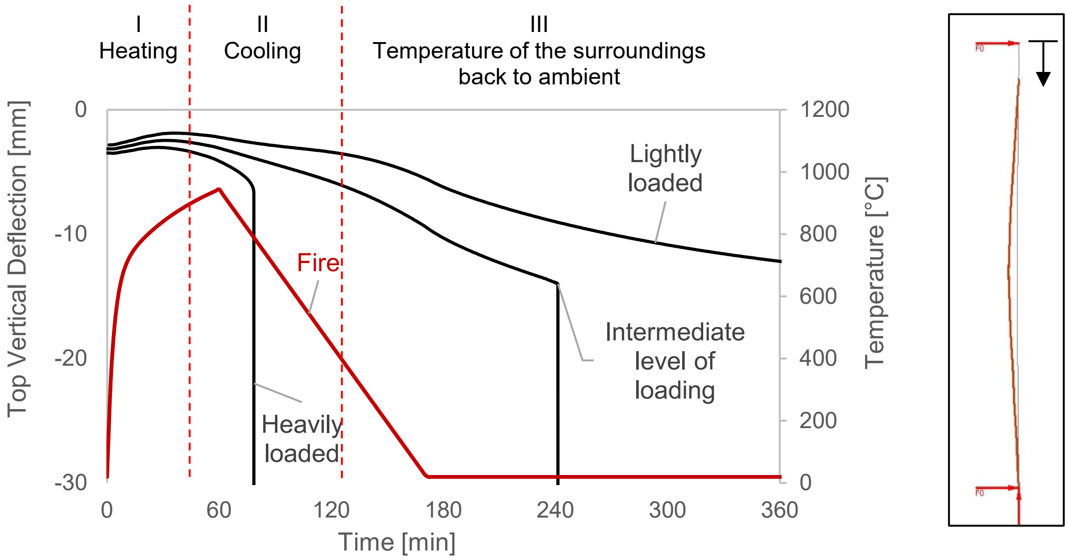

Fig 2. Time evolution of top vertical displacement for a reinforced concrete column exposed to a 60-minutes heating phase natural fire, for different levels of applied compressive load (Gernay and Franssen, 2015).

2.1.2 Duration of Heating Phase (DHP) indicator

The fundamental concept underpinning the proposed indicator is the characterization of the fire performance of a structural member with a characteristic time of a natural fire. This approach parallels the principle of fire resistance rating (R), which characterizes the performance through the duration of exposure to a standard fire until structural failure occurs. In the context of a natural fire, this characteristic duration is defined as the duration of the heating phase (DHP).

As with the standard fire resistance rating 'R', this indicator 'DHP' requires defining a standardized fire exposure. It also depends on the applied load ratio. Hence, for any given structural component under specific loads and boundary conditions, it is possible to establish the shortest natural fire duration that will eventually lead to its failure. This presupposes the adoption of a set of 'standardized natural fires,' allowing for a ranking of fires by severity.

One practical choice for standardized natural fires is the use of Eurocode parametric fires, wherein the parameter Γ is set to 1. When Γ is set to 1, the heating phase of the parametric fire closely approximates the ISO 834/EN 1363 standard temperature-time curve, offering a clear definition of the fire event in terms of a single variable, the duration of the heating phase (DHP, measured in minutes). These curves closely follow the ISO 834 (or nearly equivalent ASTM E119) curve for the heating phase, followed by a linear cooling phase. This alignment allows for the comparison between DHP and the standard fire resistance (R) of a member under the same loading conditions, providing insights into the impact of the cooling phase on the member's stability. Notably, as the loadbearing capacity of a concrete member continues to diminish after the peak gas temperature, the DHP is always shorter than R.

In essence, the DHP serves as a metric to quantify the longest heating duration according to the standard fire for which a structural member will <u>not fail</u> throughout the entire fire event, including the decay phase. It categorizes fires into those where the member remains standing (heating phase shorter than DHP) and those where the member fails (heating phase longer than DHP). Accordingly, a component's burnout resistance, B, is defined as the DHP of the longest 'standardized natural fire' it can withstand, see figure 3.

The burnout resistance B, akin to fire resistance, is a standardized rating. It should be viewed not as an exact time measurement but as a qualitative index for comparing the performance of various structural components in real fire scenarios. This rating correlates with a component's ability to endure a fire until complete burnout, effectively categorizing the time domain between fires that can be survived until burnout and those that generate such heat and damage that eventual collapse is inevitable.

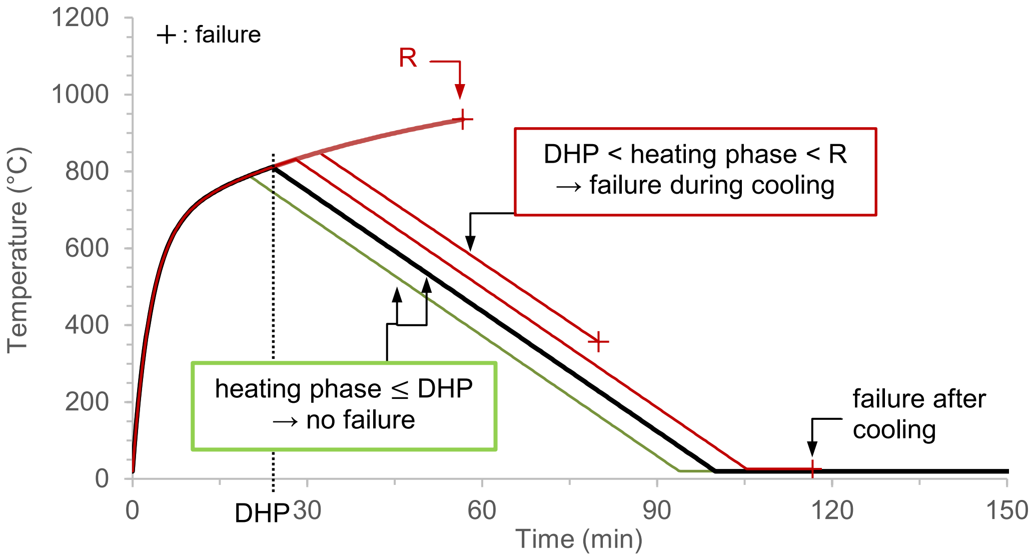

Fig. 3 Conceptual definition of the DHP indicator (burnout resistance B) and set of time-temperature curves based on the Eurocode parametric fire model (Gernay et al., 2022).

Characterizing a structural member using the pair of indicators, B (Burnout resistance) and R (Fire Resistance), holds significant practical implications, particularly for firefighting operations. At the practical level, this combination of indicators enables the conceptual division of the post-flashover time domain into three distinct phases for a structure during a fire event (at least when the temperature evolution in the post-flashover phase aligns with the standardized fire). For illustration figure 4 plots the indicators for a structural member with a B of 42 minutes and an R of 60 minutes.

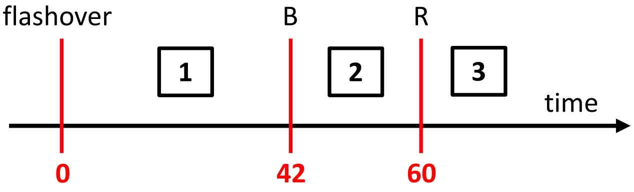

Fig. 4 On a timeline representing the post-flashover time of heating, the B marks the point of no return, from which the structure has been affected to such an extent that it will fail even if the fire stops thereafter.

In the described context the time domain can be interpreted as follows:

(1) First Phase: This initial phase commences at flashover and continues until reaching the time corresponding to DHP (B). During this period, the structure is theoretically safe. It possesses the capacity to withstand the fire's effects, and should the thermal exposure begin to decrease within this phase, the structure could potentially endure indefinitely.

(2) Second Phase: The second phase extends from the time corresponding to DHP (B) to R. In this part, the structure is still standing even if the thermal exposure has been continuously increasing from the flashover. However, if the fire is still in its heating phase at that time, the structural integrity has been compromised to a degree where even if the fire were to enter the cooling phase shortly thereafter, structural failure becomes inevitable.

(3) The third part of the time domain starts at the time corresponding to R. In this part, if the thermal exposure has not started decrease yet, the structure is theoretically collapsed.

This discussion highlights the major significance of the DHP and the equal burnout resistance B: it marks a point of no return for the structure. If, at the time of DHP, the thermal exposure has not commenced a cooling phase, it is expected that the structure will inevitably collapse.

As is the case of the standard fire resistance, the DHP rating is intimately associated with the choice of the fire curve (including the cooling branch). With a natural fire different from the Eurocode parametric fire, the value of the DHP would change – as the value of R only hold with the ISO 834 time-temperature curve. However, the concepts remain valid regardless of the choice of the natural fire.

It must be noted that, in many situations, the engineer must evaluate the fire performance of a member before knowing its final use in a specific compartment geometry with a defined fire load. In these situations, standardized indicators such as R and B are particularly useful (figure 5). Of course, these indicators are not meant to replace a performance-based analysis that can be completed once the final use of a member or structural assembly is determined. Nevertheless, these indicators have their role and usefulness to characterize the standardized performance and compare and rate structural members.

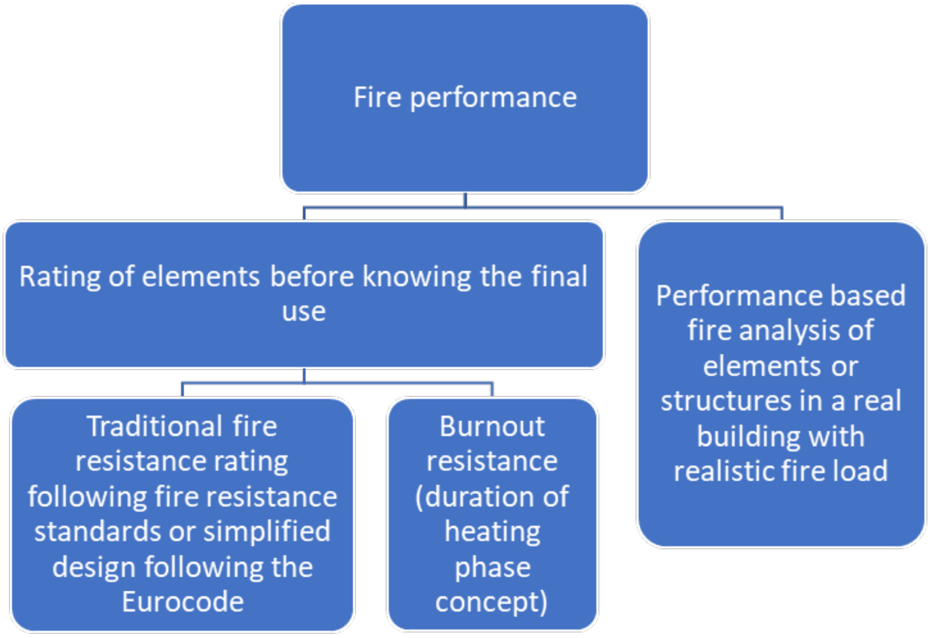

Fig 5. Different ways of evaluating the fire performance/resistance of a structure.

Determining the Burnout resistance (B) connected with the DHP (Duration of Heating Phase) concept for a component involves an iterative procedure. Temperature-time curves of increasing heating phase durations are applied until failure is observed. Each calculation or test must run sufficiently long to ensure temperatures return to ambient levels inside the sections and that no further failure is imminent. The length of evaluation will be further discussed in a later chapter.

This iterative process can be done experimentally or numerically. In the numerical case the process can be automatized through a simple script and a finite element model (figure 6). It then involves multiple thermo-mechanical simulations for a given component.

Figure 6 serves as a simplified flowchart for determining the Burnout Resistance (B) in relation to natural fires defined by their DHP. Note that this flowchart can be optimized for practical applications. For instance, initialization can start with a much higher value of DHP instead of starting from 0(e.g., starting with DHP = 60 minutes instead of DHP = 0). If the member fails, DHP is decreased by t_step, and the process continues until a value of DHP is identified where failure no longer occurs. The largest tmax value that results in the structure surviving represents the B.

The parameter t_step influences the accuracy of the burnout resistance determination. A larger t_step reduces the number of iterations but compromises B accuracy. It should ideally remain within a few percent of the B value to maintain precision if using numerical calculations. Note that the fire resistance R should also be determined for the same member under the same loading conditions; this requires a single calculation.

Note that, in a regulatory context, the important requirement may be to demonstrate that a member meets the minimum required burnout resistance. In this context, a single evaluation is sufficient. For example, if a member needs to have a burnout resistance of 30 min, it suffices to test that member under the fire with duration of heating phase of 30 min, and if the member maintains its function until full burnout, the test is passed, and the member obtains the required rating. No iteration is needed in this context.

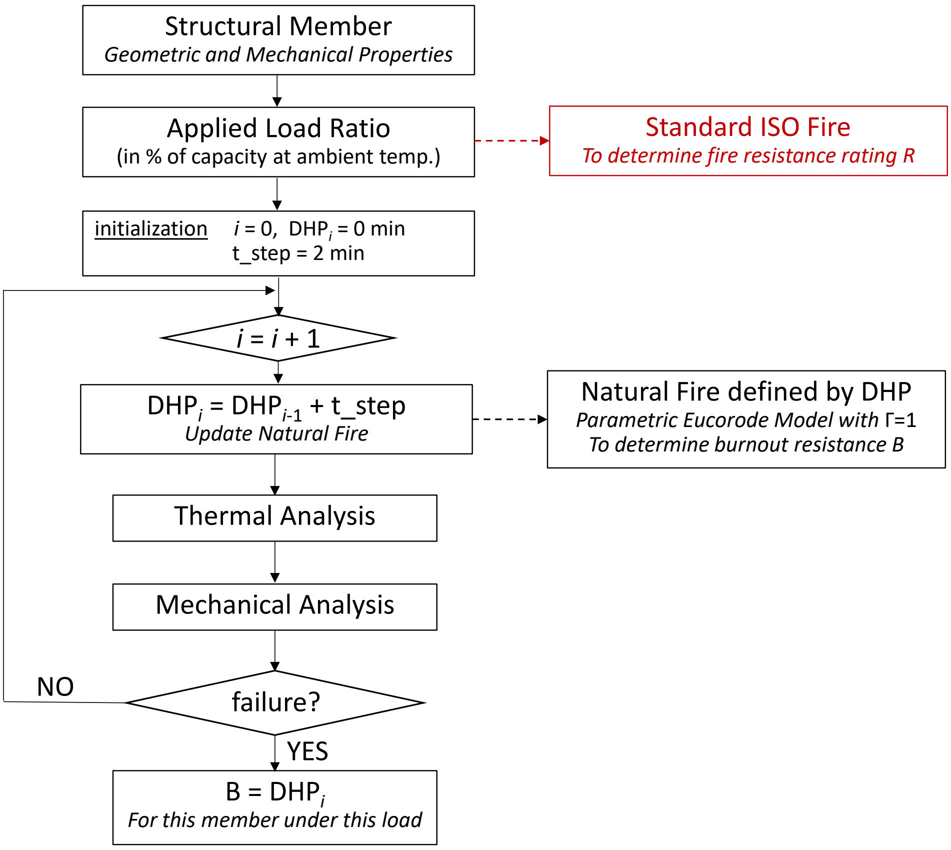

Fig 6. Algorithm to find the DHP through iterative calculations.

Truongh et al. used a very similar approach with the same type of calculations as when determine the DHP but they focused on the delayed failure time "DelayT" being the time at failure minus the time of the heating phase (Truong et al., 2017).

2.1.3 Qualification by testing and/or calculations

The determination of the DHP and the Burnout resistance, B, can also be performed experimentally. For a given structural member under a given applied loading, two situations must be distinguished:

- **(i)** **Verification of a minimum required burnout resistance**. For example, a regulation requires the vertical load-bearing members to have a minimum required B, based on the criticality of the building and other considerations (evacuation, fire service intervention, consequences of collapse, spread to adjacent structures, etc.). A single experimental test is therefore sufficient to verify whether the member design meets this requirement. The experiment consists in subjecting the loaded member to the furnace temperature-time curve with the DHP corresponding to this minimum burnout resistance followed by the prescribed cooling.
- **(ii)** **Evaluation of the precise burnout resistance value**. Several tests are required to identify the precise value of the Burnout resistance. Indeed, the member must be subjected to fires with varying durations of heating phase until finding the longest one that can be survived until full burnout. This entails at least one experiment that survived burnout and one that results in failure, with only a small difference in the durations of heating phase of these experiments. Therefore, in practice, this would typically require at least 3 or 4 experiments, in order to reasonably bound the limit value.

The proof of concept to determine the burnout resistance value in furnace tests has been successfully demonstrated on reinforced concrete columns (Gernay et al., 2022) and glulam timber columns (Gernay et al., 2023). In the two studies, published in 2022-2023, full scale columns were tested in standard furnaces according to the DHP procedure. These experiments showed that the procedure can be applied experimentally on loadbearing structural members. Specifically, the studies showed that:

(i) it is possible in a standard furnace to control the thermal exposure in the furnace to closely follow the standard ISO 834 curve until a certain time followed by a linear cooling according to the parametric fire. That was achieved with great accuracy, except once the temperature in the furnace decreased below 150 °C, at which point the cooling started being more gradual than the intended linear decrease.

(ii) the tested structural members (RC column and timber column) did indeed experience failure during the cooling phase for certain time-temperature exposures, while the applied load was maintained constant.

Additional descriptions of the experiments will be provided in the respective material chapters. Additional discussions on qualification of burnout resistance by testing will be provided in the discussion chapters.

2.2 Concrete members

2.2.1 Physical behavior

Ordinary concrete has a high density and relatively low thermal conductivity resulting in a slow spread of heat from the fire exposed surface layers inwards in cross sections. At elevated temperatures the thermal conductivity of concrete decreases due to loss of moisture and increasing porosity (primarily caused by dehydration and crack growth). During cooling the thermal conductivity remains more or less constant at the lowest value obtained during heating. The variation with temperature, and its stability during cooling, have been documented in thermal conductivity measurements (Ödeen and Nordström,1971) (Jansson, 2004). Thermal conductivity is defined as the rate of heat flow through a unit thickness of a cross section during a unit temperature difference. During fire exposure of concrete moisture migration will influence the apparent thermal conductivity (“apparent” thermal conductivity includes moisture flow and other phenomena). Consequently, thermal conductivity curves, such as those found in Eurocode 2, are calculated in reverse from fire tests through a fitting procedure that takes into account moisture migration and other influences. This approach serves as a fundamental basis for thermal calculations related to heat transfer in concrete. However, for more precise calculations, it's essential to know the specific thermal conductivity of the concrete mix (Flynn, 1998). Several factors influence thermal conductivity (McNamee et al., 2019):

- Type of aggregate
- Aggregate volume
- Water cement ratio of cement paste
- Moisture content

In the reverse calculation approach used in developing the Eurocode, the specific heat of concrete is defined by a function that incorporates a peak between 100 and 200°C. This peak accounts for the latent heat of vaporization of water, a crucial consideration when assessing concrete's behavior under varying temperatures.

In engineering a common way of modelling concrete behaviour at high temperatures is to rely on the mechanical models described in the fire part of Eurocode 2. In the Eurocode the stress strain relationship at high temperatures implicitly includes transient state strain[1] effects. The type of function adopted for describing the stress strain follows the idea of Popovics who developed the function for room temperature (Popovics, 1998) high temperature behaviour (RILEM 44 PHT, 1985) previous studies by Schneider and Haksever facilitating simple calculations (Schneider and Haksever, 1976). According to the RILEM committee the model had been used with success in fire investigations but was not suitable for more complex calculations. For more complex calculations the committee recommended using explicit calculation of transient state strain effects according to the methods by Schneider or Anderberg/Thelandersson. The most obvious limitation in the simplified stress strain model in the Eurocode is the fact that the model is reversible even though transient state strain effects are not reversible.

During some circumstances concrete can spall during fire exposure, i.e., parts of the cross section of a structural member flake away in a violent manner (Jansson, 2013). Our knowledge of parameters influencing the occurrence of spalling is based on empirical observations and there is no validated advanced theoretical calculation model for predicting spalling (Jansson McNamee and Boström, 2015) (McNamee, 2019). This is a parameter that is included in the standardized fire resistance evaluation, but theoretical calculations of the fire resistance often assume no spalling.

2.2.2 Numerical

In 2019, Gernay conducted a study on the burnout resistance of reinforced concrete columns (Gernay, 2019). The study adopted the DHP concept to quantify the performance of RC columns under fires with a cooling phase. This was a numerical study, conducted with the nonlinear finite element software SAFIR. A dataset of 74 fire resistance tests on RC columns was compiled. Numerical modeling was applied first to reproduce the standard tests. The obtained ratio between the computed and experimental fire resistance had an average value of 0.95 with a standard deviation of 0.29. Then, the numerical models were used to evaluate the DHP of the 74 columns. The relationship between R and DHP was found to be approximately linear, see figure 7a. Based on this work, an equation was proposed to estimate the DHP of reinforced concrete columns directly from their standard fire resistance:

$$DHP = 0.72 \times R - 3.0 \quad \text{(in min)} \qquad \text{Eq. 1}$$

The work was extended in a 2023 study by Gernay et al. (Gernay et al., 2023b). In the latter, the cooling rate of the gas temperature was varied. In other words, the study assessed the effect of a different time-temperature cooling rate on the DHP. The natural fires used were still following the ISO 834 curve in the heating phase, but the (linear) cooling phase had various rates of cooling, varying from 2 °C/min to 20 °C/min. The results, shown in figure 7b, showed that the DHP decreases with decreasing values of the cooling rate (i.e., with slower cooling). In other words, faster cooling rates reduce the likelihood of failure in cooling.

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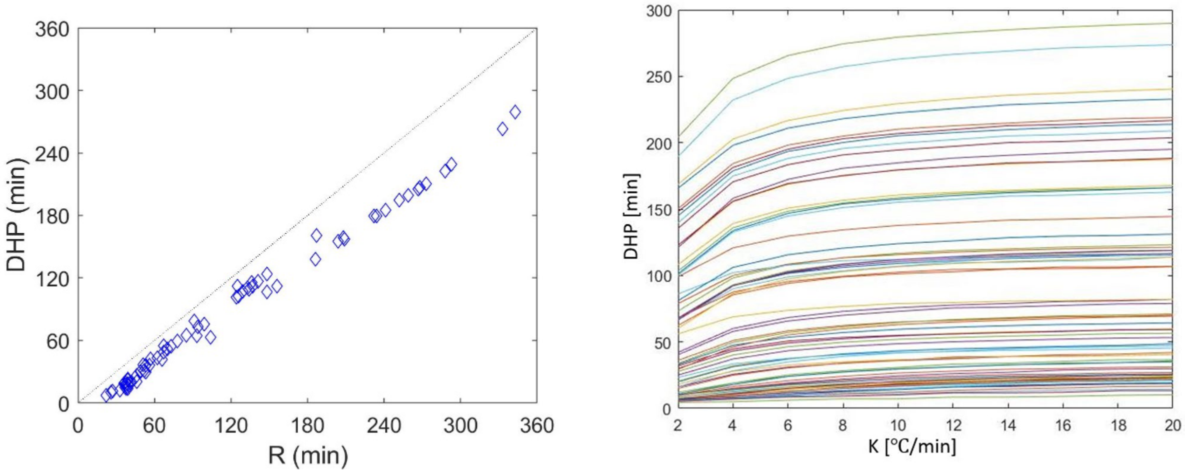
[1] Transient state strain is an experimental determined strain component in the opposite direction of thermal expansion during heating of concrete under compressive load.



(a) (b)

Fig 7a-b. Results from a numerical study on the DHP of 74 reinforced concrete columns. (a) Relationship between R and DHP using the cooling rate from EN1991-1-2 (Gernay, 2019). (b) DHP as a function of cooling rate K (Gernay et al., 2023b).

Other researchers have studied numerically the behavior of loaded reinforced concrete members during the heating and cooling phases of a fire. This includes work by Bamonte et al. on prestressed concrete beams (Bamonte et al., 2018), work by Thienpont et al. on concrete slabs (Thienpont et al., 2021), and work by Hua et al. on tunnel slabs (Hua et al., 2022).

2.2.3 Experimental

In 2022, a set of experiments were conducted to evaluate experimentally the DHP of reinforced concrete columns (Gernay et al., 2022). The experiments were conducted in the Fire Testing Laboratory at the University of Liege. Figure 8 shows one of the columns at the end of the test.

Fig 8. One RC column in the furnace after the test.

Four experiments were conducted. They were all on identical specimens. The difference was the fire exposure, see figure 9a. Test 1 was subjected to the ISO fire until failure. Test 2, 3, and 4 were subjected to the ISO fire for respectively 45, 55, and 72 minutes, followed by a linear cooling phase.

The columns were 3000 mm long with a section of 300 x 300 mm². The specimens were loaded at 1009 kN. This represented 56 % of the design load bearing capacity at ambient temperature (1815 kN) calculated according to Eurocode EN1992-1-1. The columns were designed for a standard fire resistance of 60 minutes.

The results showed that the standard fire resistance of the column was 83 minutes (Test 1), but the same column failed during the cooling phase when the burners were shut off after 72 minutes while the load was maintained (Test 4). The two other specimens survived exposure to heating of 45 and 55 minutes, respectively. Their residual capacity was measured to quantify the reduction in capacity due to the fire exposure, see Table 1. So the DHP or Burnout resistance in this case was between 55 minutes and 72 minutes (and, if the requirement was to prove a minimum required B, it can be stated that the Burnout resistance is at least 55 minutes).

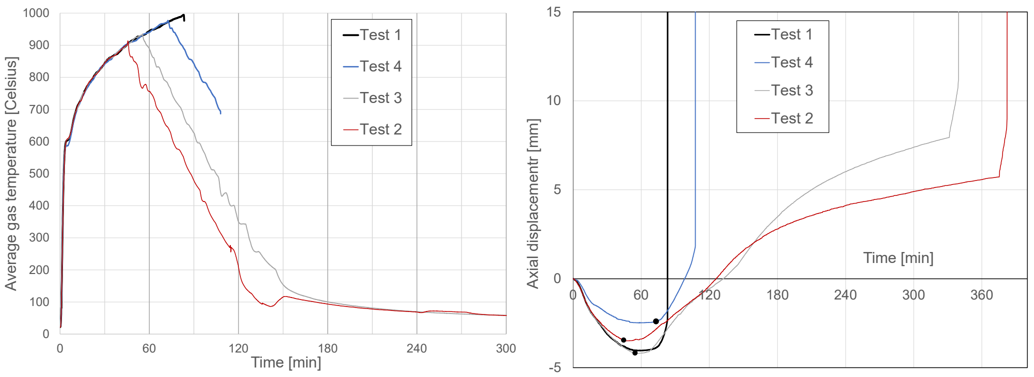


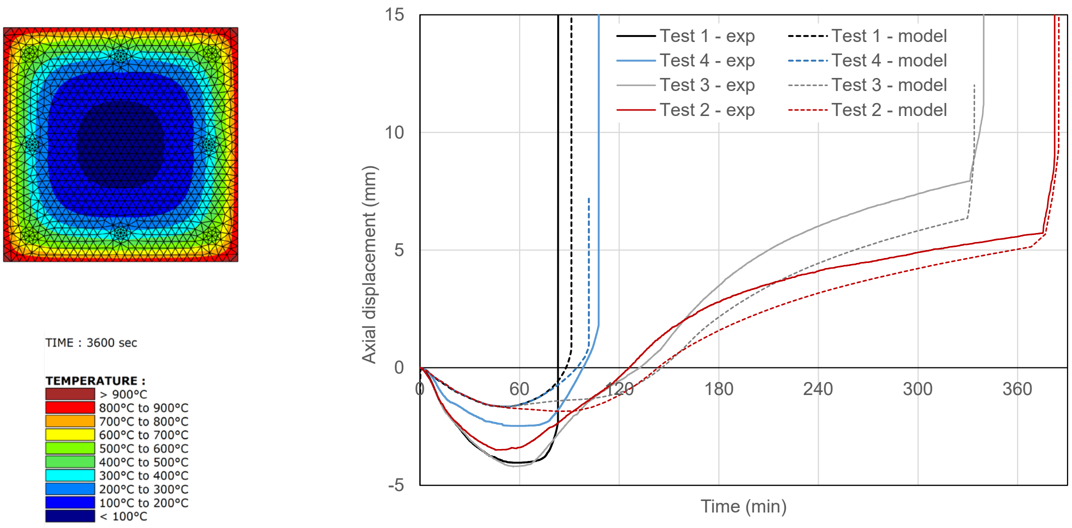
Fig 9. (a) Evolution of the temperature in the furnace. (b) Evolution of the axial displacement of the columns over the whole test duration. Tests 2 and 3 are loaded to failure after the end of the heating-cooling sequence. Negative values correspond to elongation.

Table 1 Results of the tests

Test	Time of collapse in the heating phase	Start of the cooling phase	Time of collapse in the cooling phase	Failure load after cooling[(*)]
	Minutes	Minutes	Minutes	kN
1	83	-	-	-
2	-	45	-	1527
3	-	55	-	1497
4	-	73	108	-

(*)Cooling was not yet exactly down to ambient

Numerical analyses of the experiments using SAFIR show agreement with the tests, see figure 10. Specifically, the model predicted a failure during the cooling phase for Test 4, and survival until burnout for Tests 2 and 3. This shows the applicability of numerical methods for evaluating burnout resistance of concrete columns.



(a) (b)

Fig 10. Finite element model of the concrete column tests. (a) Mesh for the thermal analysis of the cross-section, shown here for Test 1 with temperature distribution at 60 min. (b) Comparison between experimental and numerical values for the evolution of the axial displacement. Negative values correspond to elongation.

2.3 Timber members

2.3.1 Physical behavior

The Eurocode EN1995-1-2 provides relationships for the temperature-dependent reduction of mechanical properties of timber (EN 1995-1-2, 2004).

Recently, a study collected experimental data published in the literature on properties at elevated temperatures (Garcia-Castillo et al., 2023). These data are plotted in figure 11 for compressive strength parallel to grain and in figure 12 for tensile strength parallel to grain. The Eurocode relationships are also plotted for comparison. It can be seen that the data exhibit a significant scatter, and that the Eurocode relationships correspond to a low percentile of the experimental data (in other words, the Eurocode is conservative when compared to the average elevated temperature strength of timber).

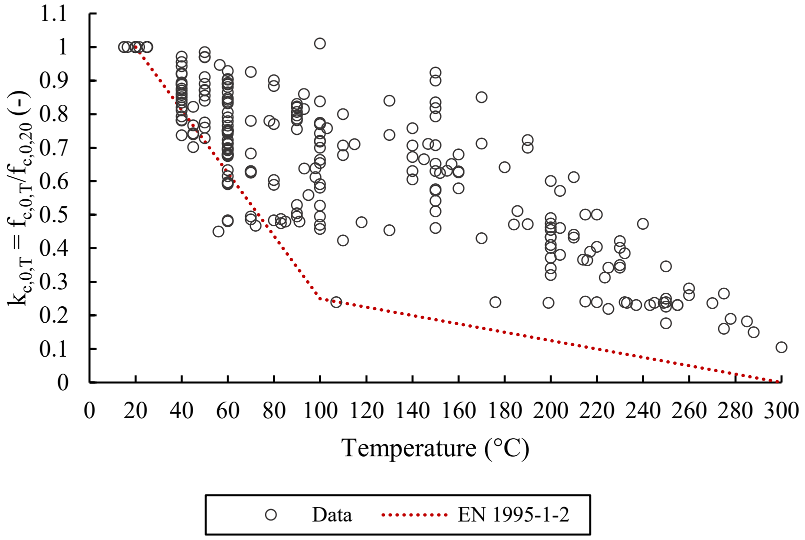


Fig 11. Reduction factor data points for timber compressive strength parallel to grain ($k_{c,0,T}$)(Garcia-Castillo et al., 2023) .

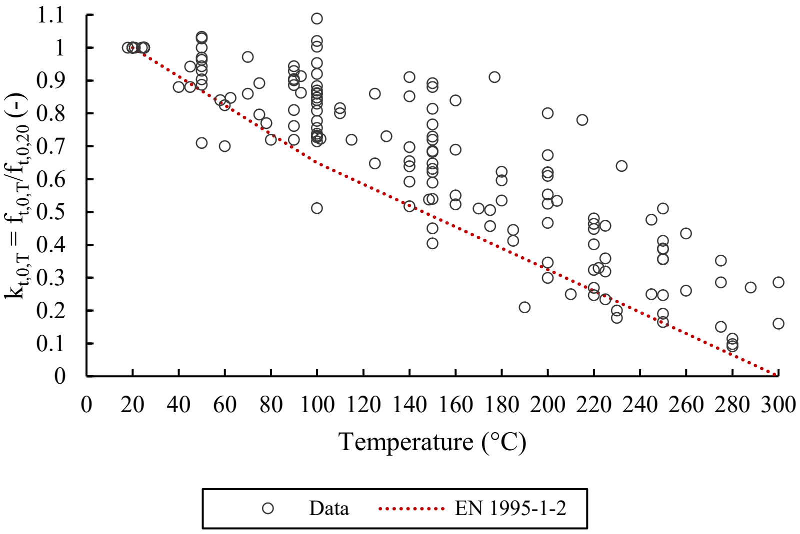


Fig 12. Reduction factor data points for timber tensile strength parallel to grain ($k_{t,0,T}$) (Garcia-Castillo et al., 2023) .

2.3.2 Numerical

In 2021, Gernay conducted a study on the burnout resistance of timber columns (Gernay, 2021). The study followed the same methodology as the 2019 study on RC columns, but applied to glued laminated (glulam) timber columns. It adopted the DHP concept to quantify the performance of timber columns under fires with a cooling phase. This was a numerical study, conducted with the nonlinear finite element software SAFIR. A dataset of 49 fire resistance tests on timber columns, tested in Germany in the 1970s and reported by Stanke et al., was considered.

Numerical modeling was applied first to reproduce the standard tests. The test database showed fire resistance times ranging from 21 min to 114 min for the tested columns. The fire resistance calculated with SAFIR ranges between 15 min and 103 min. The numerical model tended to be conservative with a ratio between the computed and experimental fire resistance of an average value of 0.84 and standard deviation of 0.14. It was noted in the study that the mechanics-based method from the AWC TR (American Wood Council 2015) yielded the same average value of the ratio (0.84) but a larger standard deviation (0.18). Lie's method, which assumed a slower charring rate and was partly based on empirical fit, yielded a better agreement with the test data set than the numerical model, with an average of 0.93 and standard deviation of 0.13. Numerical modeling with strength reduction factors higher than those from Eurocode (see data in Figure 11-12) would also be expected to improve the agreement since it would increase the average of the computed fire resistance. However, the study was conducted using the generic available models (i.e., Eurocode 1995-1-2).

Then, the numerical models were used to evaluate the DHP of the 49 timber columns. The DHP was found to vary between approximately 0.20 and 0.50 times the standard fire resistance R, see figure 13. For 26 of the 49 columns, the DHP was shorter than 10 min. This low value of the DHP, relative to the fire resistance R, was explained by the combined effect of delayed heating and loss of mechanical properties at relatively low temperatures. Indeed, heat transfer analyses showed that the heat wave continues penetrating the section for hours after the end of the fire, even under a relatively short exposure to the ISO fire followed by a linear cooling at a rate of 10 °C/min, see figure 14. Furthermore, the mechanical properties of timber are already reduced at temperatures of 50-100 °C (see figure 15). This combined effect results in a significant loss of loadbearing capacity with a delayed effect after exposure to fire, and hence to a relatively low DHP.

Based on this work, a set of equations was proposed to estimate the DHP of timber columns directly from their standard fire resistance, see Eq. 2-3. In these equations, LR is the load ratio (i.e., ratio of the applied load in the fire situation to the ultimate capacity at ambient temperature), between 0.1 and 0.4 based on the studied data.

$$DHP = \left[0.48 - 0.25 \times \frac{LR-0.1}{0.14}\right] \times R \qquad 0.10 < LR < 0.24 \qquad \text{(in min)} \qquad \text{Eq. 2}$$

$$DHP = 0.23 \times R \qquad 0.24 < LR < 0.40 \qquad \text{(in min)} \qquad \text{Eq. 3}$$

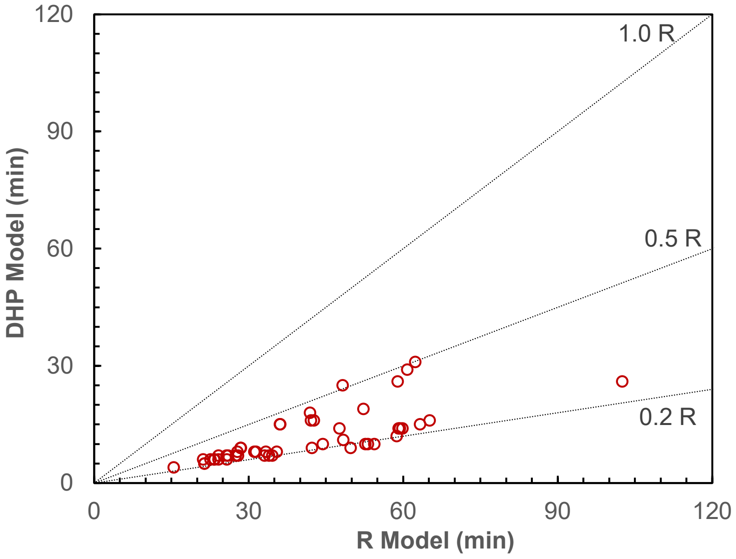


Fig 13. Relationship between DHP, i.e. an indicator of 'burnout resistance' under natural fire, and R, i.e. the fire resistance under standard fire, for 49 timber columns (Gernay, 2021)

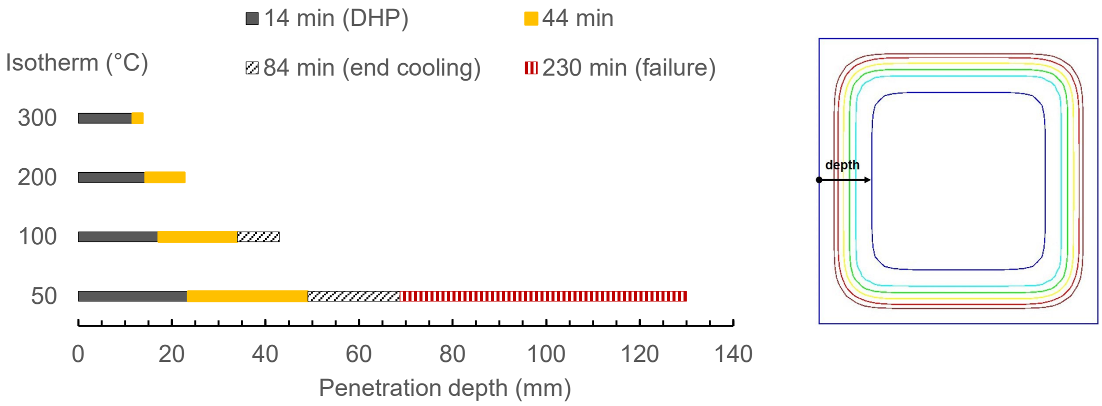


Fig 14 . Penetration depth of the 50 °C, 100 °C, 200 °C and 300 °C isotherms in the cross-section of the H26A timber column under the natural fire with a 14 min duration of heating phase (DHP), as obtained by finite element analysis.

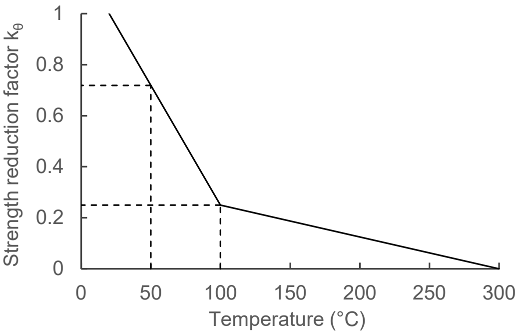


Figure 15. Reduction factor for compression strength of timber (EN 1995-1-2 (2004)).

2.3.3 Experimental

An experimental program was conducted at Braunschweig in 2022 to evaluate experimentally the DHP of glulam timber columns (Gernay et al, 2023). The timber columns were tested in a standard furnace. Figure 16 shows two of the glulam columns at the end of the test.

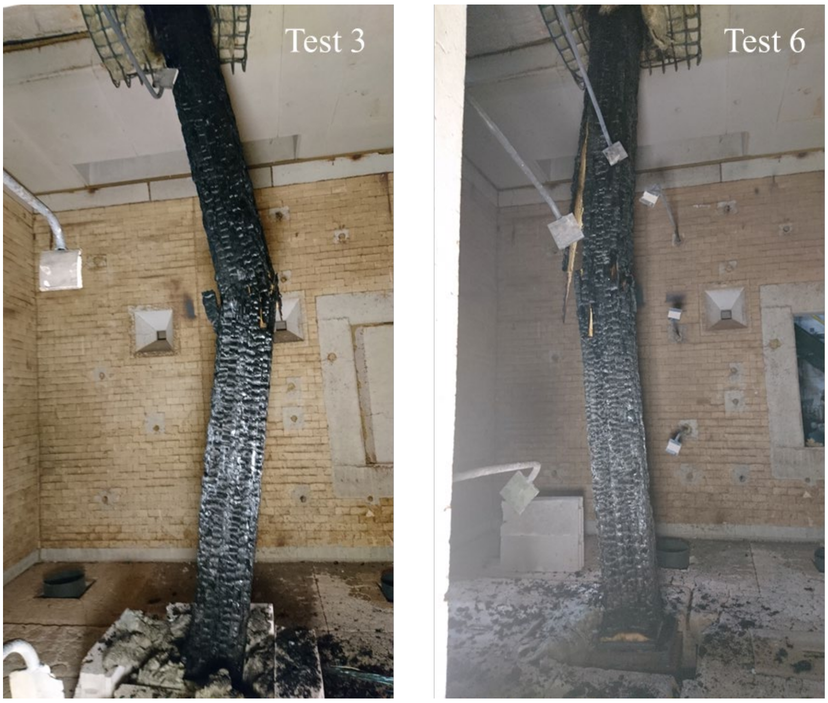


Fig 16. Two timber column specimens in the furnace after failure (Gernay et al., 2023)

A total of eight columns were tested in the program. The objective was to measure their burnout resistance. The columns had identical dimensions: 280 by 280 mm² cross-section and 3.7 m length. The first column was hinged-fixed, all the other columns were hinged-hinged. The difference between the tests was the fire exposure, specifically the heating durations. The columns were subjected to applied loading of 322 kN. The design and applied load in the fire situation were defined to achieve a standard fire resistance of 60 minutes according to the Eurocode fire design rules draft (prEN 1992-1-2 with d_0=14 mm).

Two of the columns were subjected to a standard fire resistance test (i.e., ISO 834 heating until failure). Their measured fire resistance was 55 and 58 minutes, respectively.

Two identical columns were subjected to 15 minutes of ISO 834 heating followed by controlled cooling according to the DHP procedure. Both of these columns failed during the cooling phase. They failed after 98 and 153 minutes, respectively. It is noteworthy that this time of failure is significantly after flame self-extinction, which was observed after approximately 40 minutes. Some smoldering continued locally. At the time of failure of the columns, the furnace temperature was lower than 120 °C. Results for these two specimens (Test 3 and Test 6) are plotted in figure 18 and 19.

Another two identical columns were tested under 10 minutes of ISO 834 heating followed by control cooling. These two columns both survived the defined heating-cooling exposure. Thermocouples inside the columns show sustained temperature increase for hours after the end of the heating phase. At the end of the tests, the load on these columns was increased to failure, to measure their post-fire residual loadbearing capacity. Results are given in Table 2.

From these experiments, it can be determined that the Burnout resistance of the columns is between 10 min and 15 min. Their fire resistance, on the other hand, is between 55 and 58 minutes. These experiments highlighted the fact that the loadbearing capacity of timber columns exhibit a major "delayed" reduction in a fire, due to the low thermal conductivity of the timber and to the fact that even a moderate heat wave results in a reduction of mechanical properties, as discussed above.

The experimental results are compared with the numerical predictions on a dataset of 49 glulam columns discussed in Section 4.2, see Figure 20. It can be seen that the experimental results align with the numerical modeling that was performed before the test campaign.

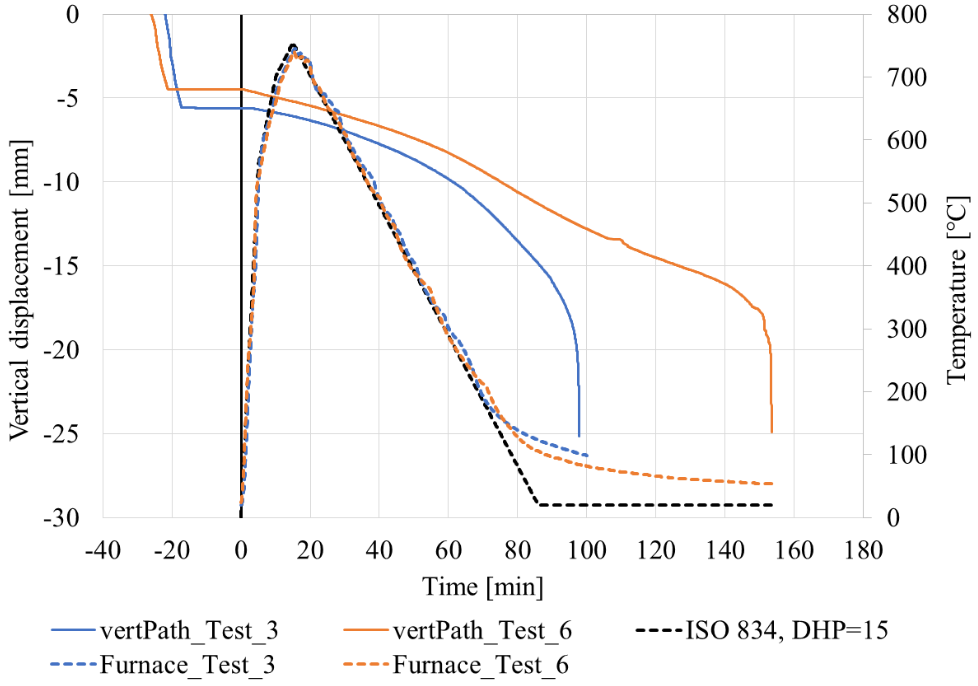


Fig 18. Evolution of the vertical displacement and furnace temperature for Tests 3 and 6. These two columns, loaded with 322 kN, were subjected to the ISO 834 gas temperature-time curve for 15 minutes followed by a cooling phase. The two columns failed during cooling

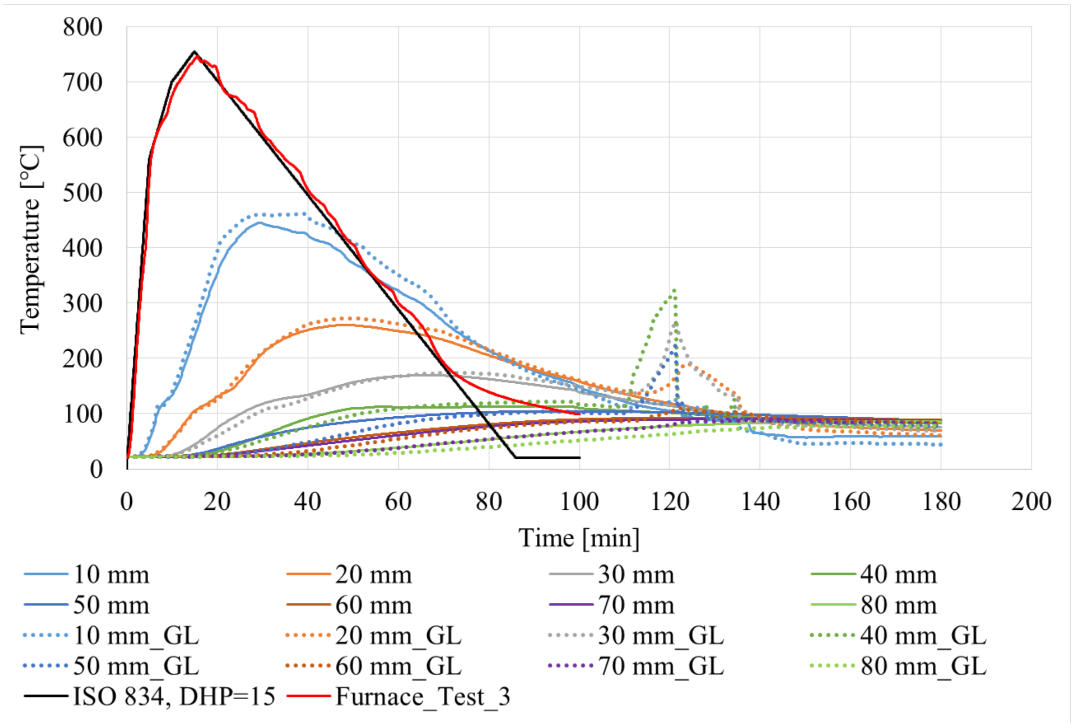


Fig 19. Time-temperature development inside the timber column at different depths under exposure to the 15 minutes heating fire (DHP = 15 min), test 3

Table 2 Tabulated results of the timber column fire tests

Test #	Boundary conditions (Euler case)	Fire exposure	Failure time [min]	Ultimate load capacity [kN]
Test 1	Hinged – Fixed (3)	ISO 834	78	322
Test 2	Hinged – Hinged (2)	ISO 834	55	322
Test 3	Hinged – Hinged (2)	DHP = 15 min	98	322
Test 4	Hinged – Hinged (2)	DHP = 10 min	survived	893
Test 5	Hinged – Hinged (2)	ISO 834	58	322
Test 6	Hinged – Hinged (2)	DHP = 15 min	153	322
Test 7	Hinged – Hinged (2)	DHP = 10 min	survived	865
Test 8	Hinged – Hinged (2)	none	-	2159

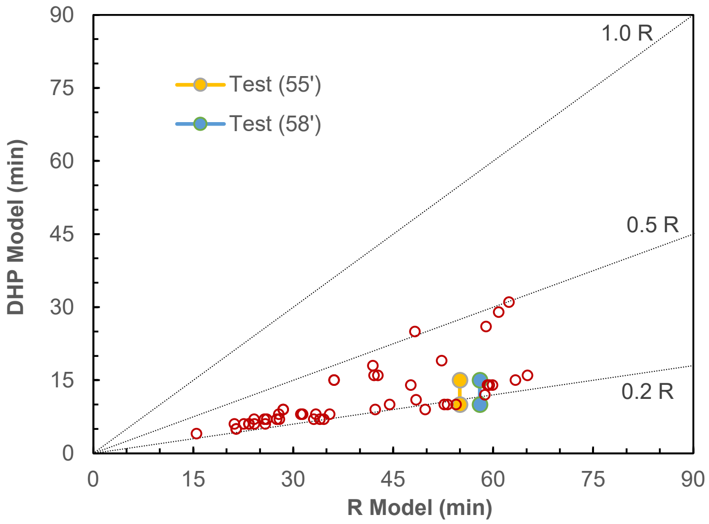


Fig 20. Comparison between experimental results from this test campaign and numerical results from Gernay (2021) on the fire resistance and burnout resistance of timber columns (Gernay et al, 2023)

2.4 Steel members

2.4.1 Physical behavior

The thermal properties of steel are well known. These properties are also known to be reversible during cooling. Therefore, analysing the heat transfer process in a bare steel member during heating and cooling under well-defined conditions does not pose any particular challenge. In the case of calculating the thermal response of unprotected members the definition of the boundary conditions is of essence for the precision of the results.

However, it's important to note that in practical applications, steel structures are typically protected. Consequently, the thermal response of these structures depends on two key factors: the steel cross-section and the thermal behaviour of the protective system. In Europe, the thermal protection of steel is rigorously evaluated according to the EN 13381-8 (2013) standard for reactive systems like intumescent paint. Intumescent paint undergoes chemical reactions when exposed to heat, resulting in the physical expansion of the painted layer, thereby enhancing thermal insulation. When conducting assessments in accordance with this standard, the initial step involves performing a series of fire tests of different cross sections and loads to evaluate the thermal performance and adhesive properties[2] of the protective system. Based on these test results, one of four assessment methods is chosen to generate diagrams and tables for simplified engineering purposes. These diagrams and tables, which are based on the design temperature, section factor[3], and the desired fire resistance class, allow engineers to determine the required thickness of the protective system. Two of the evaluation methods, known as the constant and variable Lambda methods, involve the calculation of effective thermal properties. These properties enable a more detailed analysis of the thermal response of systems with varying thicknesses and section factors. However, it's important to be aware of two limitations associated with these effective thermal properties. Firstly, they are only valid for standard fire exposures, and secondly, they are not applicable during the cooling phase. It is also crucial to bear

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[2] If the protective layer is too thick then it may fall of during exposure, i.e., the stickability is lost.

[3] Ratio of the fire exposed outer perimeter area of the steel structural member itself, per unit length, to its cross sectional volume per unit length

in mind the prescribed thickness limits specified in the certificate, as exceeding these limits may result in system failure during a fire event. This failure can be attributed to the combined forces of gravity and fluid dynamics in the surrounding environment. Contrary to expectations, adding an additional layer of intumescent coating beyond the tested limits may not enhance safety but could, in fact, compromise it (Jansson McNamee et al., 2016).

For passive protection systems designed to safeguard steel structures, the testing procedure follow a similar approach as that used for active systems, as specified in the EN 13381-4 (2013) standard.

The presence of this thermal protection on the steel members adds thermal inertia to the sections. Under fire exposure, this results in a slowed (delayed) heating of the steel that is behind the protection. When considering the full fire event with the cooling phase, the steel temperature will peak after the gas temperature has peaked, and the more protection on the steel the longer the duration of the shift in maximum temperatures (between gas and steel). Therefore, thermally protected members have a higher probability of failing during the cooling phase than unprotected members. Given this influence on heat transfer, the thermal protection will play a key role in the burnout resistance of steel members.

2.4.2 Numerical

The observations discussed above on the effect of thermal protection and thermal inertia on the propensity to fail during the cooling phase have been confirmed by numerical simulations. Finite element analyses (FEA) with the software SAFIR (Franssen and Gernay, 2017) were conducted on a steel column with different levels of fire protection. The DHP method was applied, i.e., the columns were subjected to natural fires on their four sides with varying durations of heating phase until finding the longest fire that could be survived to full burnout. The DHP of this longest fire was determined to be the burnout resistance (B) of the column.

The analyses considered HEB 400 steel columns in grade 355 MPa (Gernay, 2016). The columns were all 4 m in length and simply supported at both ends. The columns were modeled with fiber-based beam finite elements in SAFIR. For geometric imperfection, the column node line had a sinusoidal shape with maximum amplitude of L/300 at mid-height. Flexural buckling about the weak axis of the section was prevented. The columns were loaded axially at the top and the load was maintained constant during the fire. Different values of the load were considered to assess the response under different load ratios. The steel behavior was adopted from the Eurocode (EC3, 2005). When the steel material was cooling, a loss of residual yield strength of 0.3 MPa/°C was assumed once heated beyond 600 °C. Below this temperature of 600 °C, the steel strength was taken as fully reversible, which means that the strength was recovered to full initial value during cooling if the temperature in steel had not exceeded 600 °C. The steel columns were analyzed with two different thermal protections: (P1) a thermal protection providing a fire resistance of 60 minutes under 50% applied load ratio; (P2) a thermal protection providing a fire resistance of 120 minutes under 50% applied LR, which was achieved with a thickness of 20 mm of sprayed fire-resistive material (SFRM) with the following thermal properties: thermal conductivity 0.12 W/mK, specific heat 1200 J/kgK, specific mass of the dry material 350 kg/m³, water content 20 kg/m³.

The results of the analyses are reported in Table 3 (Gernay, 2016). As can be seen, for a given column under a given load the burnout resistance (B) is always lower than the fire resistance (R). As the load ratio decreases, both the burnout resistance (B) and fire resistance (R) increase. The difference between B and R is an indirect indicator of the propensity of delayed failure. Indeed, a member for which B is very close to R will be likely to either fail during heating or survive full burnout. Inversely, a member for which B is much lower than R still has a relatively high likelihood to fail during cooling. The table shows that the difference between B and R is greater for column P2 than P1. This reflects the fact that the thermal protection P2 has greater thermal inertia than P1, thus the effect of the heat wave reducing the capacity during the cooling phase is greater with P2.

In Table 3, the ratio between B and R varies between approximately 0.65 and 0.75. This is comparable with the results obtained for reinforced concrete columns (see Section 2.2.2), which showed a ratio of about 0.72. These ratios for steel and reinforced concrete are significantly higher than for timber columns, which were between 0.20-0.50, see Section 2.3.2. These numerical results suggest that all members may fail during the cooling phase of a fire, but timber columns are particularly vulnerable.

Table 3. Indicators of Burnout resistance (B) and fire resistance (R), in minutes, for protected HEB400 steel columns under different load ratios (Gernay, 2016).

Time in min	**Steel Column (P1)**		**Steel Column (P2)**	
Load Ratio	**B**	**R**	**B**	**R**
60%	35	54	72	108
50%	43	61	84	120
40%	50	69	97	135
30%	60	79	111	153

Chu and Truong made numerical studies of the fire behaviour of composite steel-concrete columns including the cooling phase (Chu and Truong, 2018). In the study the difference between the traditional fire resistance time and the DHP were from 5 to 30 minutes when the fire resistance was between 49 and 147 minutes. The load ratio and the slenderness of the columns were shown to largely affect both the fire resistance and the DHP but the eccentricity of load and concrete strength had a minor influence if the load ratio was not changed.

2.5 Extension to structural assemblies

The issue of structural failure during cooling is also relevant for structural assemblies. Specific effects such as load redistribution during cooling can affect stability. Similar to the redistribution of heat and stress during the cooling phase of an individual member, stress and strain redistribution will also take place in structural assemblies, which may consist of several or numerous members, during the cooling phase. Analysing or testing structural assemblies under fires including the cooling phase can improve understanding of the behaviour, effects of thermally-induced deformations, redistributions and redundancies. It may also result in more efficient structural designs, where failure of one member does not necessarily lead to failure of the entire assembly, thus allowing optimization. Therefore, a systematic study of the behaviour of structural assemblies subjected to heating-cooling sequence is valuable. While the concept of the duration of heating phase (DHP) applies primarily to structural members, as a parallel to the concept of fire resistance rating, it is discussed here to what extent the concept, or parts thereof, can be extended to structural assemblies.

As an example of effort toward highlighting the behaviour of assemblies during the cooling phase, numerical analyses were conducted by Gernay and Gamba on steel-framed structures, under thermal exposure including a cooling phase as a parallel to the DHP concept (Gernay and Gamba, 2018). Initially, a model of a frame experiment was developed, which included localized heating of a column at the center of the assembly, as shown in Figure 21. This particular assembly was one of the large-scale tests carried out by Jiang et al. (2017). The heating of the central column led first to thermal expansion and an increase in axial force in the column (because the expansion is restrained by the surrounding frame). This is followed by a reversal in axial displacement as the column becomes progressively weakened by the fire. Toward the end of the heating, the weakened column has experienced shortening and a reduction in the carried axial force. Then, during cooling, the thermal expansion strain is progressively reduced, which leads to further shortening and reduction in axial force. Eventually, the column ends up being shorter (due to plastic strains having developed during the fire) and pulling on the frame. The observed displacement behavior during the test is accurately captured by the SAFIR model (see figure 21).

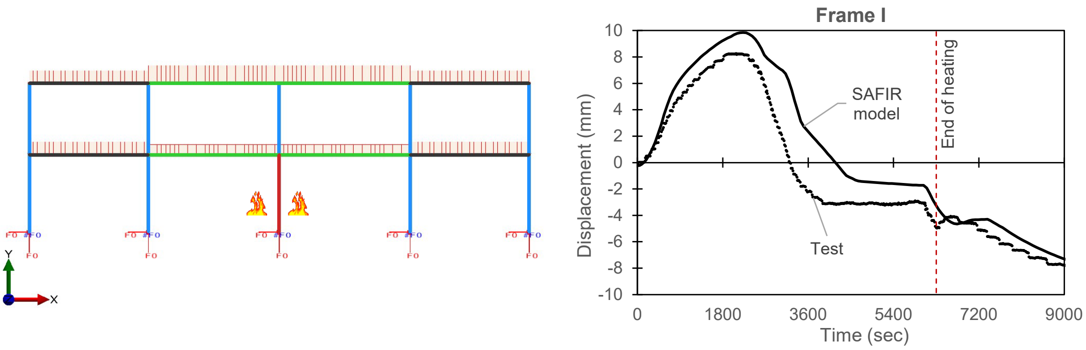

Fig 21. Numerical model of the test Frame 1 by Jiang et al. (2016) and comparison of measured and computed vertical deflections at the top.

Gernay and Gamba (2018) then conducted parametric analyses, varying the level of restraint providing by the frame or the initial level of loading. These numerical analyses show that, under certain conditions, the reversal of displacements and axial forces experienced in a steel column during the cooling phase could lead to large tensile forces and, eventually, to failure of adjacent (non fire-exposed) columns that become overloaded. Indeed, the fire-exposed vertical members may eventually "pull" on the frame and therefore apply additional compressive forces on adjacent vertical members, which add to the external gravity loading. This is illustrated in figure 22. In the figure, it can be seen that the assembly loaded at 50% load ratio (LR) fails during the cooling phase, because the two columns adjacent to the fire-exposed columns are overloaded and buckle. Yet, frames loaded at a lower LR are able to bridge over the loss of the fire-exposed column, with no progressive collapse. Figure 23 shows the distribution of axial forces in the columns for one of the cases. Additional discussions and parametric analyses are provided in the Ref. (Gernay and Gamba, 2018).

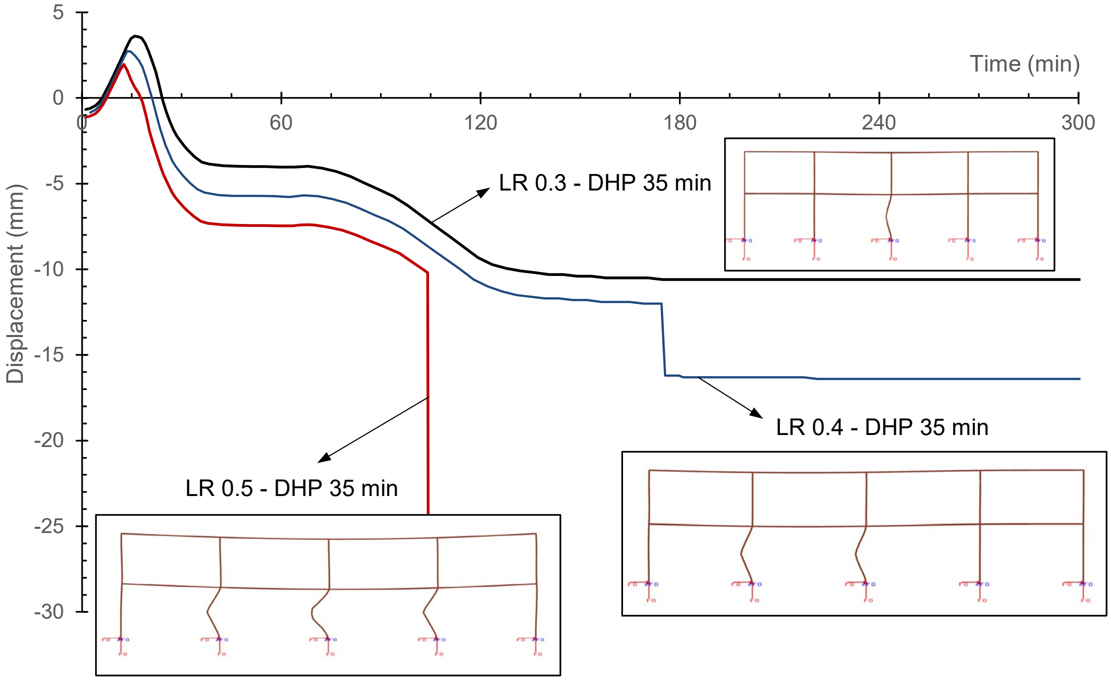

Fig 22. Effect of localized fire on a central column of a steel frame, for a duration of heating of 35 min followed by cooling, and considering different initial applied loads

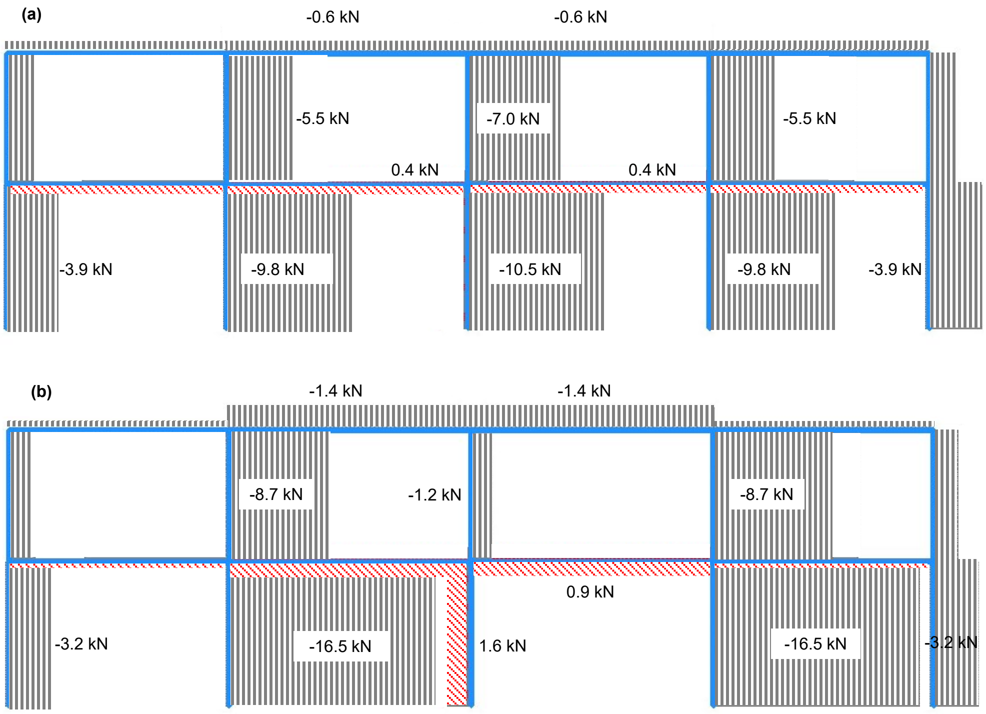

Fig 23. Axial forces in the frame members (a) before the fire and (b) at the end of the fire. Compressive forces are negative.

Finally, this method can be extended to a full building. Gernay and Gamba (2018) analyzed a 20-story moment resisting frame steel building with a fire attacking one of the ground level columns, see figure 24. The redistribution of forces during the cooling phase leads to massive tensile forces developing in the fire-exposed columns and being redistributed as additional compression to the adjacent columns. The authors suggest that it is unlikely that such single-column fire would result in complete collapse in a normal design, owing to reserve in resistance and redundancy in such structures. However, they point out that the “locked-in” forces after a fire event would be very significant and should be taken into account when assessing the structural reliability level after the fire.

These results show that the effects of fire with cooling phase in statically indeterminate structural assemblies are significant and complex, due to restrained thermally-induced deformations and inelasticies. Further studies to investigate the ability of structural assemblies to withstand fires until burnout are needed, Including for other materials and structural types.

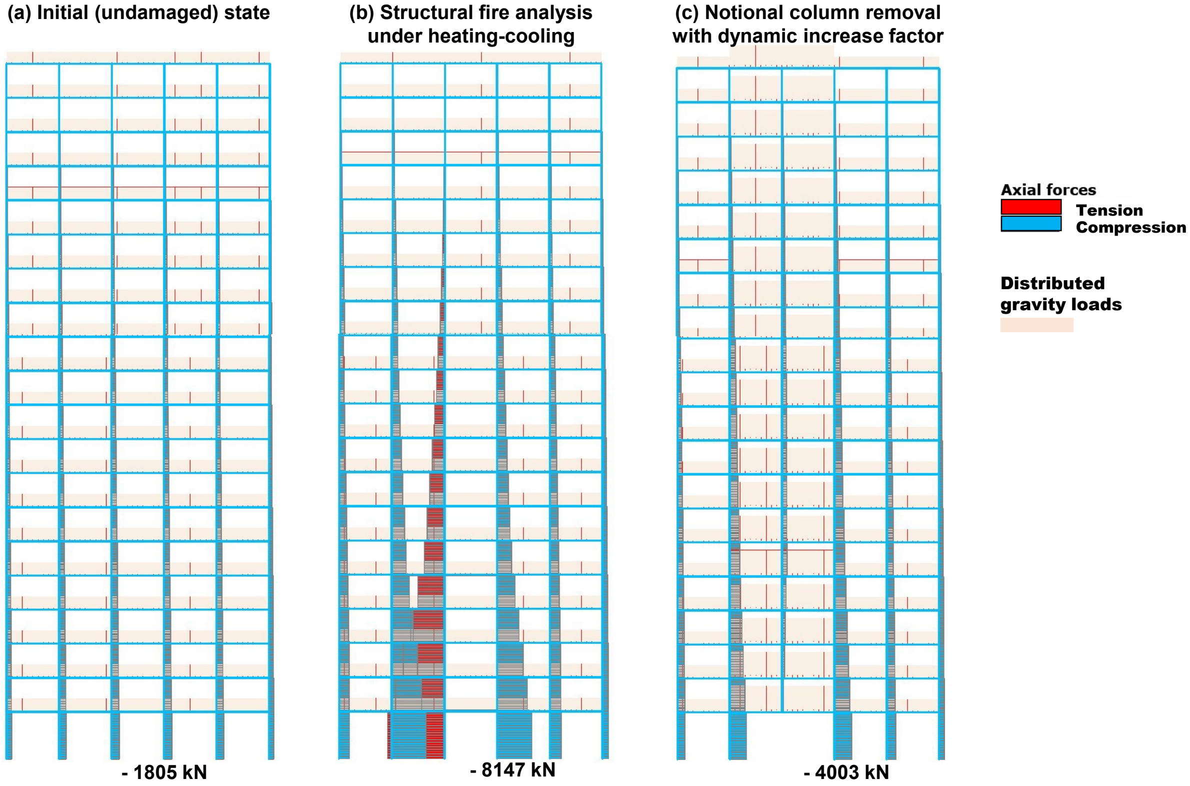

Fig 24. Numerical modeling of a scenario of natural fire attacking one ground level column in a 20-story moment-resisting steel frame building. The plotted axial forces in the columns show large tensile forces building up in the fire-exposed column at the end of the cooling phase.

2.6 Extension to insulation criterion

The ongoing discussion has predominantly centered around the load-bearing capacity criterion in fire scenarios. However, it is worth noting that when evaluating the fire performance of building components, we often consider multiple criteria (Gernay and Franssen, 2016). For example, the insulation criterion may become crucial when assessing the fire performance of elements like concrete slabs or walls. Here, we examine how this insulation criterion is influenced during the cooling phase of a fire.

According to the Eurocodes, when verifying the separation function for the average temperature rise, assuming a standard normal temperature of 20°C, the following requirements come into play:

1. The average temperature on the unexposed side of the structure must be restricted to 160°C during the heating phase until the maximum gas temperature in the fire compartment is achieved.

2. During the decay phase, the average temperature on the unexposed side of the construction at or below 220°C.

Numerical analyses are used to evaluate the heat transfer across the depth of a concrete slab subjected to fire at its lower face. To meet the heating phase criterion for a duration of 120 minutes, the minimum required slab thickness is determined to be 117 mm. Essentially, this means that a 117 mm concrete slab subjected to an ISO fire from its lower surface reaches an average temperature on the upper surface of 160°C after 120 minutes. If we extend the simulation to cover the decay phase of the fire, following the parametric Eurocode fire model, the average temperature on the unexposed side climbs to 252°C. To satisfy the criterion for the decay phase, the slab thickness must be increased to 138 mm, as illustrated in Figure 25.

Conversely, if the slab remains fixed at a thickness of 117 mm, the maximum allowable duration for the heating phase, while still meeting the decay phase criterion, is 85 minutes. Therefore, the 117 mm slab achieves a Duration of Heating Phase of 85 minutes (B rating of 85 min) with respect to the insulation criterion when including the decay phase requirement, while it satisfies the insulation heating phase requirement for 120 minutes (R rating of 120 min). Note that these analyses assume that the decay phase of the natural fire aligns with the Eurocode parametric fire model.

Further discussion on the extension of the DHP concept to the insulation criteria is done in chapter 3.2.

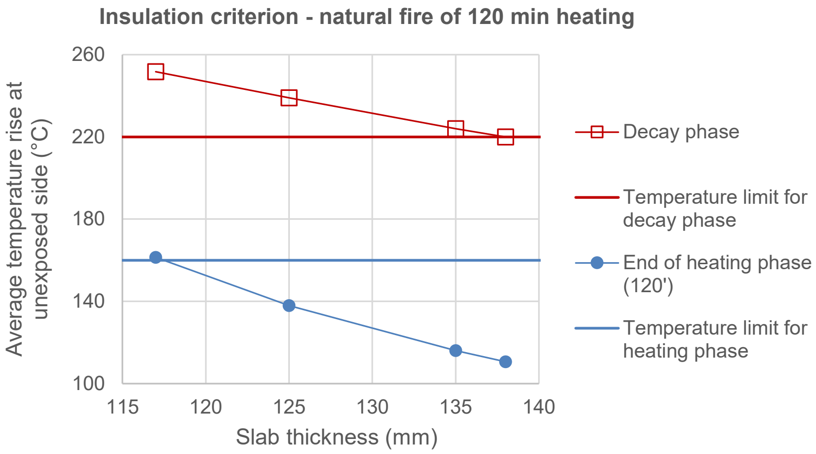

Fig 25. The insulation criterion in Eurocode (average temperature at the unexposed side) for a concrete slab is more severe during the decay phase than during the heating phase Gernay and Franssen, 2016).

3 Implications and Discussion

3.1 Delayed collapse

A key consideration discussed throughout this report is that, even if structures are still standing at the time of peak heat exposure, they may collapse at a later stage. The studies reviewed in this report have elucidated this behavior, highlighted various key factors for different materials, and demonstrated including through experiments that such delayed collapse can indeed occur. It is critical to point out that this behavior is not merely due to the fact that the fire brings an additional amount of energy during the cooling phase; it is in fact mostly due to the effects of thermal inertia of the structure, i.e., the heat penetrating the outer layers of the cross section are redistributed to the inner part with a delay.. We believe that this phenomenon has major implications, for safety of fire service and occupants, for resilience, and sustainability of designs. Therefore, it is our opinion that the structural fire design paradigm needs to account for this phenomenon, which is currently not the case when applying solely the fire resistance rating concept. The proposed DHP concept including the burnout resistance can meet this need for a pragmatic method to capture, and take into account, in a simplified way for practical use the sensitivities of structural members to delayed collapse.

3.2 Extension of the concept beyond member loadbearing capacity

The DHP concept was initially defined for the design parameter of load bearing capacity. In this chapter we will discuss a possible extension to other criteria's such as the insulation or integrity.

As described in chapter 2.6, evaluation of the insulation criteria including the cooling phase is already incorporated in the calculation models of the Eurocode where the allowed temperature when including the cooling phase is higher than when only including the heating phase. This difference in acceptance criteria is based on the reasoning that it is not fair to have in practice stricter demand when including the cooling phase (Anderberg and Pettesson, 1992).

So, it is not straightforward to include the temperature on the cold side of a fire exposed element as a failure criterion in the DHP concept. If the same criteria as in standardised fire resistance testing is used, i.e., maximum 140°C average temperature rise and maximum 180°C in one point, then the limit is more strict than defined in the Eurocode when including a cooling phase. But if it is instead decided to follow the Eurocode provision described in Chapter 2.6 the demand during the heating and cooling phases are different, which is not the case when defining the DHP based on load bearing capacity. The concept of using the DHP concept for the insulation criteria needs more investigation.

There is also a possibility to extend the DHP concept to the integrity criteria for elements used in compartmentation. The integrity criteria in EN 1363-1 are evaluated by i) a cotton pad test, ii) gap gauges evaluating the size of openings and iii) occurrence of flaming on the cold side of the test specimen. In theory these three measures could also be evaluated during the cooling phase. However, this extension of the DHP concept is not straightforward either when doing furnace testing. Both when doing the evaluation with a cotton pad or observations of flaming, the pressure difference between the furnace and the surroundings are a key influencing parameter. When doing standardized fire tests of vertical elements like walls in Europe, the upper part of the specimen is exposed to a pressure giving a flow of combustion gases out from the furnace if there is an opening. But if the opening is in the lower part of the specimens, lower then 500 mm from the lowest part, there is a pressure difference leading to a suction in of gasses into the furnace, i.e. the neutral pressure plane is at 500 mm. This is in line with what is happening in real ventilation-controlled fires where external air is flowing into the fire along the floor and pushed out higher up in the external plume. But during the cooling phase when different amounts of cold air is pushed into the furnace to follow the prescribed cooling curve the pressure is very difficult to control. This means that one of the driving parameters for breaking the integrity by igniting the cotton pad or getting external flaming has a random component. Further investigation regarding the possibility to regulate the pressure during cooling of fire resistance furnaces is needed before the DHP concept can be extended to include the integrity criterion.

3.3 Performances objectives of repairability and resilience

Moving beyond fire resistance to quantify the response until burnout will support designs for safety of occupants and firefighters throughout the fire and promote repairability and resilience.

This framework puts the emphasis on designing structures to withstand an entire fire event. This shift in perspectives allows considering additional performance objectives beyond the current traditional lens of life safety. Structures designed to survive burnout can more easily be repaired and re-used.

In addition, knowledge developed when investigating the concept of burnout resistance will also enable better understanding and modeling of structures throughout fire events, for example to evaluate the damage and the post-fire capacity after a fire. This is useful also for existing structures that may experience a fire. Indeed, if these structures survive, the knowledge gained will support better damage and repair assessment, which in turn leads to faster and safer re-use of buildings after a fire event.

3.4 Fire resistance testing to determine the DHP

The Duration of Heating Phase concept or the determination of the Burnout resistance is not included in any testing or classification standards for fire resistance. The fire tests performed in the studies described in the previous chapters followed the present standards as closely as possible while extending the scope of the experiment to include the cooling phase. Yet, there remain some open questions that need to be defined prior to including the DHP concept in the regulatory system. Let us first summarize the system we have now.

When determining the fire resistance rating of structures, the experimental procedure is defined in fire resistance standards. In Europe, the general requirements for fire resistance testing are described in the standard EN 1363-1 (2023) while additional product specific procedures are defined in complementary test standards. The second step in a fire resistance classification is to classify the product or element according to the classification standard EN 13 501-2 (2023). This is the standard describing the requirements for achieving a certain fire resistance class using data from fire resistance tests. The most commonly used classes are loadbearing capacity R, integrity E, and thermal insulation I. These different criteria are then followed by a time, e.g., a 60 minute rating of a wall withstanding the insulation and integrity criteria may be classified EI 60 or REI 60 if the wall was loaded during the test.

The way forward to introduce the DHP concept in the regulatory system as a complimentary robustness measure would be to define a class defined by the DHP when the element survives cooling down. The new fire resistance rating may then be expressed as “R60 B40” where the traditional fire resistance is 60 minutes (load bearing capacity) and the longest standard fire including cooling that the structure can survive is 40 minutes. The letter B is then representing the “Burnout resistance”. The burnout resistance rating, B, of an element is defined based on the concept of DHP, i.e., B40 represents the ability to survive the “standardized” fire with Duration of Heating Phase of 40 minutes followed by cooling.

Neither the standard describing the general requirements for fire resistance testing EN 1363-1 (2023) nor the complementary standard EN 1363-2 (1999) include a definition of a cooling phase. We thus suggest introducing a cooling phase in the fire resistance standard following the procedure in the Eurocode that is actually based on the fire resistance standard ISO 834 from 1975. We recommend for this cooling phase to be the linear cooling from the Eurocode parametric fire. It seems to us that this curve is appropriate for the purpose of subjecting building elements to a standardized heating-cooling protocols to determine their burnout resistance, and it has the advantage of simplicity and of being already including in the Eurocode (thereby being already familiar to many in the fire engineering community). The selection of this particular cooling phase is not meant to represent a specific “real” fire, as in any case all fires are different. It is understood that a real fire would exhibit a different cooling phase (and all fires’ cooling phases would be different between them). Another significant advantage of using this curve is that it has been demonstrated previously by two different fire resistance labs (Gernay et al. 2022, Gernay et al. 2023) that it is possible to follow the curve with reasonable accuracy and reproducibility when testing full-scale concrete or timber columns in standard furnaces. That being said, the details of implementing this curve in furnaces warrant further examination, as discussed hereafter.

Fire resistance furnaces are in general not designed to follow a specified cooling curve as fire curves with cooling are seldom used (only when testing elements for tunnels a cooling phase is sometimes included). Therefore, we do not think a simple extension of the precision demands regarding thermal exposure defined in EN 1363 is realistic. There is a limit on how much individual plate thermometers defining the thermal exposure are allowed to deviate from the standard fire curve during testing. This limit is defined after 10 minutes of exposure as plus minus 100 degrees Celsius from the standard fire curve. In a test including a cooling phase it may in practice be difficult to keep all plate thermometers in this span, so we suggest to only keep the lower limit during cooling (higher thermal exposure is on the safe side). This is illustrated in figure 26.

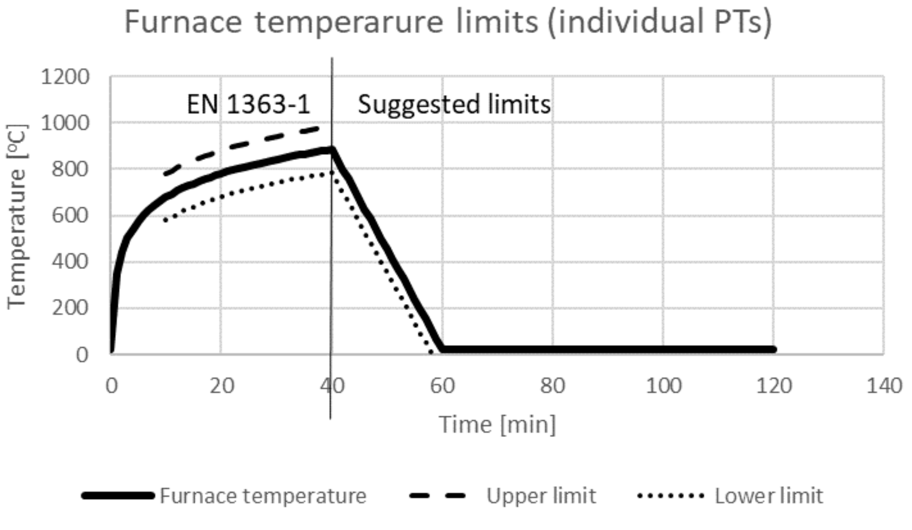

Fig 26. Suggested limits for individual plate thermometers when including a cooling phase in the test standard.

There is also a criterion in the standard that the area under the average temperature curve in the furnace do not deviate too much from the standard fire curve. In the case of DHP, we suggest to require that the area under the average temperature curve in the furnace remain continuously above the prescribed area, which is on the safe side during the cooling phase. The transition between the criteria for heating and cooling would be progressive, e.g., over a five minute period as illustrated in figure 27.

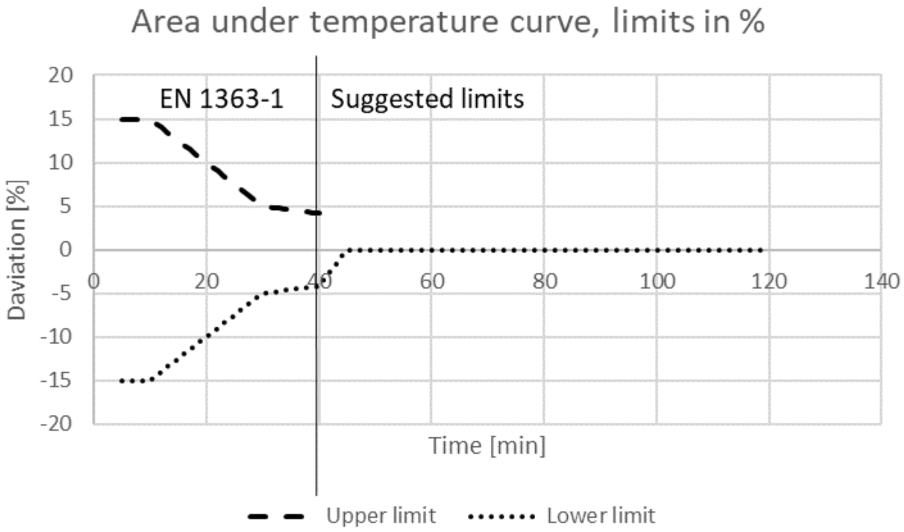

Fig 27. Suggested limits for deviation of the area under the fire curve compared with the area under the standard fire curve when including a cooling phase.

Finally, there is a criterion in the EN 1363 standard on minimum oxygen content of 4% in the furnace when testing a non-combustible element. Laboratories in general try to stay close to this defined lower limit, thus not adding a substantial amount of extra oxygen. In the cooling phase, especially in the later stages, a lot of energy needs to be transported away from the furnace chamber and this is usually done with air ventilation. The consequence of this is that the oxygen level rises in the furnace chamber during cooling. When testing combustible products this rise in oxygen content during cooling may lead to a period of elevated self-heating in the tested objects due to combustion or charring. This could lead to more onerous conditions, although this would be on the safe side and possibly in line with in-situ situations where, during the cooling phase of elements in real fires, a rise in oxygen content may occur. Thus, defining a restriction on the oxygen content in the cooling phase may not be a priority.

3.5 Extension of the concept to other basic exposures than the standard fire curve

According to the proposed DHP concept, the fire growth part is still defined by the standard ISO 834 fire curve. This may be assessed as a limitation as we know that real fires can have a variety of growth patterns. One could argue that a possible extension of the concept is to define the DHP for alternative exposures. However, this would not be preferable in our opinion. The fundamental idea that the DHP is a complementary measure to the standard fire resistance would no longer be valid. The idea of the DHP is to use it as an extra robustness measure of elements or structures before the final use is known. The DHP, and burnout resistance B, are intended to be used in a similar (and complementary) framework as the standard fire resistance rating R is currently used. It improves the R-concept by accounting for the very distinct effects of cooling phases in various members and materials, but it is not intended to be a substitute for a full performance-based analysis under a well-defined scenario. If the final use is known more detailed object specific analyses of the behavior during heating and cooling are always possible without using the DHP concept.

4 Gaps and Roadmap

4.1 Fire resistance testing including the cooling phase

To experimentally evaluate the Duration of Heating Phase (DHP) indicator of a building element, an extension of the fire resistance test procedure to include the cooling phase needs to be done. It is possible to perform fire resistance tests including the cooling phase already now, as shown in previous chapters, but to reach a wider acceptance and use of the concept some more parameters need to be set. In the previous chapter deviation limits during the cooling phases were suggested for some key parameters:

- Furnace temperature limits
- Area under the average temperature curve
- Oxygen content

An important question to solve or define is also how long the evaluation of the behaviour in the cooling phase should carry on. If we choose to define that the test shall continue until the whole cross section is at room temperature, then the test time for some cross sections will be very long (can exceed 10 hours for a 40 cm by 40 cm timber section). So, a rational/practical criteria for when a test is ending needs to be developed. When establishing criteria for test termination, there are two viable options to consider:

- **Time-based Termination:** One option worth investigating is the feasibility of a time-based termination criteria, although this should be carefully assessed to remain consistent with the goal of assessment until full burnout. Tests could be terminated after a specific duration, which may either be a constant timeframe or linked to the duration of the heating phase, or a combination of both. For instance, an approach might involve setting the cooling phase duration as a fixed multiple (e.g., five times) of the heating phase. However, if the cumulative test duration exceeds a predefined limit, such as three hours, the test is terminated after three hours. A shortcoming of this approach is that it does not account for the heat transfer processes in the specimens. In other words, a set duration could be sufficient to enable heating-cooling for certain materials and section sizes while it would be too short for others, thus failing to fully capture the effect of delayed heating in the core of the section. This is why we would recommend careful feasibility studies first if this option was to be further considered.
- **Temperature-based Termination:** Alternatively, tests can be terminated based on the temperature reached in the test specimen. Given that specimens with varying geometries and materials exhibit different cooling rates, setting a temperature threshold for both the centre and surface of the specimen can serve as a termination criterion. For instance, the criterion could specify that temperatures at both the centre and surface should be below 50°C or even lower and exhibiting a decreasing trend (studies would be needed to determine suitable thresholds). While this approach is physically more satisfying as it is based on temperature, a shortcoming of this approach is that it would still result in very long testing times for insulative materials and/or large sections.

The final decision of what criteria to use may be investigated more in depth by numerical simulations of the temperature fields and the load bearing capacity for different cross sections during different heating scenarios.

4.2 Characterization of properties during the cooling phase

When conducting numerical modelling to assess the load-bearing capacity of a structure during or after a fire event, the selection of thermal and mechanical properties plays a pivotal role in the accuracy of the calculations. Presently in fire safety engineering, thermal and mechanical properties for materials such as concrete, wood, and steel are predominantly derived from Eurocodes. However, these properties are based on measurements either during heating or at a steady-state elevated temperature or by a best fit of parameters in a calculation model to replicate experiments.

Therefore, an effort is needed to characterize the material properties during the cooling phase of a fire. Data, understanding of the phenomena, and models are needed to capture the thermal and mechanical behavior of materials (steel, concrete, timber, gypsum, etc.) during the cooling phase. This will require designing new experiments specifically conceived to measure during cooling. This will also require efforts to align models with experimental data. For this purpose, two approaches can be considered:

- **Developing Detailed Empirical based Material Models:** Creating more intricate empirical models that account for the influences of various factors.
- **Combining Experimental and Calculation Schemes:** Implementing a combined experimental and calculation approach to determine effective properties for the materials in use. Given that many engineering properties are not fundamental, commonly used test methods can influence outcomes to varying extents. Therefore, a rational approach involves fitting properties in a calculation to replicate behaviour in a well-designed experiment. This optimized approach allows for the modelling of cross-sections and load situations specific to the experiment, subsequently enabling extrapolation from the fundamental experiment conducted.

As an example, in a recent research project funded by the American Concrete Institute (ACI) Foundation, the thermal and mechanical properties of concrete were measured throughout the heating and cooling (Gernay and Bamonte, 2022). This was done using new, customized experimental protocols designed at Politecnico di Milano in Italy, for the specific purpose of collecting data on properties that can be used in simulations of fires with heating and cooling phases. Further similar efforts are needed to study other materials and testing protocols. This will provide the effective thermal and mechanical properties required in models.

4.3 Modeling and design

To determine the DHP only based on experiments is expensive as repeated fire resistance tests are needed. Therefore, theoretical calculations or a combination of experiments and calculations is a way to reducing costs but what criteria shall a theoretical calculation fulfil? In the case of using pre-calculations for designing what experiments to perform we may not need detailed criteria but in the case of determining the DHP theoretically without testing we need to develop a framework for how we validate the calculations. Another area where calculation could be useful is when we have a determined DHP for a certain cross section and load and want to extend the results to other loads and cross sections.

The precision attained in numerical modelling of high-temperature behaviour is crucial for a robust evaluation scheme of the burnout resistance. The review of previous studies provided in this report has highlighted some validation exercises, notably for reinforced concrete columns, but test data on loaded structural members under heating and cooling remain scarce. Also, while this report has primarily delved into the behaviour of straightforward cross sections comprising concrete, wood, and steel, it is important to remember that structural elements may also involve a composite of these materials or may incorporate additional components made of other materials. Further research may be warranted to validate numerical models for some of these combinations.

Moreover, even when considering the thermal and mechanical aspects of simpler cross sections made of concrete or wood, some behaviours cannot be modelled accurately without the incorporation of advanced models encompassing both heat and mass transfer phenomena. An example is smouldering in timber members, which can develop over many hours during cooling. These complexities underscore the evolving challenges for developing more advanced models, where the dynamic interplay between different materials and the nuanced interactions of heat and mass transfer may demand a heightened level of detail in numerical simulations.

Overall, knowledge of the behavior of materials under heating-cooling from fire exposure has been the subject of still relatively limited studies.

For steel, models are available based on data collected from a large number of experiments, including data on residual properties post-fire. Models have been validated against full-scale fire tests, including natural (e.g., wood crib) fires. Therefore, numerical modelling of the response of steel members and structures throughout a fire event can be conducted with confidence, at least if the properties of the protection materials (gypsum, intumescent, sprayed) are known.

For concrete, models also exist for the behavior during heating and cooling, based on experimental data, although there remain some challenging issues such as spalling. Also, concrete is more complex than steel because there are many types of concretes. An effort remains needed to characterize the properties during cooling of various concrete types and to better understand the influence of the governing parameters. Nevertheless, recent simulations of full-scale DHP tests (Gernay et al. 2022) showed that the overall behavior of loaded RC members can be quite well predicted with FE models.

For timber, there have been comparatively fewer research efforts to model the thermal-structural behavior of timber to date. Effective properties provided in the Eurocodes for advanced modelling of timber in fire were calibrated based on standard fire exposure only. Also, the combustible nature of the material makes it more challenging to model, especially when considering the cooling phase since a mere determination of charring rate is not appropriate to evaluate the behavior during this phase. There are still a lot of unresolved questions, for example pertaining to combustion and self-extinction, smoldering, effective properties in different fire regimes, or reversibility of properties in cooling. Research will be needed to address these gaps. At the same time, this is particularly crucial since experiments have shown that the issue of burnout resistance is particularly relevant for these timber members, as discussed in Section 2.3.

In chapter 2.5 it was shown numerically that the effects of fire with cooling phase in statically indeterminate structural assemblies are significant and complex, due to restrained thermally-induced deformations and inelasticities. Further studies to investigate the burnout resistance of structural assemblies made of a combination of materials are needed.

4.4 Research directions

The previous paragraphs in this chapter have pointed out several important areas for development regarding the burnout resistance as a complementary robustness measure to the traditional fire resistance. There are three main areas for further development:

- Theoretical
- Experimental
- Numerical

The theoretical basis of this concept hinges on the conventional fire curve and predefined cooling scenarios, which are used to construct a framework for assessing the resilience of elements or structures subjected to fire. It serves as a means to evaluate performance before determining the ultimate application of the element, much like how the fire resistance rating is employed today. However, the question arises: What cooling scenario best represents the real-world conditions? Figure 7b in chapter 2.2.2. explores the impact of incorporating various alternative cooling scenarios on the outcomes, yet it's important to note that this factor may vary for different structures and geometries.

To enhance the widespread adoption of this concept, especially with the aim of incorporating it into testing standards, a more detailed definition of experimental procedures is required. In Chapter 3.4, some initial suggestions and discussions regarding this matter are provided. A critical aspect of adopting this concept from an experimental perspective is its practicality and feasibility in laboratory settings. This includes determining the appropriate duration of the test, which is a theoretical question. The test duration should be long enough to accurately capture the processes occurring during cooling and the potential for delayed failure, while still being reasonably short for economic and practical considerations.

From a numerical perspective, it is essential to establish criteria for validating calculations. This raises several key questions:

- When can calculations be a suitable substitute for a fire test?
- In what circumstances can calculations be used to extrapolate experimental results? Is it as an example feasible to extrapolate test results from one load level to other load levels using calculations?

Another critical aspect of numerical modelling involves ensuring access to sufficiently accurate material data, which is essential for modelling the behaviour of materials at elevated temperatures, including the cooling phase.

In a wider perspective than just the burnout concept for individual members, further studies of the burnout resistance of structural assemblies are needed, including for materials and structural types other than discussed in this report.

5 Conclusions

The framework for determining burnout resistance using the duration of the heating phase has been elucidated in this report. The latest advancements in applying this concept to different materials and elements have been outlined, accompanied by a critical discussion on the current state of the art and potential areas for further development. The key conclusions can be synthesized into the following points:

1. **Definition of Burnout Resistance (B):** The burnout resistance, denoted as B, is conceptualized as the longest Duration of the Heating Phase (DHP) of a 'standardized natural fire'—comprising both a heating phase following the standard time-temperature curve and a cooling phase as defined in the Eurocode—that the member can withstand. This measure serves as a complement to the standard fire resistance rating and functions as an indicator for assessing elements before their final utilization, similar to traditional fire resistance ratings. It captures the sensitivity to cooling phases, particularly, the propensity of members to fail after the thermal exposure have peaked in the compartment due to delayed heat transfer towards the inner parts of the section and other material-dependent factors. Our opinion is that both the burnout resistance and the standard fire resistance rating have their purpose, and one cannot fully replace the other. The fire resistance indirectly correlates to a duration of endurance to fire before collapse; but it does not say whether the structure would survive to burnout. Inversely, the burnout resistance correlates to the ability of the structural member to endure the fire exposure until full burnout; but it does not inform on a minimum duration of endurance under continuous heating. Therefore, we do not think that B can replace the standard fire resistance framework, but rather it can act as an extra robustness indicator for key elements in structures.
2. **Experimental Determination Considerations:** During the experimental determination of burnout resistance, several complementary definitions are needed. Fire resistance furnaces, typically designed for the heating phase, require redefined performance limits for the cooling phase. This includes considerations such as allowed deviations of individual plate thermometer temperatures during cooling and permissible variations in the area under the average temperature curve in the furnace. Suggestions for these limits are included in the report in an effort to work towards a standardized framework to determine the burnout resistance rating of members experimentally.
3. **Termination Criteria:** Defining the termination time for a test or calculation is an important aspect. Previous experimental campaigns allowed extended cooling times, and these showed that failures may occur after several hours of testing. Meanwhile, the determination of burnout resistance, to become widely accepted and used, necessitates clear and practical criteria for end of testing, and probably with manageable test durations. Otherwise, it may be difficult to get the concept implemented in test standards. Two approaches for termination have been discussed:
    a. **Time-based Termination:** In this option, tests can conclude after a specific duration, either a constant timeframe or linked to the heating phase duration, or a combination of both. For instance, an approach may involve setting the cooling phase duration as a fixed multiple of the heating phase, with a predefined limit on the cumulative test duration. However, this option raises important questions to ensure that the test actually captures the behaviour until full burnout. It is thus a priori not the preferred

    option, and would require careful studies to assess consistency with the concept and appropriate thresholds.

    b. **Temperature-based Termination:** Alternatively, tests can be concluded based on the temperature reached by the test object. Considering varying geometries and materials, a termination criterion involves setting a temperature threshold for both the centre and the surface of the object. For example, the criterion may stipulate that temperatures at both locations should be below 50°C, showing a decreasing trend as criteria for termination of the test. The actual limits would need to be assessed based on detailed studies.

4. **Numerical modelling:** Numerical modelling by advanced methods (i.e., FEM) will necessarily be a component of the determination of the burnout resistance of elements, given the cost of repetitive furnace testing. This report provided a review of studies aiming to quantify the DHP and burnout resistance B of different structural members, including in the case of concrete and timber columns comparison against furnace tests. These studies suggest that numerical modelling can be used for this purpose, however, this report also highlights a number of limitations and research gaps. Notably, further efforts are needed to define thermal and mechanical properties for materials applicable throughout the fire event. Specific efforts are also needed for timber, since its fire behaviour is more complex and the maturity level of models is less advanced than for other construction materials. Advancing the capability to simulate the response of members, notably in timber, throughout the cooling phase of fires is identified as an important priority to improve safety, sustainability and resilience of the built environment.

5. **Burnout resistance of structural assemblies and whole buildings:** While the conventional analysis suggested focuses on the burnout resistance of individual components subjected to the standard fire curve before we know the final use of an element, it is imperative to extend this examination to encompass structural assemblies and, in the most extreme cases, entire buildings. This expanded perspective necessitates a refined understanding of burnout resistance. Through this refinement, structural fire safety engineers can access improved tools for developing practical, performance-based solutions. This advancement not only enhances safety measures but also promotes the efficient utilization of building materials.

6 Dissemination

This report includes a literature summary and roadmap for introducing the concept of Burnout Resistance (B) to a wider audience. References to peer-reviewed scientific publications are listed in the report to provide further technical background and validation. An accompanying webinar is also freely available online on the Brandforsk YouTube channel. The authors hope that this report can be a step towards further development in this area including work towards the development of an international standard to rate structural members for their performance until full burnout of a fire. In the meantime, the presented information can already serve fire safety engineers, structural engineers, and rescue services who can adopt the concept to compare the fire safety and robustness of different solutions.

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