SiF 2024 – The 13th International Conference on Structures in Fire
University of Coimbra, Portugal, 19 to 21 June 2024

COMPARING VARIOUS METHODS FOR ESTIMATING THE FIRE DECAY AND THE COOLING PHASE IN STRUCTURAL FIRE ENGINEERING

Andrea Lucherini[1], Ruben Van Coile[2], Bart Merci[3]

ABSTRACT

The current research study discusses the relevance and main characteristics of the fire decay and cooling phase of post-flashover compartment fires, crucial phases for ensuring structural integrity during and after fire. The study evaluates and compares various engineering methods for performance-based structural fire engineering, ranging from analytical formulations to zone-models, focusing on the fire decay and cooling phase. Comparative analysis of methods reveals discrepancies in defining the fire heat release rate and thermal boundary conditions to structural elements during these phases. A case study is presented to investigate the range of defined fire conditions in terms of estimated temperature evolutions and the consequent in-depth temperature profiles and thermal energy gain within load-bearing element according to the various methodologies. This research stresses the necessity for refined methods to properly consider the fire decay and cooling phase in modern performance-based design procedures to ensure the fire safety of structural systems.

as well as the in-depth temperatures and thermal energy experienced by structural elements

Keywords: Fire decay; cooling phase; fire dynamics; natural fires; compartment fires; structural fire engineering; fire safety

1 INTRODUCTION

Traditionally, design methodologies for structural systems exposed to fire adopt the standard fire curve as the only design scenario for post-flashover fires. This fire exposure is represented by a monotonically growing temperature-time curve, often claimed to represent the worst-case scenario for traditional construction materials during the growing and fully-developed phases of a typical natural fire [1]. However, research in the last decades has highlighted the relevance of adopting holistic performance-based methodologies for the design of fire-safe structures that ensure structural integrity until complete fuel burnout [2]. These approaches analyse the behaviour of load-bearing systems during all the typical fire phases in an enclosure: growing, fully-developed, decay, and cooling [3]. The distinction between the fire decay and cooling phase has been extensively explained in [3] and the most important aspects are recalled in Section 2 below. During these phases, the load-bearing capacity of structural elements may continue to decrease due to the continuous penetration of the heat wave and the possibly irreversible reduction of the mechanical properties, resulting in reduced strength and/or stiffness [4-5]. Indeed, delayed failure may occur during or after the fire decay and cooling phase, and a few cases have been reported [6-7].

[1] PhD, Senior Researcher, Slovenian National Building and Civil Engineering Institute (ZAG), Slovenia
e-mail: andrea.lucherini@zag.si, ORCID: https://orcid.org/ 0000-0001-8738-1018
[2] PhD, Professor, Ghent University, Belgium
e-mail: ruben.vancoile@ugent.be, ORCID: https://orcid.org/ 0000-0002-9715-6786
[3] PhD, Professor, Ghent University, Belgium
e-mail: bart.merci@ugent.be, ORCID: https://orcid.org/ 0000-0002-2600-0098

Recent research has proposed different engineering approaches to evaluate the thermal exposure of natural fires on structural elements. These methods rely on different assumptions and simplifications: from analytical formulations to zone-models and computational fluid dynamics (CFD) simulations [8]. However, there is limited understanding on how these approaches can be reliably adopted to reproduce realistic natural fire exposures, including all phases. In particular, even though numerous studies related to this topic are being published, little effort is placed in clarifying the differences between the fire decay and the cooling phase and their treatment remains highly inconsistent [3]. For instance, one of the most adopted methodologies, the Eurocode parametric fire curves (EPFC), adopts a simplified linear approximation for the “cooling” phase, which mixes up fire decay and cooling and is not based on fundamental physical principles or a comprehensive research study [9]. Other examples relate to experimental and modelling studies aimed at assessing the load-bearing capacity of structural elements under fire conditions which include different formulations of the fire decay and cooling phase [2, 4-7, 10-11]. In particular, experimental campaigns, for instance using standard furnaces [6-7], lack comprehensive definition and characterisation of the reproduced thermal conditions and justification for the selected fire scenarios.

This paper discusses the relevance and main characteristics of the fire decay and cooling phase of post-flashover compartment fires and compares several methods for performance-based structural fire engineering, focusing on the definition of the thermal boundary conditions to structural elements during all the fire phases. Special attention is paid on the definition of the fire heat release rate and the estimated temperature evolution for the fire exposure definition, as well as the in-depth temperatures and thermal energy experienced by structural elements according to the various methodologies.

2 FIRE DECAY AND COOLING PHASE

2.1 The various fire phases

Even if the structural fire engineering practice has been traditionally concentrating on the fully-developed phase of post-flashover fires (focus on its duration and temperatures), the fire decay and cooling phase are facing an increasing interest for ensuring the stability and integrity of structures in performance-based design approaches. Even though their treatment has been often mixed up, recent research has carefully defined and discussed their main characteristics and differences (refer to Figure 1) [3].

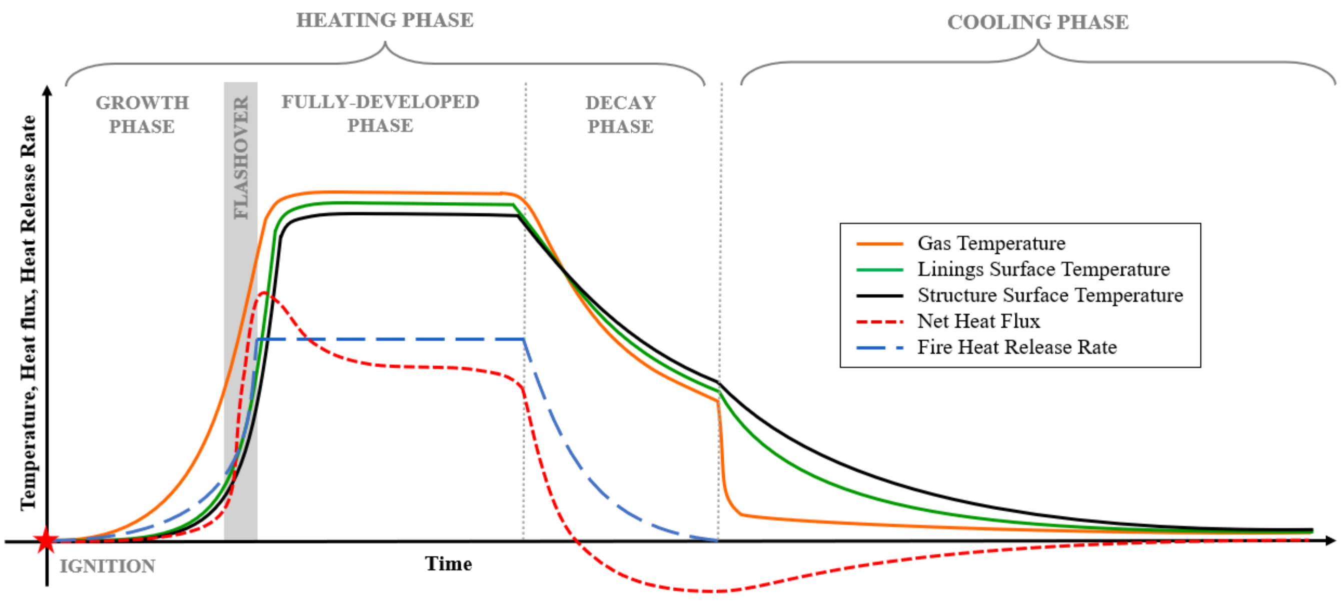

Figure 1. Comparison between gas, compartment linings surface temperatures, structural element surface temperature, net heat flux, and fire heat release rate during the various phases of a post-flashover compartment fire [3].

2.2 Thermal boundary conditions

To perform an accurate assessment of the fire performance of structures, it is important to understand the various phases that occur during a fire event and, more importantly, properly define the thermal conditions at the boundaries of the structural element under analysis [12]. A general definition of the thermal boundary conditions to an exposed structural element j can be written in accordance with equation (1), which considers the convective heart transfer with the surrounding gases and radiative heat transfer with the various compartment elements i and the fire flames [3]:

$$\dot{q}''_{net,j} = h_c\left(T_g - T_{s,j}\right) + \sum_{i=1}^{n} F_{i-j}\bar{\varepsilon}\sigma\left(T_i^4 - T_{s,j}^4\right) + \dot{q}''_f \quad (1)$$

where $\dot{q}''_{net,j}$ [W/m^2] is the net heat flux received at the exposed surface of the structural element j under analysis, which has a surface emissivity ε_j [-] and a surface temperature $T_{s,j}$ [K]; h_c [W/m^{2}K] is the convective heat transfer coefficient; T_g [K] is the temperature of the surrounding gases; σ is the Stefan–Boltzmann constant (5.67 x 10^{-8} W/m^{2}K^4); F_{i-j} [-] is the view factor between the structural element j under analysis and another compartment element i, which has a surface emissivity ε_i [-] and a surface temperature T_i [K]; $\bar{\varepsilon}$ [-] is the effective emissivity, which can be calculated combining the emissivities of the emitting and receiving body (ε_i and ε_j); $\dot{q}''_f$ [W/m^2] is the radiative heat flux from the fire flames. Equation (1) can be utilized to accurately characterise the heat transfer occurring at the element surface throughout different fire phases. The objective is to accurately replicate the heat fluxes experienced by the compartment elements being studied.

However, within the structural fire engineering practice, the fire exposure is commonly defined by a single temperature-time curve and the thermal boundary conditions are simplified as equation (2):

$$\dot{q}''_{net} = h_c\left(T_g - T_s\right) + \varepsilon\sigma\left(T_g^4 - T_s^4\right) \quad (2)$$

This equation is also in line with the thermal boundary conditions defined in Eurocode 1 [13], which are characterised by a single-temperature time curve and given heat transfer coefficients (convective and effective emissivity) and therefore to be considered as a theoretical adiabatic surface temperature [14]. This concept applies well for the fully-developed fire phase, where the compartment is characterised by an optically-thick medium (smoke) and a single gas temperature can provide an appropriate estimation of radiative and convective heat transfer from the compartment gases to the analysed structural element.

However, even if the concept (i.e. mathematical expression) can be also applied to other phases, in the fire decay and cooling phase, the theoretical adiabatic surface temperature cannot be readily interpreted as corresponding to a single physical gas temperature because of the significantly different contributions of convection and radiation [3]. In the fire decay and cooling phase, equation (1) represents a more appropriate and generalised expression for the definition of the thermal boundary conditions to structural elements during and after fire. However, this solution may become complex, for instance the quantification of the radiative heat flux from the fire flames ($\dot{q}''_f$) and the radiation exchange between compartment elements.

In any case, in order to reproduce realistic fire conditions as boundary condition for structural fire engineering calculations, during the various fire phases, the thermal boundary conditions should be specified in accordance with the fire dynamics within the compartment. This is particularly relevant for the fire decay and cooling phase, which significantly differ from the fully-developed fire phase and have been traditionally overlooked.

3 COMPARING METHODS

Recent research advances have been critically analysing and proposing various engineering approaches to estimate the thermal exposure of post-flashover compartment fires on load-bearing structural elements. The available literature offers a vast range of methods of various complexities, which have been more or less successful and worldwide adopted by the structural fire engineering practice [8]. Table 1 lists and compares the main methods for performance-based structural fire engineering, focusing on the definition of the thermal boundary conditions to structural elements during all the fire phases.

Table 1. Comparison between available methods to estimate the thermal exposure of post-flashover compartment fires, focusing on the defined thermal boundary conditions to structural elements during the various fire phases.

Method	**Type**	**Fully-developed phase**	**Fire decay phase**	**Cooling phase**
Standard fire curve [13]	Analytical	Single T-t curve	Not included	Not included
Eurocode parametric fire curves (Annex A) [13]	Analytical	Single T-t curve	Unclear distinction decay/cooling Onset of decay/cooling at fuel burnout Single T-t curve with linear decay	
iBMB parametric fire curves [15]	Analytical	Single T-t curve	Distinction between fire decay and cooling Onset of fire decay at 70% fuel load Single T-t curve with parabolic decay	
BFD curves [16]	Analytical	Single T-t curve	Distinction between fire decay and cooling Onset of fire decay at 70% q_f Single T-t curve with parabolic decay	
Lucherini *et al.* [17]	Analytical	Single T-t curve	Not included	Onset of cooling at fuel burnout Convective cooling with ambient temperature (T_g) Radiation exchange with surrounding elements (T_w)
OZone [18-19]	Zone model	Single T-t curve	Distinction between fire decay and cooling Onset of fire decay at 70% fuel load Single T-t curve	
C-FAST [20], B-RISK [21]	Zone model	Single T-t curve	Distinction based on input fire HRR Single T-t curve	
FDS [22]	CFD	Distinction between various phases based on input fire HRR Various thermal boundary conditions		

The various methods compared in Table 1 rely on different assumptions and simplifications: from analytical formulations to zone-models and computational fluid dynamics (CFD) simulations. Starting with the ISO 834 standard fire curve, this approach only examines the fully-developed fire phase with a monotonically increasing temperature-time curve and structural elements are tested or assessed for a specific duration. This method does not have any consideration of the fire decay and cooling phase and it has been extensively criticised over the last few decades [1].

The following analytical methods introduce the fire decay and cooling phase, even though these are not often distinguished or comprehensively defined. The Eurocode parametric fire curves [13] are a widely adopted methodology which was developed starting from the Swedish fire curves and offers analytical expressions to generate the temperature-time fire curves as a function of the compartment geometry, fuel load, and compartment linings. However, after the fully-developed phase, the fire curve is simplified into a linear decay relationship, which confuses fire decay and cooling and prescribes constant cooling rates with no physical basis [9]. In addition, the fire heat release rate is not made explicit. However, the duration of the fully developed phase is calculated based on the total fuel load, therefore assuming that the end of the fully-developed phase corresponds to fuel burnout (hence onset of cooling) and disregarding the fire decay phase [3].

Similar methods based on analytical parametric fire curves are the iBMB parametric fire curves [15], which have been adopted in the German annex of Eurocode 1, and the BFD curves [16]. Both methods have been obtained from regression analyses of simulations or fire tests data and they calculate key durations and temperatures to define temperature-time fire curves which can be subdivided in four parts: growth, fully-developed, decay and cooling. After the fully-developed fire phase, both methods theoretically foresee a fire decay phase, which commences when 70% of the total fuel load has combusted, and then a cooling phase. These phases are characterised by a parabolic/exponential decay curve. However, the authors do not provide any distinct specification to definte the thermal boundary conditions during the fire decay and cooling phases (i.e. continuous temperature-time curve).

A zone-model, such as OZone [18-19], C-FAST [20] and B-RISK [21], adopts fundamentals of thermo- and fluid-dynamics to typically simplify the fire compartment in two zones, an upper layer constituted by hot smoke and a lower layer constituted by cold air at ambient temperature. They enable the direct input and control of the time-history of the fire heat release rate, therefore the distinction between the various fire phases is up to the user. In OZone, the fire heat release rate is defined according to the advanced fire models from Annex E of Eurocode 1 [13], where the fire decay begins when 70% of the total fuel load has combusted, followed by a cooling phase. Nevertheless, for the quantification of the fire exposure, also zone-models typically provide a single temperature-time curve, which is usually taken as the temperature evolution of the upper (smoke) layer.

In general, the above-mentioned methods define a single temperature-time (T-t) curve to define the thermal boundary conditions to structural elements in fire conditions. This temperature evolution is usually treated as a theoretical adiabatic surface temperature [14] and equation (2) is usually adopted in accordance with Eurocode 1 [13]. However, as discussed in Section 2.2, this simplification may introduce significant errors in the fire decay and cooling phase due to the major differences in the compartment fire dynamics with the fully-developed fire phase, which has been traditionally the main focus of structural fire calculations [3].

Directly defining the fire heat release rate, separating the various heat transfer components, and defining comprehensive thermal boundary conditions (e.g. net heat flux) are usually possible in more complex methodologies, like the Computational Fluid Dynamics (CFD) software Fire Dynamics Simulator (FDS) [22]. However, this approach typically requires a much more accurate level of detail and overall effort.

With a view on developing an analytical model to estimate the thermal exposure to structural elements during a natural fire, focusing on the cooling phase and separately considering the convection and radiation heat transfer contributions, a simplified model based on a first-principles approach has recently been proposed [17]. According to this methodology, first, the compartment thermal conditions during the heating phase are approximated according to the Eurocode parametric fire curves [13]. After fuel burnout, the compartment gases are assumed to return to optically thin conditions and the gas temperatures to return to ambient values, while the compartment solid elements (e.g. linings) slowly cool down by convection and provide radiation exchange to the exposed structural elements. While these simplifications introduce quantitative errors, they enable an analytical solution for transient heat conduction that captures all key heat transfer processes.

4 METHODOLOGY

4.1 Case study definition

In order to compare the discussed methods to estimate post-flashover compartment fires for performance-based structural fire engineering, a case study has been selected from the existing literature with specific ventilation conditions, geometry, compartment linings materials (i.e. thermal inertia), and fuel load density. The chosen case is extracted from the series of full-scale fire tests carried out in 1999-2000 at the BRE Cardington facilities within the scope of the “Natural Fire Safety Concept 2 (NFSC2)” series [23]. The series was conducted on a compartment measuring 12 m x 12 m in plan, 3.4 m in height, a traditional compartment with incombustible linings where flashover and ventilation-controlled fires are expected. The testing campaign involved a total of eight scenarios, which differed for ventilation conditions, fuel load composition, and compartment boundaries. Test 8 is chosen for analysis, an exemplar case which has been largely used for various past analyses and modelling studies [23-25]. This scenario is characterised by an opening factor of 0.10 $m^{0.5}$ (unique opening, 7.2 m wide and 3.4 m high), a fuel load density of 680 MJ/m^2 (80% wood cribs and 20% plastic, by calorific value), and insulating compartment linings with an approximated thermal inertia of 740 $J/m^2s^{0.5}K$ [23-24].

The case study has been modelled according to some of the available methods presented in Section 3: analytical formulations like the Eurocode parametric fire curves [13], the German iBMB parametric fire curves [15], and the BFD temperature-time curves [16]; the first-principles model for the cooling phase proposed by Lucherini *et al.* [17]; and the zone-model OZone [18-19]. All the relevant model parameters (i.e. geometry, compartment ventilation condition, compartment linings materials, fire growth rate and heat release rate, fuel load density, etc.) have been defined and calculated in accordance with the above-mentioned case study. As regards to the compartment linings, they were defined in line with the thermal inertia reported in the test series and they were modelled with the following constant thermo-physical material properties: thermal conductivity 0.45 W/mK, mass density 1150 kg/m^3, and specific heat capacity 1000 J/kgK (properties similar to lightweight concrete, with a thermal inertia equal to 720 J/m^{2}s$^{0.5}$K).

4.2 Thermal analysis and comparison

The main outcomes of the various models are then analysed and compared. In particular, the various cases are compared in terms of the time-history of the fire heat release rate and several temperature evolutions, which include the compartment gas phase (T_g), the compartment linings surface (T_w), as well as the theoretical adiabatic surface temperature (T_{adb}). The various approaches and the corresponding thermal exposures during all the fire phases are compared, and their implications are discussed.

To investigate the implications of the various estimated fire exposures for structural fire engineering, a pure conduction one-dimensional heat transfer model is formulated to investigate the heat transfer within structural elements exposed in the analysed compartment. The solid is discretised into a number of finite elements, associated to nodes, and it explicitly solves a one-dimensional heat conduction problem by resolving energy-balance equations in the main direction of the heat flow. The heat transfer model focuses on the thermal boundary conditions and the heat penetration within the lightweight concrete compartment linings, assumed as load-bearing elements like a compartment ceiling/slab or wall. The thickness of the load-bearing element is set to 200 mm to ensure its thermal thickness, taking into consideration the defined material properties and thermal conditions. The solid space is discretised in finite elements with a thickness of 1 mm, and the time step is set to 0.01 s, following numerical stability criteria.

The thermal conditions at the fire-exposed surface are defined according to the various methodologies, which include both the heating and the cooling phases of the fire scenario. When the thermal boundary conditions for the fire exposure are expressed as a single temperature-time curve and not stated otherwise, the thermal boundary conditions (radiation and convection) are defined in accordance with Eurocode 1, as reported in equation (2), with a convective heat transfer coefficient equal to 35 W/m^{2}K (advanced fire models) and a surface emissivity equal to 0.8 [13]. As a result, the temperature profiles within the structural element obtained following the different methodologies are analysed and compared to investigate the implications of various thermal boundary conditions at the exposed surface on the in-depth temperatures experienced by the load-bearing structure, both during the heating and cooling phase.

Finally, the effects of the various estimated fire conditions are compared in terms of the thermal energy accumulated within the solid (i.e. load-bearing element) during and after the fire. In particular, the evolution of the total in-depth thermal energy gain (per unit area) within the structural element, E''_{th} [MJ/m^2], is calculated in accordance with equation (3) [17]:

$$E''_{th}(t) = \int_0^d \rho c_p \Delta T(x,t)\, \mathrm{dx} \quad (3)$$

where, ρ is the mass density [kg/m^3], c_p is the specific heat capacity [J/kgK], and $\Delta T(x,t)$ [K] is the time-varying in-depth temperature rise (above ambient temperature, 20°C) within the thickness of the solid (d [m]). The rise and decrease of the in-depth thermal energy accumulated in the structural material are compared at the end of the fully-developed fire phase, as well as at fuel burnout and onset of cooling.

5 RESULTS AND DISCUSSION

5.1 Fire heat release rate

To investigate the thermal conditions produced by the various models for the presented the case study, the analyses first investigate the time history of the fire heat release rate assumed by the various models and compared to the experimental data, as shown in Figure 2. The fire heat release rate represents the most important parameter to characterise the fire conditions and dynamics inside the compartment. Information about the fire heat release rate also enables the distinction between the fire decay and cooling phase [3].

As regards to the experimental data shown in Figure 2, the estimated fire heat release rate follows a typical trend for ventilation-controlled compartment fires, with a rapid growth phase (about 10 min) and a quasi-steady fully-developed fire phase (about 20 min). The fire decay begins after around 30 minutes and has a long duration (approximately 45 min) with a gradual decrease branch, typical of charring fuels like wood cribs [3]. After about 70 minutes, the fire reaches fuel burnout and the onset of the cooling phase.

For the various engineering methods, the fire heat release rate can be an input or output depending on its characteristics. The fire heat release rate is usually an input for zone models, as well as for applications in Computational Fluid Dynamics (CFD). As regards the zone-model OZone [18-19], the fire heat release rate is defined according to the advanced fire models from Eurocode 1 [13]. Fuel load densities, effective heat of combustion, fire growth rates, and maximum values of fuel-controlled fire heat release rates are prescribed, and engineers can estimate the ventilation-controlled (based on opening factor) or fuel-controlled (based on building occupancy) maximum fire heat release rate for each specific case. This value is assumed constant throughout the entire fully-developed fire phase, while the decay phase is assumed to decrease linearly starting when 70% of the total fuel load has been burnt and completed when the fuel load has been completely burnt. Figure 2 reports the resulting time history of heat release rate obtained for the presented case study according to this methodology. In this case, due to the large compartment size, the maximum heat release rate is limited by the fuel conditions, in particular the maximum heat release rate per unit area and therefore the fire size (36 MW). Nevertheless, even if it contains strong assumptions, the methodology is generally robust and provides a clear definition of the fire decay phase and fuel burnout.

In contrast, the Eurocode parametric fire curves [13] do not have this rigorous definition of the energy contribution (i.e. fire heat release rate) and the fire decay phase, as for the natural fire models. It is common belief that Eurocode parametric fire curves methodology is based on the same principle as natural fire models. However, the duration of the fire fully-developed phase is in effect calculated assuming that the total fuel load is consumed during the fully-develop phase at a steady-state heat release rate (ventilation- or fuel-controlled) and therefore the end of this phase should correspond to the beginning of the cooling phase, without any decay phase [3]. In the case presented in Figure 2, according to this methodology, the duration of the fire fully-developed phase is calculated based on the opening factor and the total fuel load and the fire results ventilation-controlled, with a maximum fire heat release rate equal to 62.7 MW. The recently-proposed model for the cooling phase [17] adopted the same assumption to allow for a consistent comparison of the EPFC cooling rates with cooling rates obtained through a first-principles approach.

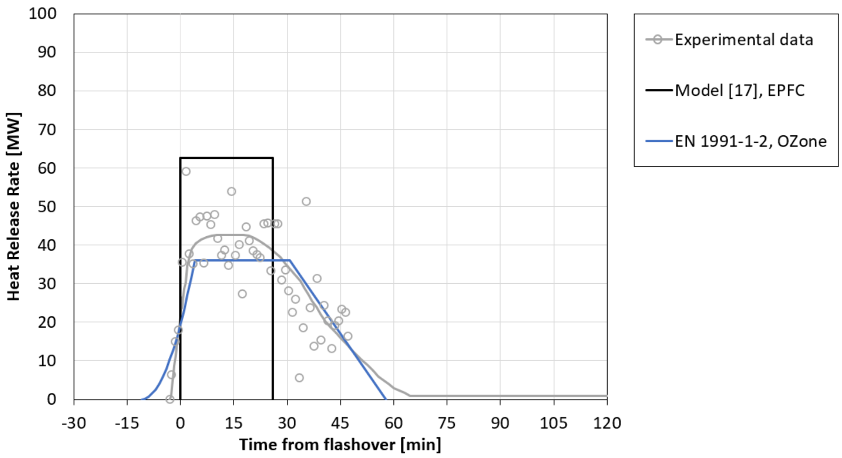

Figure 2. Fire heat release rate according to different methods, including experimental data [25].

5.2 Compartment temperatures and thermal boundary conditions

For the selected case study, the thermal exposures in terms of temperature-time curves estimated according to different methods for post-flashover compartment fires and obtained experimentally from the large-scale fire test are compared and shown in Figure 3. Similarly to Figure 2, since some methods include the growth phase of the fire and other not, for illustration purposes, the temperature-time curves are shifted to achieve flashover at the same instant (assumed to occur when the smoke layer temperature achieves 550°C [26].

The different methods can be adopted to reproduce a range of natural fire exposures, but each approach evidences specific characteristics and shortcomings. As it has been already underlined by several other researchers [9], the results confirm that the constant cooling rate of the Eurocode parametric fire curves is noticeably inaccurate to reproduce the thermal exposure during the fire decay and cooling phase. Indeed, after the fully-developed phase, temperatures are normally characterised by a parabolic/exponential decreasing branch. Regarding the other methods, the iBMB parametric fire curves appear to define the most critical scenario (highest temperatures and longest fully-developed phase duration), while the zone-model OZone specifies the lowest temperatures, amongst the studied approaches.

While Figure 3 seems to demonstrate an overall agreement between models and experiments, this is purely based on temperature measurements and does not describe the heat transfer environment. Indeed, the thermal exposure to structural elements during fire directly depends on the defined thermal boundary conditions. In most cases, a single temperature-time curve is defined, as it is usually treated as a theoretical adiabatic surface temperature with given heat transfer coefficients [14].

The only method that attempts to separate the convective and radiative heat transfer during the cooling phase is the one proposed by Lucherini *et al* [17]. As shown in Figure 3, at fuel burnout (end of the fully-developed phase), the compartment gas temperature (T_g) quickly drops to ambient temperature and the compartment elements cool down by natural convective cooling, which also defined radiative heat exchange between the exposed compartment surfaces (T_w). In order to provide a direct comparison between the various temperature-time curves, Figure 3 also reports the adiabatic surface temperature (based on Eurocode 1 heat transfer coefficients) for this case, which was calculated starting from the net heat flux to the structural element estimated according to the defined thermal boundary conditions. In general, the simplified method offers reasonable agreement with the temperature evolution, as it is based on a correct phenomenological description of the compartment conditions during the various fire phases, explicitly including consistent treatment of the thermal boundary conditions and the fire heat release rate.

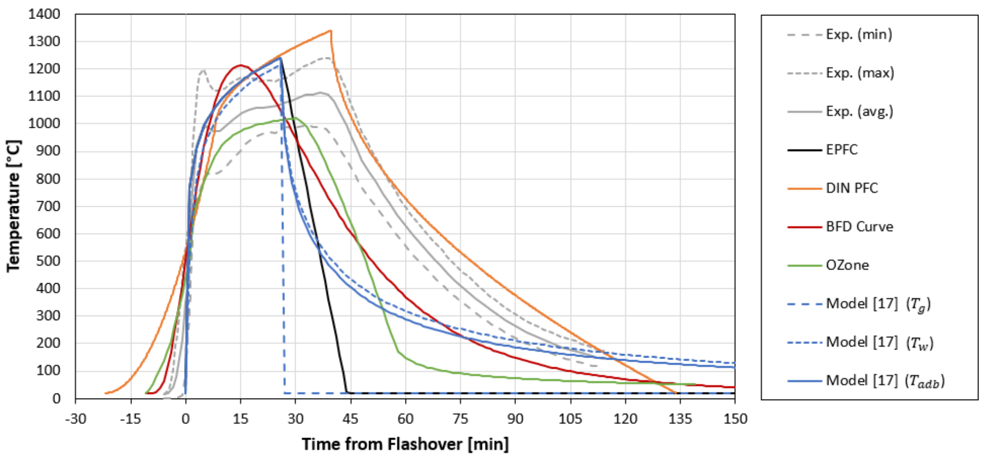

Figure 3. Comparison between experimental results [23] and the temperature-time curves estimated according to different methods (shifted to achieve flashover at the same instant, defined when temperature reaches 550°C) [26].

5.3 In-depth temperature profiles and accumulated thermal energy

To investigate the actual implications of the various estimated fire exposures and defined thermal boundary conditions for structural fire engineering, the heat penetration and in-depth temperature profiles within the studied load-bearing element (lightweight concrete wall/slab) are analysed thanks to the described one-dimensional heat transfer model (refer to Section 4.2).

Figure 4 reports and compares the in-depth temperature profiles within the analysed structural element according to different methods at the end of the heating phase, i.e., the instant of maximum fire (gas) temperature, and 30 minutes later. Without a doubt, the observed in-depth temperature profiles illustrates the direct consequence of defining the temperature-time curves shown in Figure 3. As regards to the end of the heating phase, the temperature profiles within the structural element are distinctive for the defined thermo-physical properties (i.e. thermal diffusivity), with higher surface temperatures and deeper thermal penetrations when the fire exposure achieves higher temperatures and the fully-developed phase lasts for longer durations (i.e. iBMB parametric fire curve). As regards to the temperature profiles during cooling, the surface temperature is again directly dependent on the fire exposure and the surface thermal boundary conditions. However, the thermal penetration in the load-bearing material is affected by the total thermal energy that has been provided (and lost) at the exposed surface, which is the direct effect of the thermal boundary conditions. For instance, the direct comparison between the temperature profile for the iBMB parametric fire curve and BFD curve highlights how, even if the surface temperature is practically identical 30 minutes after the instant of maximum fire (gas) temperature, the thermal penetration for the iBMB curve is significantly deeper due to the longer fully-developed phase with higher temperatures.

The effects of the various estimated fire conditions according to the different methods is then more evident when the rise and decrease of thermal energy accumulated within the solid (i.e. load-bearing element) is calculated according to equation (3) and compared. Figure 5 displays the temporal evolution of the total in-depth thermal energy gain (per unit area) within the structural element (E''_{th}) during the whole fire event. In particular, Figure 5 also highlights the instant of maximum fire temperature, which corresponds to the end of the fully-developed fire.

Figure 5 underlines how, even if the thermal energy gain during the fully-developed phase is almost identical for most cases (except OZone), during the fire decay and cooling phase, the accumulated thermal energy in the analysed structural element differs significantly between the various methods. More importantly, in most models, the energy gain does not stop at the end of the fully-developed phase, but still increases up to additional 30 minutes and more than 35% (BFD curve). On the contrary, according to the cooling phase model [17], in which the fully-developed phase is assumed as fuel burnout and convective cooling occurs after this point leading to significant heat losses, the end of the fully-developed phase corresponds to the beginning of thermal energy decrease and solid cooling. Similar conditions are also produced by the iBMB parametric fire curve.

In conclusion, this result evidences the impact of the definition of the thermal boundary conditions and the significant differences between the various approaches in terms of the amount of the thermal energy which is absorbed by fire-exposed structural elements.

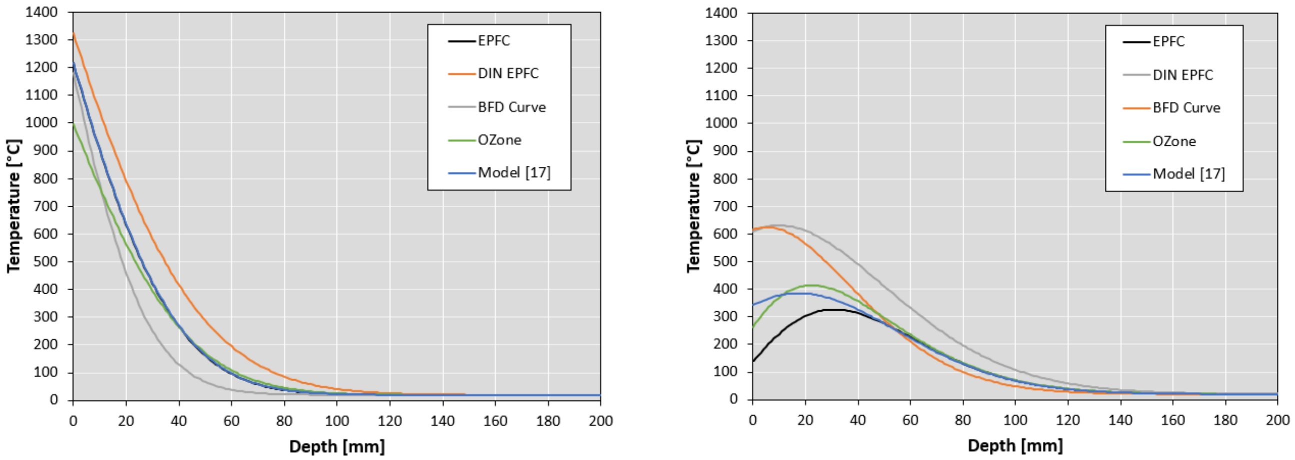

Figure 4. In-depth temperature profiles within the analysed structural element according to different methods at the instant of maximum fire (gas) temperature (left), and 30 minutes later into the fire decay or cooling phase (right).

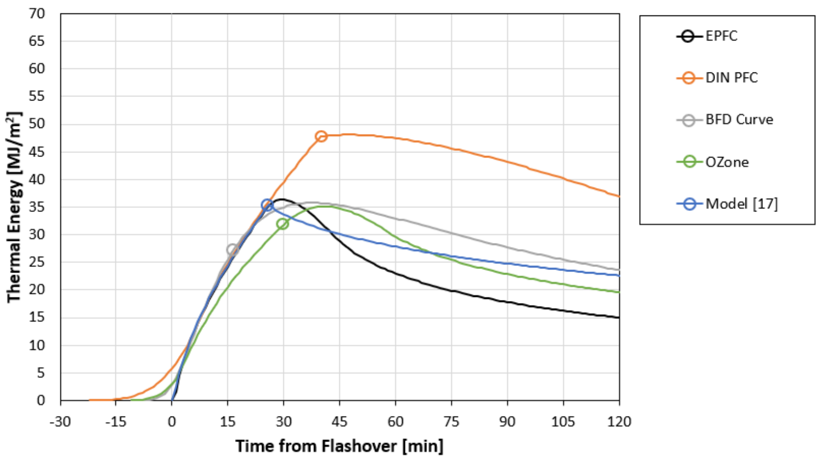

Figure 5. Total in-depth accumulated thermal energy within the analysed structural element according to different methods, highlighting the instant of maximum fire temperature (circles).

6 CONCLUSIONS

The current research study aims at discussing the fire decay and cooling phase of post-flashover compartment fires. Despite their distinct heat transfer characteristics, these phases are often mixed up, yet they play crucial roles in ensuring the structural integrity and stability of fire-safe structures.

The study examines their primary characteristics, and it underlines how the existing methodologies lack explicit and homogenised definitions of the fire decay and cooling phase and the corresponding thermal boundary conditions, often simplified into a single temperature-time curve. In addition, comparing how different methods define and treat the fire decay and cooling phase clarifies how the assumed/defined fire heat release rate and thermal boundary conditions can have a direct effect on the thermal energy and in-depth temperature profiles of structural elements, hence the assessment of their load-bearing capacity.

This research study highlights how specific methods may under- or over-estimate the thermal exposure of the fire decay and cooling phase, although the overall fire exposure is the most relevant aspect because the definition of the single phases provides little relevance to the overall assessment. In any case, this study confirms that the relevance of properly considering the fire conditions during the fire decay and cooling phase in modern performance-based methodologies for structural fire engineering.

ACKNOWLEDGMENTS

The authors would like to gratefully acknowledge the financial support for the FRISSBE project within the European Union's Horizon 2020 research and innovation programme (GA 952395) and for the FIReSafeTimber project within the European Union's Horizon Europe Marie Skłodowska-Curie Postdoctoral Fellowship (GA 101064840).

REFERENCES

[1] Law A., Bisby L.A. (2020). The rise and rise of fire resistance. *Fire Safety Journal*, 116, 103188.

[2] Gernay T., Franssen J.M. (2015). A performance indicator for structures under natural fire. *Engineering Structures*, 100, 94-103.

[3] Lucherini A., Torero J.L. (2023). Defining the fire decay and the cooling phase of post-flashover compartment fires. *Fire Safety Journal*, 141, 103965.

[4] Gernay T. (2019). Fire resistance and burnout resistance of reinforced concrete columns. *Fire Safety Journal*, 104, 67-78.

[5] Gernay T. (2021). Fire resistance and burnout resistance of timber columns. *Fire Safety Journal*, 122, 103350.

[6] Gernay T., Franssen J.-M., Robert F., McNamee R., Felicetti R., Bamonte P., Brunkhorst S., Mohaine S., Zehfuß J. (2022). Experimental investigation of structural failure during the cooling phase of a fire: Concrete columns. *Fire Safety Journal*, 134, 103691.

[7] Gernay T., Zehfuß J., Brunkhorst S., Robert F., Bamonte P., McNamee R., Mohaine S., Franssen J.-M. (2022). Experimental investigation of structural failure during the cooling phase of a fire: Timber columns. *Fire and Materials*, 1-16.

[8] Khan A.A., Usmani A., Torero J.L. (2021). Evolution of fire models for estimating structural fire-resistance. *Fire Safety Journal*, 124, 103367.

[9] Hopkin D., Van Coile R., Hopkin C., LaMalva K., Spearpoint M., Wade C. (2022). Design Fires and Actions. In: International Handbook of Structural Fire Engineering, *The Society of Fire Protection Engineers Series*.

[10] Gernay T., Pei J., Tong Q., Bamonte P. (2023). Numerical analysis of the effects of fire with cooling phase on reinforced concrete members. *Engineering Structures*, 293, 116618.

[11] 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.

[12] Torero J.L., Law A., Maluk C. (2017). Defining the thermal boundary condition for protective structures in fire. *Engineering Structures*, 149, 104-112.

[13] EN 1991-1-2:2002. Eurocode 1: Actions on structures – Part 1.2: General actions – Actions on structures exposed to fire. *European Committee for Standardization (CEN)*. Brussels, Belgium.

[14] Wickström U. (2016). Temperature calculation in fire safety engineering. *Springer Cham*.

[15] Zehfuss J., Hosser D. (2007). A parametric natural fire model for the structural fire design of multi-storey buildings. *Fire Safety Journal*, 42(2), 115-126.

[16] Barnett C.R. (2002). BFD curve: a new empirical model for fire compartment temperatures. *Fire Safety Journal*, 37(5), 437-463.

[17] Lucherini A., Jovanovic B., Torero J.L., Van Coile R., Merci B. (2024). Thermal characterisation of the cooling phase of post-flashover compartment fires. *International Journal of Thermal Sciences*, 199, 108933.

[18] Cadorin J.F., Franssen J.M. (2003). A tool to design steel elements submitted to compartment fires—OZone V2. Part 1: pre- and post-flashover compartment fire model. *Fire Safety Journal*, 38(5), 395-427.

[19] Cadorin J.F., Franssen J.M. (2003). A tool to design steel elements submitted to compartment fires - OZone V2. Part 1: pre- and post-flashover compartment fire model. *Fire Safety Journal*, 38(5).

[20] Richard D. Peacock R.D., Reneke P.A., Forney G.P. (2021). CFAST – Consolidated Model of Fire Growth and Smoke Transport (Version 7). Volume 2: User's Guide. NIST Technical Note 1889v2, *National Institute of Standards and Technology (NIST).*

[21] Wade C., Baker G., Frank K., Harrison R., Spearpoint M. (2016). B-RISK User Guide and Technical Manual. SR364, *Building Research Association of New Zealand*.

[22] National Institute of Standards and Technology (NIST). (2022). Fire Dynamics Simulator (FDS). https://pages.nist.gov/fds-smv/

[23] Lennon T., Moore D. (2003). The natural fire safety concept - full-scale tests at Cardington. *Fire Safety Journal*, 38, 623-643.

[24] Welch S., Jowsey A., Deeny S., Morgan R., Torero J.L. (2007). BRE large compartment fire tests - Characterising post-flashover fires for model validation. *Fire Safety Journal*, 42(8), 548–567.

[25] Kumar S. *et al*. (2005). Natural fire safety concept - The development and validation of a CFD-based engineering methodology for evaluating thermal action on steel and composite structures". *Report EUR 21444 EN*.

[26] Drysdale D. (2011). An introduction to fire dynamics. *John Wiley & Sons*, 3rd Edition.