V4 guidelines on advanced structural fire safety design with Eurocodes

Visegrad Fund

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LIST OF SYMBOLS AND ACRONYMS

Symbols

c	[J·kg⁻¹ K⁻¹]	Specific heat
c_a	[kJ·kg⁻¹·K⁻¹]	Specific heat of steel
$\dot{h}_{net,d}$	[kW·m⁻²]	Design value of the net heat flux per unit area
k_{sh}	[—]	Correction factor for the shadow effect
$\dot{q}$	[W]	Heat flux
$\dot{q}"$	[W·m⁻²]	Heat flux over the elementary area
$\dot{q}''_{con}$	[W·m⁻²]	Convective heat flux
$\boldsymbol{s}$	[—]	Unit vector normal to the surface
t	[s]	Time of fire exposure
A_m	[m²]	Surface area of the member per unit length
A_m/V	[m⁻¹]	Section factor for unprotected steel members
C_{PT}	[J·m⁻²·K⁻¹]	Heat capacity of the Inconel plate plus a third of the heat capacity of the insulation pad (see plate thermometer description in [32])
E	[W]	Rate of increase of the energy
K_{PT}	[W·m⁻²·K⁻¹]	Heat conduction coefficient for the heat lost by conduction through the insulation pad plus along the Inconel plate
S	[m²]	Surface of the elementary area
V	[m³]	Volume of the member per unit length
α_c	[W·m⁻²·K⁻¹]	Convective heat transfer coefficient – 25 W·m⁻²·K⁻¹ for exposure to ISO 834 fire curve
λ	[W·m⁻¹ K⁻¹]	Conductivity
δ	[m]	Boundary layer thickness
ε_f	[—]	Emissivity of the surface = 1unless other than nominal fires are not considered;
ε_m	[—]	Emissivity of the surface, for steel profiles equal to 0.7
ε_{PT}	[—]	Surface emissivity of the plate thermometer
θ_g	[K]	Gas temperature (for standard fire exposure: ISO 834 fire curve, see p.3.2.1. EN 1991-1-2)
θ_m	[K]	Surface temperature (for steel profiles we assume $\theta_m = \theta_a$);
θ_{PT}	[K]	Plate thermometer temperature
θ_r	[°C]	Radiation temperature (for nominal fire we assume $\theta_r = \theta_g$)
θ_s	[K]	Surface temperature
ρ	[kg·m⁻³]	Density

ρ_a	[$kg \cdot m^{-3}$]	Steel density
σ	[$W \cdot m^{-2} K^{-4}$]	Stefan-Boltzmann constant equal to $5.67 \cdot 10^{-8}$ $W \cdot m^{-2} K^{-4}$
Φ	[—]	Configuration factor = 1unless other than nominal fires are not considered

Acronyms

AST	Adiabatic Surface Temperature
CFAST	Consolidated Model of Fire and Smoke Transport
CFD	Computational Fluid Dynamics
DNS	Direct Numerical Simulation
FDS	Fire Dynamics Simulator
FEM	Finite Element Method
HRR	Heat Release Rate
ISO	International Standardisation Organisation
LES	Large Eddy Simulation

INTRODUCTION

The idea behind V4 guidelines on advanced structural fire safety design with Eurocodes stems from various discussions at conferences, forums and workshops. How is it possible that when experts in the fields of fire safety and structural engineering do the "same thing", the approach and sometimes even the results may be quite different? Performance-based design brings a significant degree of freedom in addressing the challenges, it also requires more expertise, responsibility, and collaboration.

Collaboration and exchange of experience and best practice was also the main idea when the V4 project proposal titled Advanced structures design – fire safety guidance for V4 was being prepared. Academics and practitioners from the Czech republic, Hungary, Poland, Slovakia and Serbia participated in this effort and shared their experience and lessons learned. The intention was to come up with a common framework and guidance that could supplement Eurocodes when advanced structural fire safety design is conducted.

The performance-based or advanced structural fire safety design is recognised by Eurocodes as a relevant approach. Given the nature of Eurocodes and the extensive areas of advanced fire and structural modelling, there is only limited guidance included. So the intent of these guidelines is to bridge the various international standards, guides, handbooks and papers on advanced fire and structural modelling, highlight important concepts, point at potential caveats, and provide examples of application.

These guidelines do not try to replace or reproduce any of the above listed standards and information sources – it would not be possible to gather all the relevant in one place and keep it up to date.

The intended target group are primarily structural and fire engineers, but also the enforcing authorities and project reviewers. The authors hope that the guidelines will reduce ambiguity and help increase quality, efficiency, safety and robustness of designs.

The guidelines are divided into 6 chapters, which should follow the chronology of a structural fire safety design. Chapter 1 introduces the Eurocode approach to structural design for fire conditions, including the simple and advanced approaches. Chapter 2 focuses on establishing the thermal effects of fire in terms of available approaches (simple nominal temperature curves to CFD fire models) as well as fire scenarios as a prerequisite for fire severity estimation. Chapter 3 links the heat from fire to the exposed structure and presents recommended way of transferring information from fire models to structural models. Chapter 4 is focused on structural modelling, primarily FEM models and their possible application in modelling mechanical response of fire-exposed structures. Chapter 5 summarises important points regarding the conceptual representation of the design task at hand, sensitivity and uncertainty associated with computer fire and structural modelling, and data quality. Chapter 6 provides selected examples of application of combined fire and structural modelling for design purposes. The Annex is an overview of fire resistance requirements for various types of construction elements in the participating countries.

1 INTRODUCTION ON EUROCODES STRUCTURAL FIRE SAFETY DESIGN

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1.1 List of Eurocodes

Currently, the Eurocodes are regarded as the most comprehensive set of standards for structural design. The Structural Eurocode programme comprises ten standards, further divided into parts, focusing on e.g., ambient, or structural fire design:

- EN 1990, Eurocode: Basis of structural design
- EN 1991, Eurocode 1: Actions on structures
- EN 1992, Eurocode 2: Design of concrete structures
- EN 1993, Eurocode 3: Design of steel structures
- EN 1994, Eurocode 4: Design of composite steel and concrete structures
- EN 1995, Eurocode 5: Design of timber structures
- EN 1996, Eurocode 6: Design of masonry structures
- EN 1997, Eurocode 7: Geotechnical design
- EN 1998, Eurocode 8: Design of structures for earthquake resistance
- EN 1999, Eurocode 9: Design of aluminium structures.

The work on Structural Eurocode programme started in 1975, when the Commission of the European Community conceived the idea of a programme. The final versions of most of the Eurocodes were published in the early 2000s, with different adaptation dates by the local law.

1.2 Fire safety design of structures

The destructive power of fire on building structures is known since the dawn of history. Since from antiquity, historical sources, show that an apparently trivial ignition of fire can result in a fire difficult to manage, with consequences so significant that refurbishment may take years. The Great Fire of London (1666) was an extremely important event. The rules and legal regulations, developed as a consequence of that fire, are regarded as the first prescriptive guidelines in "modern" history that aimed to reduce the risk of the fire and the size of its effects. For hundreds of years, up to the late 1980s, most of the knowledge about fire safety was empirical based, and the safety aspects were mainly defined by arbitrary prescriptive regulations concerning construction materials, construction products, but also the buildings themselves and their placement. Those regulations, just as they are nowadays, tended to guarantee a satisfactory level of safety of people and property. One of the biggest breakthroughs in the history of structural fire safety was the development of the temperature-time curve for a fully developed fire in compartment, referred to today as the ISO 834 curve (or cellulosic curve, or standard nominal fire curve). This achievement allowed for standardisation of fire tests of structural materials and structural elements, and the methodology originated more than 100 years ago, is widely used today. However, modern engineering approaches tend to predict the physical phenomena based on trustworthy models, rather than being based on the prescriptive rules. These types of approaches are generally called performance-based approaches. The methodology that uses performance-based approaches in the field of fire safety engineering is called performance-based fire engineering. The design that uses performance-based approaches to fulfil design objectives is called performance-based design.

Performance-based fire engineering (PBFE) is used in many different areas concerning civil engineering, e.g. design of fire safety of buildings and other engineering objects. Generally, the correct design shall fulfil certain criteria resulting from requirements provided in design codes and other regulations. Contrary to a standard prescriptive approach, performance-based requirements particularly concern the operational goals of designed object. In the performance-based approach, the requirement may be defined as: the structural safety needed to be provided by avoiding the overheating of structural members during fire. A corresponding prescriptive-based requirement would simply define the minimum thickness of the fire protection paint.

The goal of applying the PBFE approach in civil engineering is mainly to avoid the risk of fire and provide a satisfactory level of safety for people and fire brigades during the fire, and to reduce the property losses caused by the fire and its implications. To make PBFE feasible, it is necessary to develop a set of a multi-discipline methods and regulations that allow engineers to make more sophisticated analyses of construction systems in fire than standard prescriptive methods.

Although the performance-based fire engineering approach involves assessment of many components resulting from requirements of fire safety, this contribution is placed in the structural fire engineering field (SFE). In performance-based structural fire engineering, design objectives are related to the performance of the structure in fire, i.e. ensuring the lack of partial and/or complete structural collapse during the specified period of the fire. Hence, performance-based fire engineering considerations require coupling of three types of analyses: fire modelling, thermal analysis and structural analysis. The workflow in performance-based structural fire engineering problems is summarised in Figure 1–1, where possible approaches for modelling of fire behaviour, thermal response, and structural behaviour are given. More detailed information about the methods used in the performance-based structural fire engineering, theoretical bases of these methods, referring to specific physical phenomena, material properties and mathematical models of material behaviour, etc. are given in [1].

Generally, the design process carried out by a structural engineer starts with the analysis of actions and their combinations acting on a structure. The same approach is always a starting point for the structural fire design. The general design rules are given in EN 1990, which is the main part of codes that establish the basis for using Eurocodes for structural design. In structural fire design, contrary to standard design, the temperature caused by fire is taken into account as the main variable action that influences the structural response. The combination of actions used in structural fire design is called the combination for accidental design situation and the accidental action A_d represents the design value of an indirect thermal action due to fire. Depending on the type of analysis, this action should be taken accordingly in the analysis of structures in fire. Then, depending on the complexity of the structure and design objectives, some practical decisions about the design process must be taken in order to make the design rational and feasible.

Regarding fire models, two possibilities can be distinguished: nominal fire curves and natural fires. The former consists of the ISO 834 curve (the most common, called the standard fire curve), but also the hydrocarbon fire curve and the external fire curve. All of them are included in Eurocode 1991-1-2 and they can be used to evaluate the thermal exposure of structures in fire. Natural fire models are all the other than nominal curves approaches. Natural fire models are used to describe the fire both qualitatively and quantitatively. Contrary to nominal fire curves, natural fire models take into account the specific conditions that exist in the designed object, i.e. thermal parameters of walls, ventilation conditions, fire load.

The choice of the fire model is somehow related to the chosen structural model. The first correspondence between the model of thermal exposure and the structural model (element, substructure, structure) was given by Witteveen in 1983. Witteveen's findings were adopted by Purkiss and finally rearranged by other researchers.

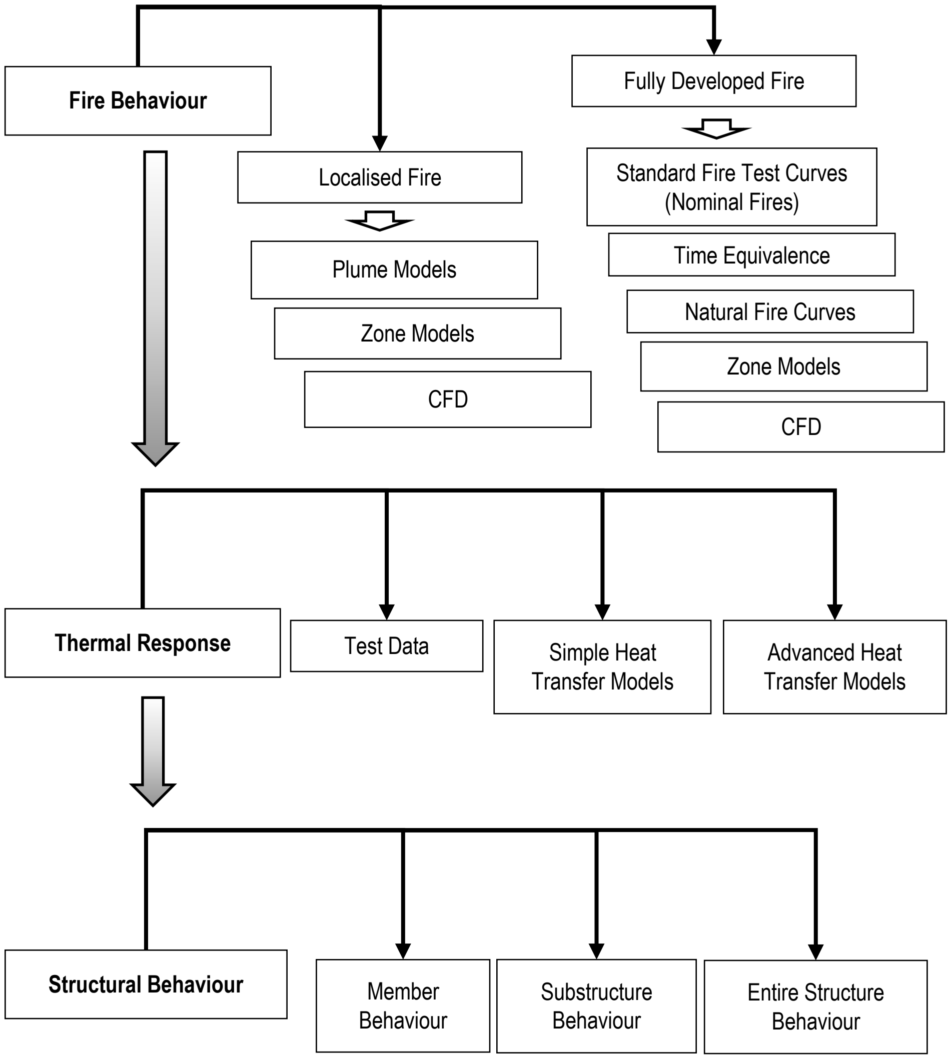

Figure 1–1 Available methods to define the Fire Behaviour, Thermal Response and Structural Behaviour

The above strategy and application procedures are all given in Eurocode EN 1991-1-2 in a straight-forward decision tree (Figure 1–2). No matter what design procedure is chosen; whether it is tabulated data, a simple calculation model or an advanced calculation model, there is always one, physically based scheme of analysis of structures in fire. Regardless of the fire condition or fire model and material of the structure, all the analyses must consist of three parts: (1) fire definition, (2) determination of temperature field inside the structure, (3) determination of mechanical response of structure. There are several methods for evaluation of those three inherent ingredients of each analysis, which are presented in Figure 1–1.

The fire resistance can be determined with either:

- Tabulated data
- Simple calculation models
- Advanced calculation models
- Testing

Short description of those methods is given in the following sections.

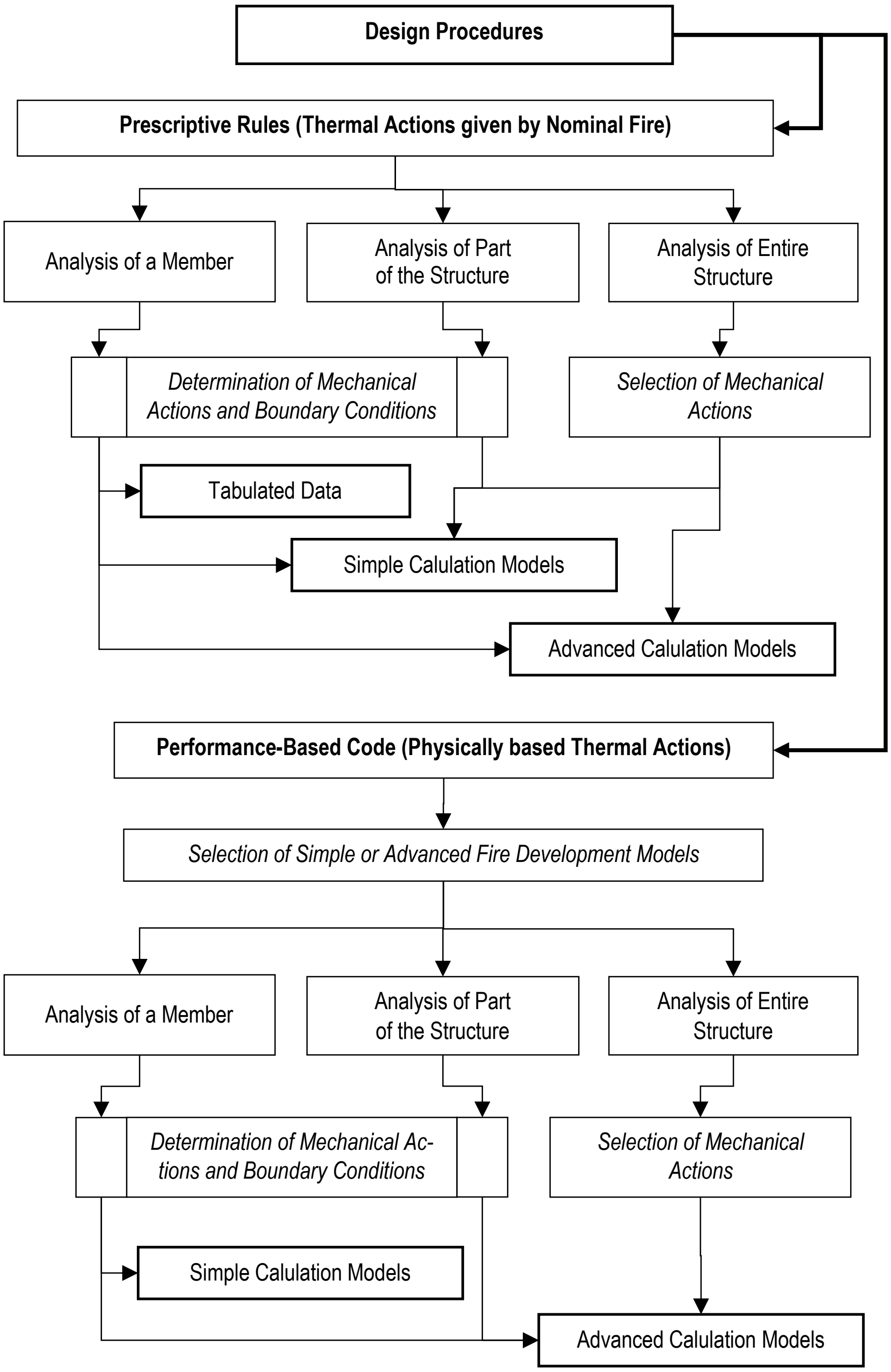

Figure 1–2 Alternative design procedures (according to Eurocode 1991-1-2)

1.3 Simple calculation models & tabulated data in Eurocodes

Tabulated design data is meant to be the first and easiest of methods in the Eurocode. It is based on an assumption that for certain, common cases, the results of calculation at ambient temperature (transient and persistent design situation) may be enough to assign a member to certain fire resistance class – this approach however is limited to standard fire exposure. The tabulated design data can be derived from tests, calculations or a combination of these two. In can be also presented in the form of an equation, such as equation 5.7 in EN 1992-1-2. Tabulated design data are believed to be conservative compared to tests or other methods, however the criteria for their derivation and validation vary from source to source. For example, one of the methods in Eurocode 2 gives results “on the safe side” only in case of 60 % of analysed test results [2], the simplified method in determination of design buckling resistance in Eurocode 3 is safe in 50 % of the cases [3]. On the other hand, the CEN/TC250 Horizontal Group Fire agreed to use the acceptance criteria for a new method, where at least 85 % of the results are on the safe side [4].

The general workflow in the design process can be found in Figure 1–3.

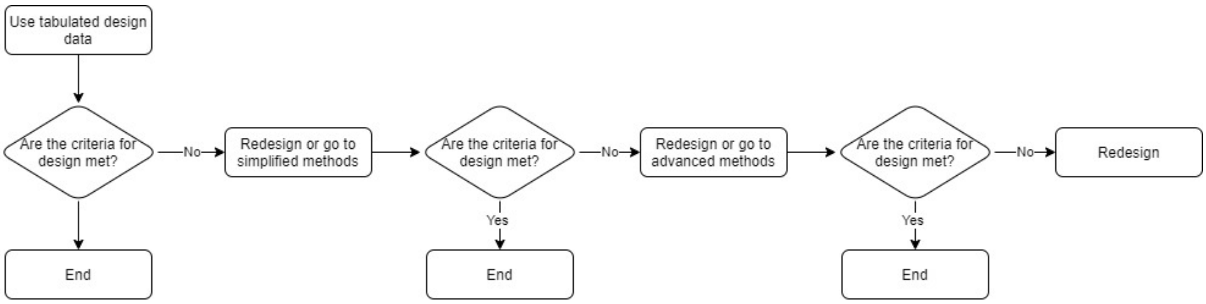

Figure 1–3 Design flowchart for the use of three level of methods in the Eurocodes

The tabulated design data can be found for concrete members (Eurocode 2), Composite members (Eurocode 4), and Masonry members (Eurocode 6). Tabular methods were not introduced to Eurocode 3, Eurocode 5 and Eurocode 9.

Tabulated data can be used for member analysis, simplified calculation models can be developed of member analysis as well as analysis of parts of the structure. Only advanced design models may be used of any type of analysis (member, parts of structure of global structural analysis). The description of advanced calculation models is given in the next section.

1.4 Advanced calculation models

Advanced calculation models can be applied for both approaches: prescriptive rules and performance-based. Since it is not possible to cover them all in details, Eurocodes give only general rules regarding their use. The advanced design methods shall be based on fundamental physical behaviour – taking into account e.g., temperatures in a section and displacements along a member. Such method may comprise two calculation models: for the determination of temperature and mechanical response model. If a potential failure mode (such as spalling of concrete or local buckling of steel) is not covered by an advanced method, it shall be prevented by appropriate means.

The advantage of advanced method is that it can be used for any cross-section, or any thermal action that can be used in association with advanced methods, providing the relevant data, such as material properties, is known.

As far as the mechanical analysis is concerned, it shall be based on the principles of and assumptions of the theory of structural mechanics. When necessary, it should take into account the effect of geometrical imperfections, geometrical and material non-linearities. Any advanced design method should be validated based on test results, preferably comparing calculated and measured quantities, such as: temperatures, deformations, and fire resistance times.

When applied for a global structural analysis, advanced design method shall cover the relevant failure mode (or modes), temperature-dependent material properties, member stiffness and the so-called “indirect” fire actions – the effects of thermal expansion and deformations.

In most design projects, the simple temperature-time relationships are used to define the fire model. Nevertheless, the temperature-time relationship is not necessarily the ISO 834 curve. The temperature-time relationships may be derived using approaches taking into account an actual fire characteristics in compartments, i.e. fire load, heat release rate, ventilation conditions and thermal properties of walls. However, the choice of the single temperature-time curve influences the way the thermal response is calculated. Currently, the advanced heat transfer models, which are able to calculate the non-uniform temperature field in a structural cross-section, are mostly used when concrete or composite structures are considered. Otherwise, a simple heat transfer model for steel structures, known from EN 1993-1-2, is commonly used. Using the simple heat transfer model for steel structures, it is possible to calculate only a single, approximated, uniform temperature of the structural member. However, applying the uniform temperature into the structural model does not make it possible to reflect the phenomena of thermal bowing, which can be substantial in some cases. Therefore, the choice of the heat transfer model influences the quality of mechanical analyses. Mechanical analyses take advantage of the development of the finite element method and are usually tailored to the example considered. Hence, the heat transfer model should also be adapted to the structural model in order to utilise its capabilities.

A more detailed description of advanced calculation models is given in next chapters. Chapter 2 concerns establishing the thermal effects of fire – fire modelling – and Chapter 4 concerns thermal and mechanical response of the structure – structural modelling. Chapter 4 bridges the gap between Chapters 2 & 4 – in Chapter 3, the connection between fire and structural models from the heat transfer perspective is described.

2 ESTABLISHING THE THERMAL EFFECT OF FIRE

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There are a number of approaches to determine the temperature of the environment which is an element or structure exposed to. EN 1991-1-2:2007 includes the following:

- Temperature curves:
    - Nominal;
    - Parametric;
- Natural fire models:
    - Simplified fire models;
    - Advanced fire models.

Each of the above approaches has a specific field of application and requires appropriate justification when applied. In general, the standard time-temperature curve is appropriate for most enclosure building fires, since it represent the temperature regime constructions elements are tested to and classified according to EN 1363-1 EN 13501-2. It should be also noted that when approaches other than the nominal temperature curves are used, the specifics of the evaluated cases (input parameters – e.g. enclosure dimension, ventilation, fuel load, etc.) become variable and play a significant role. This allows for a more detailed evaluation, however, one has to be careful about the assumption protection, i.e. how reasonable is to expect the parameters to remain fixed during the expected lifetime and what is the impact, should they change.

In general, Eurocode 1 assumes heat transfer from fire through convection and radiation as follows:

$$\dot{h}_{\mathrm{net}} = \dot{h}_{\mathrm{net,c}} + \dot{h}_{\mathrm{net,r}} \tag{2–1}$$

$$\dot{h}_{\mathrm{net,c}} = \alpha_{\mathrm{c}} \cdot \left(\Theta_{\mathrm{g}} - \Theta_{\mathrm{m}}\right) \tag{2–2}$$

$$\dot{h}_{\mathrm{net,r}} = \phi \cdot \varepsilon_{\mathrm{m}} \cdot \varepsilon_{\mathrm{f}} \cdot \sigma \cdot [(\Theta_{\mathrm{r}} + 273)^4 - (\Theta_{\mathrm{m}} + 273)^4] \tag{2–3}$$

where:

$\dot{h}_{\mathrm{net}}$	[W·m^{-2}]	Net heat flux on the fire-exposed surfaces;
$\dot{h}_{\mathrm{net,c}}$	[W·m^{-2}]	Net convective heat flux component on the fire-exposed surfaces;
$\dot{h}_{\mathrm{net,r}}$	[W·m^{-2}]	Net radiative heat flux component on the fire-exposed surfaces;
α_{c}	[W·m^{-2}·K^{-1}]	Convection heat transfer coefficient;
Θ_{g}	[°C]	Gas (fire) temperature in the vicinity of the fire-exposed member;
Θ_{m}	[°C]	Surface temperature of the fire-exposed member;
Θ_{r}	[°C]	Effective radiation temperature of the fire environment;
ϕ	[—]	Configuration (view) factor;
ε_{f}	[—]	Emissivity of the fire;
ε_{m}	[—]	Surface emissivity of the construction member.

Since the temperature of the environment (fire enclosure) changes with time, the heat transfer is transient. It is therefore necessary to appropriately determine the following:

1. temperature profile (spatial and temporal) of the environment;
2. heat transfer from the environment to the construction member or structure;
3. temperature profile within the exposed construction member or structure.

This chapter provides an overview of the approaches and methods that may be used to carry out the first step – obtaining the temperature profile.

2.1 Temperature curves

Temperature curves represent the simplest approach to obtaining the temperature profile in the fire enclosure. Eurocode 1 provides two types of temperature curves – nominal and parametric. Nominal temperature curves are standardised and are also used in fire resistance testing – furnace tests. Both nominal and parametric temperature curves assume uniform temperature distribution in the entire compartment.

2.1.1 Nominal temperature curves

There are three types of nominal temperature curves in Eurocode°1:

1. standard time-temperature curve;
2. external fire curve;
3. hydrocarbon curve (HC).

Standard time-temperature curve (also known as ISO 834 curve or cellulosic fire curve), where temperature Θ_g [°C] is expressed as:

$$\Theta_{\mathrm{g}} = 20 + 345 \cdot \log_{10}(8 \cdot t + 1) \qquad (2–4)$$

where:

t	[min]	Time.

The standard time-temperature curve represents the “standard” most often used temperature conditions for fire resistance testing of building construction elements. It should represent the conditions of cellulosic fuel fires inside enclosures.

When applying the standard time-temperature curves, the coefficient of heat transfer by convection should be taken as α_c = 25 m^{-2}·K^{-1}, as per 3.2.1 (2) of EN 1991-1-2.

External fire curve is expressed as:

$$\Theta_{\mathrm{g}} = 660 \cdot (1 - 0{,}687 \cdot e^{-0{,}32 \cdot t} - 0{,}313 \cdot e^{-3{,}8 \cdot t}) + 20 \qquad (2–5)$$

The external fire curve represents scenarios of fire exposure of the exterior face of the building envelope and external construction members, e.g. fires projecting from windows, garbage bin fires, etc. It accounts for heat loss to the exterior and hence should be used with caution where heat may not dissipate freely due to projecting construction elements or otherwise specific geometry. The maximum temperature is relatively low (680 °C) when compared to other fire curves.

When applying the external time-temperature curves, the coefficient of heat transfer by convection should be taken as α_c = 25 $m^{-2} \cdot K^{-1}$, as per 3.2.2 (2) of EN 1991-1-2.

Hydrocarbon curve is expressed as:

$$\Theta_g = 1080 \cdot (1 - 0{,}325 \cdot e^{-0{,}167 \cdot t} - 0{,}675 \cdot e^{-2{,}5 \cdot t}) + 20 \qquad (2\text{–}6)$$

The hydrocarbon curve represents fast-growing fires with a very rapid temperature increases, typical of flammable liquids, e.g. pool or spill fires. In about 5 minutes the hydrocarbon reaches approx. 950 °C, 1 050 °C in 15 minutes and stays steady at 1 100 °C from 30 minutes onwards. These are rather severe fire conditions, but should be considered when dealing with commercia, industrial or storage occupations where flammable liquids may be present in larger quantities.

When applying standard time-temperature curves, the coefficient of heat transfer by convection should be taken as α_c = 50 $m^{-2} \cdot K^{-1}$, as per 3.2.3 (2) of EN 1991-1-2.

There are also other fire curves such as smouldering fire curve [5], RWS fire curve, modified "increased" hydrocarbon curve (HC_{inc}) [6] and other. These curves may be used for specific purposes, e.g. for designing construction member to withstand tunnel fires, but their use and appropriateness should be always carefully evaluated and consulted with relevant stakeholders, together with the real-world fire scenario they are to represent.

For comparison the above described fire curves are shown in Figure 2–1.

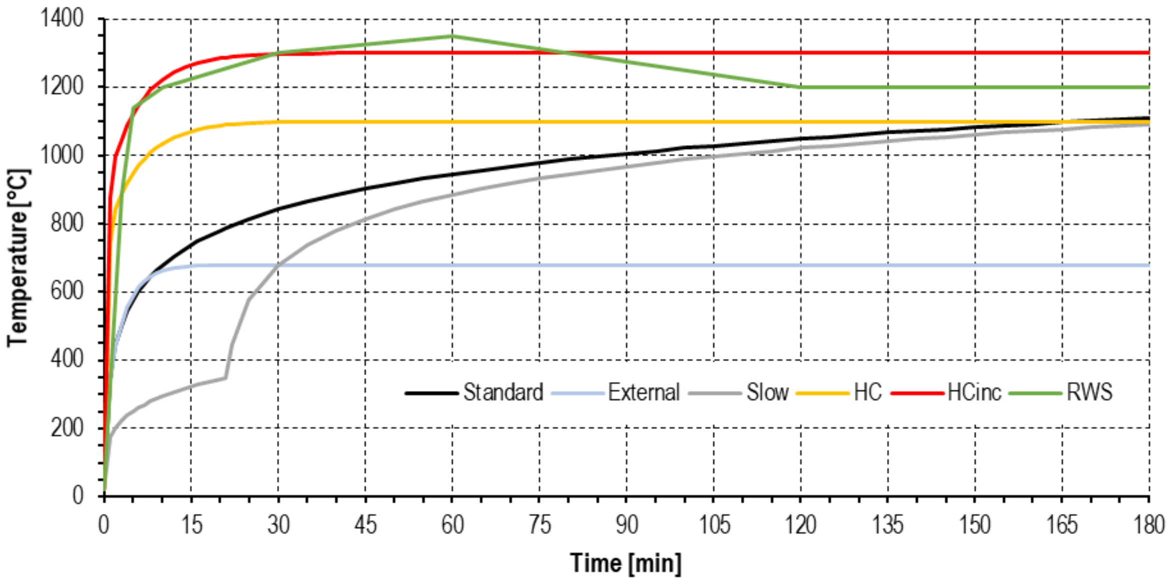

Figure 2–1 Comparison of various nominal time-temperature curves

2.1.2 Parametric temperature curves

Parametric fire curves could be considered simplified, empirically-based fire models for the prediction of temperature in the fire compartment, see also NOTE 2 of 3.3.1.2 of EN 1991-1-2. In comparison to the nominal temperature curves, they include not only the heating phase but also the cooling phase and account for a number of variables which are case-specific:

- fire compartment size and geometry;
- enclosure material thermal properties;

- compartment ventilation;
- fire load density;
- fire growth rate.

Annex A of EN 1991-1-2 provides the calculation procedure for establishing parametric temperature-time curves.

It should be noted that their application is limited to the maximum size of fire compartments of 500 m^2 and their maximum height of 4 m. The compartments must be naturally ventilated through openings in their walls; the calculation procedure is not applicable to compartments ventilated through roof/ceiling openings or forced ventilation.

When applying parametric time-temperature curves, the coefficient of heat transfer by convection should be taken as $\alpha_c = 35\ W{\cdot}m^{-2}{\cdot}K^{-1}$, as per 3.3.1.1 (3) of EN 1991-1-2.

2.2 Simplified fire models

EN 1991-1-2 divides simplified fire models in two categories:

- compartment fire models, and;
- localised fire models.

The main distinction between the above two is that the compartment fire models work with a uniform temperature distribution within the fire compartment, whereas the localised fire models with a non-uniform temperature distribution. In both cases the number of input parameters is limited, however, scenario specific.

When applying simplified fire models, the coefficient of heat transfer by convection should be taken as $\alpha_c = 35\ W{\cdot}m^{-2}{\cdot}K^{-1}$, as per 3.3.1.1 (3) of EN 1991-1-2.

2.2.1 Compartment fire models

These models assume a post-flashover situation with a uniform temperature distribution in the compartment. As a minimum EN 1991-1-2 requires that the temperature evolution in time accounts at least for fire load density and ventilation conditions. Combined, these two parameters are fundamental for the determination of fire severity (burning or heat release rate) and fire duration (fire load density / burning rate). For more adequate results the compartment boundary material properties should be also accounted for.

There are a number of such models in existence of various complexity. EN 1991-1-2 provides the parametric temperature-time curves for internal members (inside fire compartments; see also section 2.1.2) and a simplified calculation method for external members, in Annexes A and B, respectively.

2.2.2 Localised fire models

Localised fire models are representative of situations (scenarios) where flashover is not expected occur. These situations are characteristic of fuel-controlled fires. Fuel-controlled fires require sufficient/excessive oxygen (air) supply and a fuel package which is clearly bound and no fire spread is likely to occur to other fuel items inside the enclosure.

The above, however, does not mean less severe fires or lower temperature exposure. Locally, the fire may cause significant thermal stress to a construction member, e.g. a single flammable liquid storage vessel in a large production hall, which is sufficiently spatially separated to avoid fire spread. Hence, if such a fuel package and other conditions are present, the localised fire scenario and model should be considered in addition to other fire scenarios and thermal exposure models, e.g. nominal temperature curves.

The calculation procedure for the localised fire model is described in Annex C of EN 1991-1-2. The calculation procedure is based on the Annex also lists two further limits of use a maximum fire diameter of 10 m and heat release rate of 50 MW.

2.3 Advanced fire models

As advanced can be considered fire models that are able to predict the development of fire in a greater detail, taking into account gas properties, mass transfer and energy transfer (at least) within the fire enclosure.

The advanced fire models are usually based on a series of iterations with an appropriate time step. Within this group of models three categories are used:

- zone models:
    - one-zone models;
    - two-zone models;
- computational fluid dynamics (CFD) models.

EN 1991-1-2 recommends for advanced fire models the value of the heat transfer coefficient α_c = 35 W·m^{-2}·K^{-1}.

Their field and appropriateness of use is outlined in the following subsections. There are many free and proprietary models available, often with specific functionality, and it is beyond the scope and extent of these guidelines to introduce, or even list, them all. Hence, only the most commonly used ones are introduced; no endorsement or preference is imlied.

2.3.1 Zone models

Zone models are simpler due to the fact that they represent the fire environment as one or two distinct zones or layers, depending on the type of the model. Some models are able to transition from the two-zone representation (pre-flashover) to the one-zone representation (post-flashover). Each zone has uniform composition, temperature and other properties within its entire volume.

In two-zone models, the upper layer is considered hot and the lower layer cold. This approximation of the fire environment is valid for pre-flashover stages of fire, primarily local fire exposure. In addition, hot layer temperatures may be used for establishing thermal effects on structures (or their parts) which are in contact with the hot layer. Caution should be paid when the conditions are close to, or exceed, flashover limits. This may be the temperature of the hot layer of around 500 °C, the descent of the hot layer to the 20 % of the compartment height (the hot layer fills 80 % of the compartment height) [7], or radiant heat flux at floor level of around 20 kW·m^{-1}. Upon reaching these conditions, the model should transition to the one-zone, post-flashover mode, if such possibility exists. If not, then the simulation should be terminated as the results may be incorrect. The two-zone fire model approximation is shown in Figure 2–2.

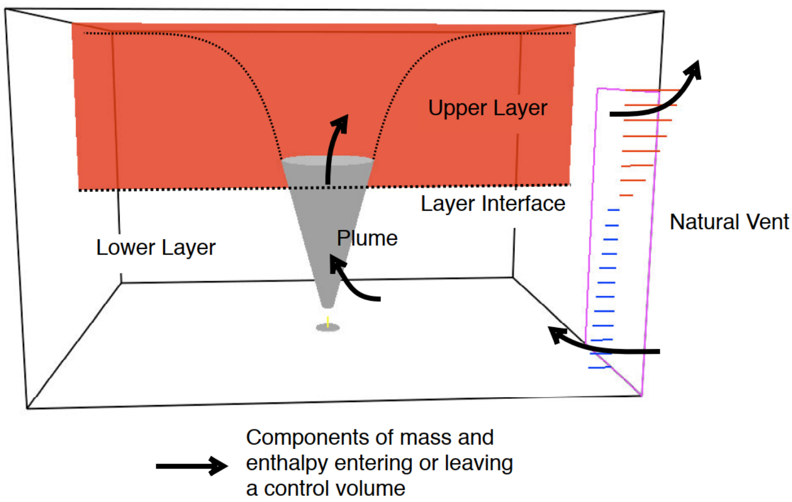

Figure 2–2 Schematic of control volumes in a two-layer zone model [8].

One-zone models on the other hand are appropriate for the prediction of thermal effects of fully developed fires. This assumes uniform exposure of all structural members (fully engulfed in fire or hot gases) within the fire enclosure, which is, in principle, similarly to the time-temperature curve exposure described in section 2.1. Further details on the recommended governing equations for one-zone models may be found in D.1 Annex D of EN 1991-1-2.

In the following subsections three common and freely available zone models will be briefly introduced.

2.3.1.1 Consolidated Model of Fire and Smoke Transport – CFAST

CFAST is a two-zone fire model capable of predicting the environment in a multi-compartment structure subjected to a fire. It calculates the time-evolving distribution of smoke and gaseous combustion products as well as the temperature throughout a building during a user-prescribed fire [8].

CFAST has been developed and maintained by the National Institute of Standards and Technology of the US. It is freely available through the Institute's website. The model itself is complemented by graphical user interface CEdit and visualisation postprocessor Smokeview, see Figure 2–3. Recently Monte-Carlo capabilities have been added to the suite through the Fire data generator CData [9]. Significant extent of verification and validation of CFAST is documented in the Software Verification and Validation Guide [10].

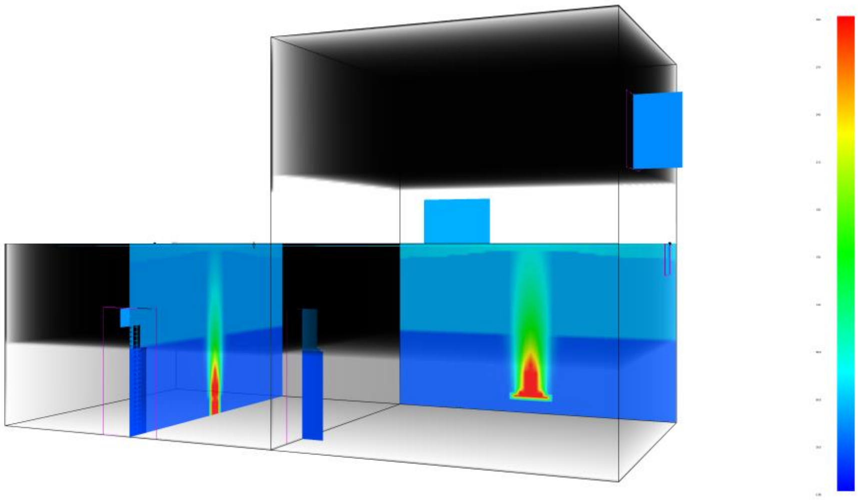

Figure 2–3 Example of CFAST simulation visualisation in Smokeview.

CFAST works with thermal properties of construction materials and measuring devices, but only with their fixed values. When predicting the hot layer temperature, the user is advised to evaluate the impact of changing values of material thermal properties on the resulting temperature. Similarly, such impact should be evaluated for the measuring devices representing construction elements – targets. Adiabatic boundary conditions are available for both enclosing surfaces as well as targets.

Fire as a heat source can be specified through its heat output (HRR [kW]), height [m] and area [m^2]. Another important parameter that requires specification is the radiative fraction [—]; the default value is 0,33. There is a possibility to specify a t^2 fire for the standard fire growth rate coefficients. When using this feature, it should be borne in mind that these standard fire growth rate coefficients assume peak HRR at 1 054 kW. If a different peak HRR value is required, then it needs to be calculated separately and then input as a combination of peak HRR and time when it is reached as per the required standard fire growth rate coefficient.

CFAST produces a range of outputs in a csv format, which can be directly utilized for mapping temperatures to construction member surfaces in structural models. In this regard the compartment surface temperature (project_walls.csv) and target temperature and heat flux (project_devices.csv) are particularly useful.

2.3.1.2 B-Risk

B-Risk is primarily a two-zone computer fire model developed by BRANZ and University of Canterbury in New Zealand. The model is based on the BRANZIFIRE model, which has been extended with various functionalities. It has the capability of running single-case simulations without variations as well as a series of runs of a particular scenario with sampled input(s) from user-defined distributions. Details on the use of the program and governing equations of the model may be found in the B-RISK user guide and technical manual [11]; the user is advised to refer to the B-RISK Software Version Release Notes on the BRANZ website and various background papers, since the user guide is from 2016 and the current version of the software from 2019. Validation of B-Risk in a form of benchmarking examples may be found in [12]. The software is freely available from the BRANZ website.

As mentioned above, B-Risk is a two-zone fire model, but it has capabilities to simulate post-flashover stages of fire. Flashover criteria can be set either to the temperature of the upper layer > 500 C or the radiant heat flux at floor level > 20 kW·m^{-2}. The simulation can then be either terminated or the model can be adjusted to the wood crib post-flashover model. Attention should be paid to the wood crib model settings and its overall appropriateness when the post-flashover submodel is utilized. There is also a simple equivalent fire resistance rating model included, which is based on the equivalence of the radiative heat for the calculated and ISO 834 exposures.

When specific fuel packages with known geometry but variable number and position are to be simulated, B-Risk design fire generator may be utilised. This feature allows the user to populate a specific space with predefined fuel packages. The fuel packages are randomly selected from the list and distributed in the designated space until a desired fire load density is achieved. Each of the fuel packages has its own predefined HRR curve to follow upon ignition. In addition to fuel package distribution, B-Risk allows to simulate item-to-item fire spread via thermal radiation.

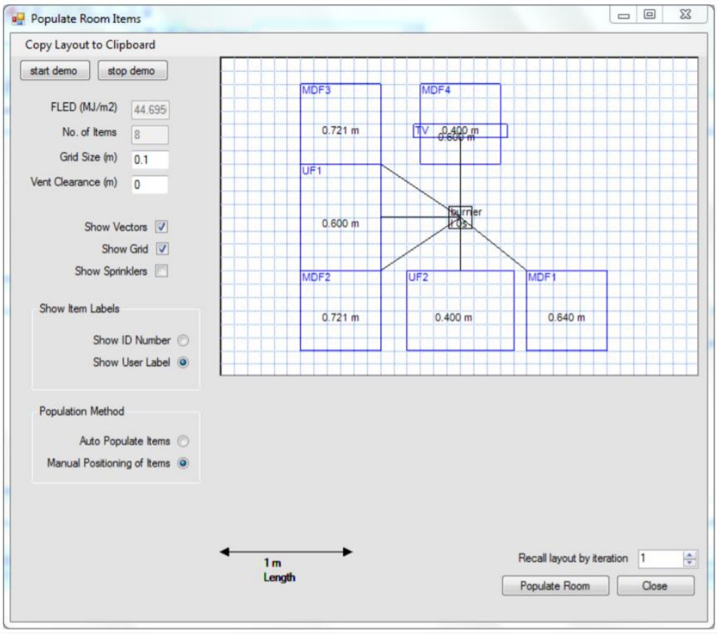

Figure 2–4 Design fire generator – room population – in B-Risk [11].

Monte Carlo simulation with stratified sampling is available for addressing uncertainty and variability associated with input parameters. Each distributed parameter is treated as independent and sampled so. The variables which allow assignment of a distribution have a dedicated button “distribution” next to the fixed input box. There are four types of distributions available:

- uniform (lower bound, upper bound);
- triangular (lower bound, mode, upper bound);
- normal (mean, variance, lower bound, upper bound);
- lognormal (mean, variance).

Except for the lognormal distribution, each of the above distributions may be truncated by specifying their upper and lower bounds.

B-Risk allows for fire simulation visualisation through Smokeview, in a similar fashion to CFAST. It has inbuild capability of showing histograms, time-series and other types of plots for analysis of the results. The console also displays important information (e.g. ignition of subsequent items, flashover, max. HRR, etc.) relevant to the fire development. The outputs for multiple iterations can also be displayed in one graph, such as in the example of HRR curves shown in Figure 2–5.

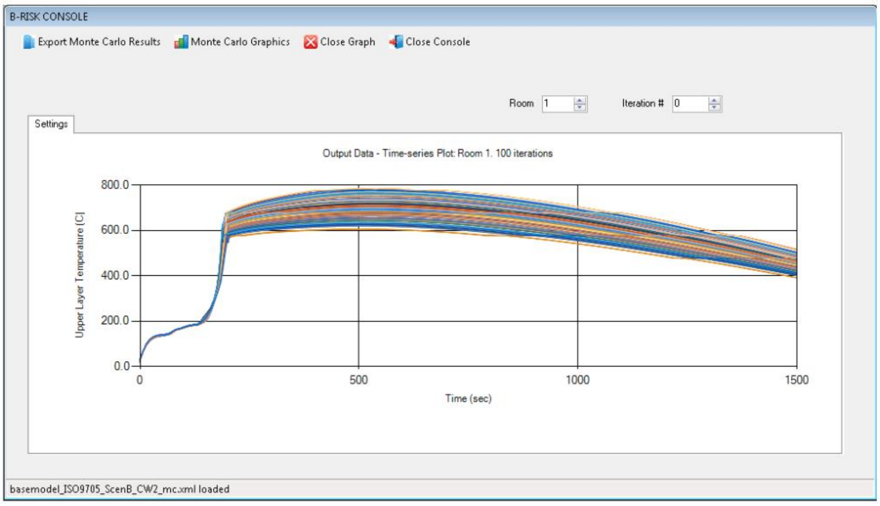

Figure 2–5 Example time series plot of upper layer temperature for multi-iteration output [11].

For further analysis, results may be exported into an excel spreadsheet. Each iteration is stored in a separate spreadsheet. This allows for certain automation in subsequent post-processing and transfer to structural models. Input and output data may be extracted from XML files; one set of XML files is created for each iteration.

2.3.1.3 Ozone

Ozone is an one / two-zone model developed by the University of Liege. The primary purpose of this computer model, which is also reflected in its functionalities, is the design of steel structures for fire conditions. The model itself is based on the Eurocode 1 (EN 1991-1-2); for unprotected or protected steel member temperature calculations Eurocode 3 (EN 1993-1-2) calculations are integrated. There are various translations of the user-guide available online.

There are three modes of Ozone fire simulation – two-zone, one-zone and combination where the model transitions from two-zone to one-zone mode upon reaching the flashover conditions. The user can set the transition criteria: upper layer temperature, combustibles (in the upper layer) ignition temperature, interface height (fraction of the compartment height) and fire area (fraction of the compartment floor area). These criteria should represent flashover conditions in general.

The user is able to set various simulation parameters, e.g. ambient conditions, heat transfer coefficients for the exposed and unexposed faces of construction members, plume air entrainment model and the approach to temperature- or time-dependent fraction of ventilation openings.

Ozone allows simulation only in a single compartment. The geometry is rectangular with various roof shapes – flat, single- and double-pitch. Thermal properties may be defined individually for each of the enclosing walls, floor and ceiling. Natural and forced vents may be used.

The fire definition follows either the Annex E of EN 1991-1-2, localised or user-defined fire. The localised fire requires a series of time–HRR data together with further definition such as fire location relative to the construction element and ceiling height; a number of localised fires can be specified for each simulation. The user-defined fire requires either HRR [MW] or burning rate [$kg \cdot s^{-1}$] defined in time. Such defined fire then subsequently determines thermal action on construction.

Thermal analysis is the second step of the analysis. The user can either utilise the calculated thermal action (see above) or one of the three temperature curves – ISO 853, ASTM E119 or hydrocarbon fire curve, see also section 2.1.1.

The thermal analysis the user can select from unprotected and protected steel profiles. These standard profiles are listed directly in the steel profile tab. Steel protection thermal properties may be either selected from the predefined values or the user can define constant or temperature-dependent values.

It is possible to copy and paste data series from the output graphs (Figure 2–6) in Ozone and print a report for each simulation. No direct interfacing is available with advanced structural models.

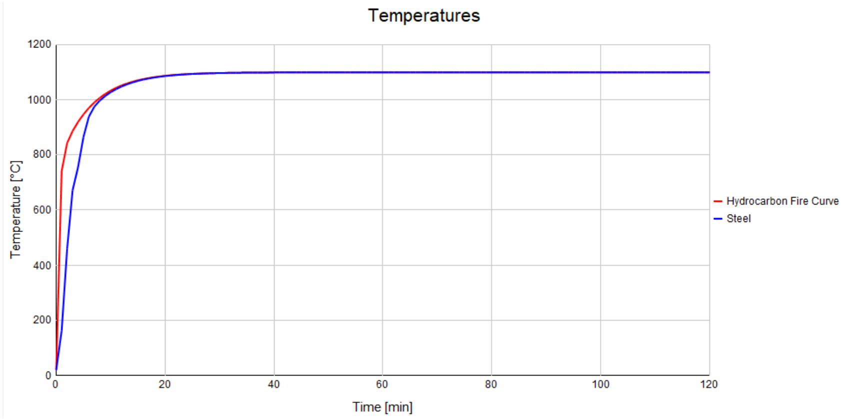

Figure 2–6 Example output from Ozone – Time vs. Gas and Steel profile temperatures.

2.3.2 CFD fire models

Computational fluid dynamics models represent the most complex modelling approach to fire. In general, they solve partial differential equations (conservation, flow, etc.) for discrete finite volumes forming a computational mesh. Given the nature of the fire phenomenon, turbulence CFD models are utilized.

Given their complexity, CFD fire models require a thorough understanding of both the fire phenomenon (physics, chemistry and thermodynamics) as well as the CFD approach to be used. Significant amount of user specified input parameters and simplifications are usually required. These include but are not limited to:

- computational domain definition – type and resolution of the computational mesh, spatial and temporal boundaries of the simulated scenario, including interfaces to the exterior and/or other spaces, boundary conditions allowing for smooth mass and heat transfer where applicable (e.g. additional space on the exterior side of the windows);
- geometry representation – simplifications of non-fitting geometry (e.g. curved to rectilinear), zero and real thickness geometry;
- material definition – material physical and thermal properties (temperature dependent), layered and non-homogenous materials, swelling and shrinking;
- fire representation – fuel type and chemistry, ignition and flame spread, prescribed vs. simulated burning rate, fuel changes when heated (charring, decomposition, burning away);

- heat transfer conditions – convective heat transfer coefficient and emissivity (ideally temperature-dependent), representation of the exposed construction geometry, type and position of data recording (e.g. surface temperature, gas temperature, net heat flux, etc.).

Since the topic of CFD fire models vastly exceeds the aim of this publication, the reader is referred to specialised publications such as [13], [14] and relevant chapters of [15].

There are a number of CFD models for various purposes and some of them specifically developed for fire modelling. Fire Dynamics Simulator (freeware, NIST) has gained a significant extent of use in the fire modelling community. Its continuous development and validation

There are also older CFD fire models available (proprietary and free) which appear no longer under development or maintenance. These include Smartfire by the University of Greenwich, FireFOAM by FM Global, Jasmine by BRE and others.

Fire Dynamics Simulator is a CFD fire model solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires. Turbulence is treated by means of the Smagorinsky form of Large Eddy Simulation (LES). It is possible to perform a Direct Numerical Simulation (DNS) if the underlying numerical grid is fine enough. LES is the default mode of operation. For most applications, FDS uses a single step, mixing-controlled chemical reaction which uses three lumped species (a species representing a group of species). FDS approximates the governing equations on a rectilinear mesh. Rectangular obstructions are forced to conform with the underlying mesh. [16].

Validation and verification of Fire Dynamics Simulator is extensive and ongoing; the verification process and cases are detailed in [17], and the validation process and cases in [18].

There are various examples of FDS use in conjunction with advanced structural models. Some are presented in section 6 and further may be found in various papers [19–22].

Due to the complex nature of FDS, only a few selected important point will be highlighted here:

- Grid sensitivity study should be always conducted to establish an appropriate resolution providing balance between accuracy and computational demand. Extremely fine grid may not necessarily further increase accuracy of calculations but will significantly increase computational time.
- Geometry simplifications are often necessary due to the rectilinear grid and its resolution. This includes arches, inclines and other non-rectangular shapes.
- Heat transfer (conduction) in solid materials has limitations. 1-D or 3-D (beta version) heat transfer sub-models are available each with its own limitations; e.g. back side boundary conditions dependent on the geometrical thickness of obstructions.
- Prescribed and obtained values of HRR should be always checked to ensure that the actual heat output is as desired, particularly within fire enclosure. The HRR for the entire computational domain may correspond to prescribed values, however, combustion may take place outside the intended enclosure/space, e.g. in exterior. Due to ventilation conditions and simplified combustion chemistry modelling, there may be discrepancies.
- To allow for proper flow of gases at windows and other openings to exterior, sufficient space should be modelled at the exterior side of the opening. When the computational domain boundaries correspond to the openings the flow may be adversely affected.
- Temperature and heat flux measuring device selection should be carefully considered from the functionality and location point of view. E.g. gas temperature in the vicinity of a

construction member may not be appropriate input for structural modelling, instead adiabatic surface temperature should be considered.

- Direct combustion and suppression simulation is rather complicated. Unless required for specific purposes, it is recommended to define fire through specifying HRR or mass loss rate.

2.4 Fire scenarios and design fires

2.4.1 Design fire scenarios

According to the ISO 16733-1:2015 [23], design fire scenario is a specific fire scenario on which a deterministic fire safety engineering analysis will be conducted. Since the number of possible fire scenarios in most built environments is endless, it is impossible to analyse all scenarios. It is inevitable to reduce the infinite set of possibilities to a manageable set of design fire scenarios that is amenable to analysis and that represents the range of fires that can challenge the engineering design that is the subject of the analysis. It means in the practice the most important, relevant fire scenarios must be selected which provides the most unfavourable results for the proper fire safety design. ISO 16733-1:2015 lists the following nine steps for fire scenario identification:

- Step 1 — Identify the specific safety challenges
- Step 2 — Location of fire
- Step 3 — Type of fire
- Step 4 — Potential complicating hazards leading to other fire scenarios
- Step 5 — Systems and features impacting on fire
- Step 6 — Occupant actions impacting on fire
- Step 7 — Selection of design fire scenarios
- Step 8 — Modify scenario selection based on system availability and reliability
- Step 9 — Final selection and documentation.

The characterization of a design fire scenario for analysis purposes involves a description of such things as the initiation, growth and extinction of fire, together with likely smoke and fire spread routes under a defined set of conditions

Each fire scenario is represented by a unique occurrence of events and circumstances associated with the nature of the facility and the sources of fire, as well as a particular set of circumstances associated with the fire-safety measures. The latter are defined by the fire safety design, while the former is required to be specified to characterize the scenario. Accordingly, a fire scenario may be characterized – in relation to the nature of the facility or built environment by the ISO 16733-1 [23] – such as the following with some practical additions:

- ventilation conditions including location and size of potential openings that could provide a source of air/oxygen during the course of the fire;
- ambient environmental conditions such as initial temperature, air movements;
- interconnections between spaces or compartments providing potential routes of fire and smoke spread;
- materials, material properties (density, specific heat and thermal conductivity) and methods of construction and the size of the compartments;

- status and performance of each of the fire safety measures, including active systems and passive features;
- detection, alarm and suppression of fire by automatic or non-automatic (human) means;
- self-closing doors or other discretionary elements of compartmentalization like active smoke barriers, glazed structures etc;
- building air handling system or smoke management system;
- reliability of each of the fire safety measures.

2.4.2 Design fires

According to the ISO 16733-2 [24], design fire is a quantitative description of assumed fire characteristics within a design fire scenario according to the ISO 16733-1 [23], see above.

The design fire can include descriptions of the heat release rate, gas temperature or heat fluxes as well as the yields of smoke and other combustion products. The most important parameter of the design fire is the heat release rate and different approaches are available to develop a design fire curve for the time-varying heat release rate from a fire.

Fire safety engineer should determine the design heat release rate curve, without intervention, as would apply if the fire were allowed to develop in well-ventilated, open-air conditions. Interventions result in a potential change in the course of the fire. They could include:

- manual fire-fighting actions by occupants or by trained fire-fighters;
- automatic or manually operated fire suppression systems;
- restricted ventilation or changes in ventilation during the course of the fire (e.g. glass breaking);
- burning enhancement due to thermal feedback from the hot gases and enclosure surfaces to the fuel surface.

Interventions in the course of the fire can be very effectively calculated with 3D fire modelling software.

2.5 Country-specific recommendations regarding the use of the above models

2.5.1 Fire simulation practice in Hungary – background

In Hungary, fire safety requirements are regulated by legislative provision called National Fire Safety Code issued by Ministerial Decree 54/2014 (XII. 05.) BM as amended by Ministerial Decree 30/2019 (VII 26) BM [25] (Figure 2–7). This is much shorter than its predecessors, consisting only the basic fire safety design principles, the required safety level and the detailed fire safety requirements. Besides the legislative provision, there are altogether 14 Fire Protection Technical Guidelines including Fire-, Smokespread and Evacuation Modelling [26]. Interesting that there are no heat release rate (HRR) curves in this guideline, leaving it to the responsibility of the fire safety engineers using international standards [23, 24], simulation software [16] and other literature (articles, reports, books etc. [15, 27]).

There are basically two different ways of fire safety design: prescriptive method or engineering methods. At prescriptive method, simple tabular or empirical requirements are used from legislative provisions and in Hungary, there are fire safety guidelines consisting the acceptable best practices compliant with the ongoing regulation which can be easily used at simple and traditional buildings. In contrast to the prescriptive methods, at engineering methods more complicated calculations, simulations are used requiring more engineering knowledge and work, special software and especially at numerical fire simulations, extensive hardware too. The most widespread software are FDS and PyroSim for fire modelling [16], and Pathfinder for evacuation modelling.


BELÜGYMINISZTÉRIUM
ORSZÁGOS KATASZTRÓFAVÉDELMI FŐIGAZGATÓSÁG

Tűzvédelmi Műszaki Irányelv
FireProtectionTechnicalGuideline
Azonosító: **TvMI 8.4:2020.01.22.**

Témakör:
Számítógépes tűz- és füstterjedési, valamint menekülési szimuláció
Fire– ,smokespread and evacuation modelling

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tűzoltósági főtanácsos
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Az alkalmazás előtt győződjön meg arról, hogy a hatályos TvMI-t használja-e.

Figure 2–7 Fire Protection Technical Guideline – Fire-, Smokespread and Evacuation Modelling.

2.5.2 Fire modelling practice in Hungary

For simulation software based on CFD principles, power type information (time distribution of heat release) is required, instead of specific heat release in the protected space. In the international literature, definition of the standard power curve is based on the materials in the protected space. In the national practice, definition of the standard heat release rate curve has been elaborated in agreement with the Fire Protection Division of the General Directorate for National Disaster Protection. The standard heat release rate curve applied in the simulation may be divided into three stages: growing, fully developed and decay.

A feature of the *growing stage* is that the heat release rate increases according to a quadratic time profile. Coefficient of the quadratic progression is a characteristic parameter of the *growing stage* (α). A constant heat release rate is typical to the *fully developed stage*. The fully developed stage may be characterized by two parameters (maximum heat release rate and duration). In the decay stage, the heat release rate reduces from a maximum, which has been approximated by an exponential function, see Figure 2–8.

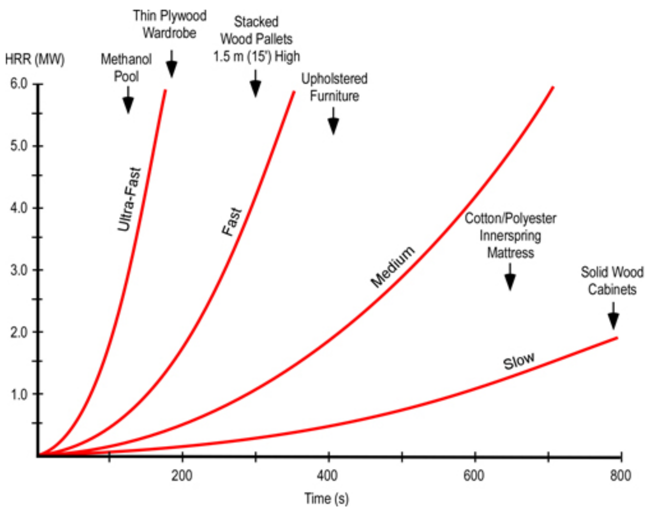

Figure 2–8 Growth phase of fire scenarios with different coefficients.

Fire scenarios used in Hungary are the following:

- basically localised fire scenarios used from the different books, publications, handbooks [15, 27];
- sprinkler controlled fire scenarios can also be used for certain purposes like test of the façade fire spread, or to determine the temperature-to-time exposure of the structural members (Figure 2–9) [28].

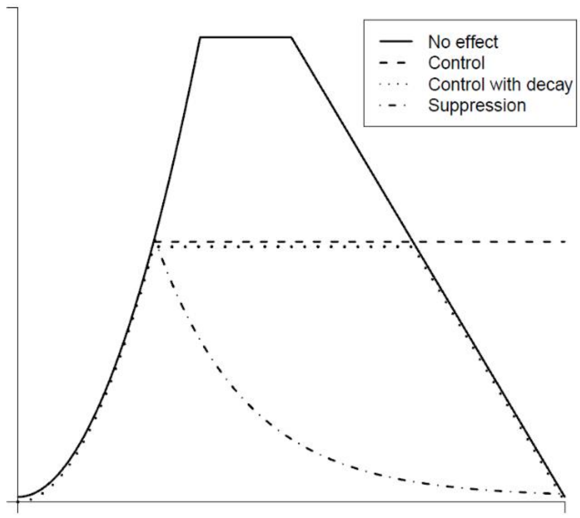

Figure 2–9 Typical heat release rates of sprinkler controlled fire scenarios. For fire modelling, con-trolled fire scenarios are used at normal sprinklers, suppression effect is accepted only at ESFR sprinkler nozzles.

Typical application of the sprinkler controlled fire is at ESFR sprinklers which have significally larger water discharge than traditional sprinklers. Therefore, ESFR sprinklers can extinguish the fire, while normal sprinklers can mostly control the fire, not letting the HRR growing over a certain value. Fire modelling practice of buildings protected with ESFR sprinkler is the following. Tests are carried out in two phases. First the heat release rate should be determined at the activation time of the first sprinkler nozzle according to the pre-determined HRR and fire growth rate. In the second phase, the previous but at ESFR sprinklers at least 3 MW HRR rate fire scenario should be

run with the same growth rate and after the activation time of the first sprinkler nozzle, simulation must run with constant HRR while the sprinkler nozzle is working continuously. From the activation of the first sprinkler nozzle the heat release rate of the fire is not growing and from the activation time of the second sprinkler nozzle, HRR reduces in linear degress to 30 %.
Smoke development is taken into consideration according to the polyurethane reaction GM 27. This is the possible worst reaction with 19 % soot yield.

3 THERMAL RESPONSE & HEAT TRANSFER – INTERFACING FIRE AND STRUCTURAL MODELS

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The analysis of structures in fire needs consideration of several physical processes. Not going into details, the general framework of integrated analysis of structural system in fire is presented in Figure 3–1. Before the analysis of physical processes starts, all the information about the building and design assumptions must be recognized. Collection of all the information about the real object (building or civil engineering object) is called here "building/structure information model". For an integrated analysis of a structure in fire, the information about the geometry, functions of a building, load conditions, fire load etc. are necessary to be specified.

Based on it, it is possible to create two separate models which aim to resolve physics of fire and structural response: the fire model and the structural model. Regardless of current possibilities to store all of this information in one superior model, e.g. using Building Information Modelling (BIM), finally both the structural model and the fire model are separate, describing two separate physical problems.

The principal goal in a structural design is to ensure an appropriate level of safety, by executing a check of the fire resistance of the structure. Thus, from a structural point of view, the selected fire scenarios should be always related to the most severe situation. All the information about the fire load, fire size and heat release rate is related to design assumptions. However, the determination of fire scenarios is not an easy task, especially when it is based on the performance criteria and the active fire protection measures have to be considered. Having fire scenarios already selected, the modelling of fire may be done. The heat exposure of structural members is an output from the fire development analysis. The heat exposure must be passed to the heat transfer model. The heat transfer analyses of the heat exchange between the fire environment and the structure are carried out to determine the history of changes of the temperature field in the structure. Knowing the temperature development in structural members, the structural analyses are carried out.

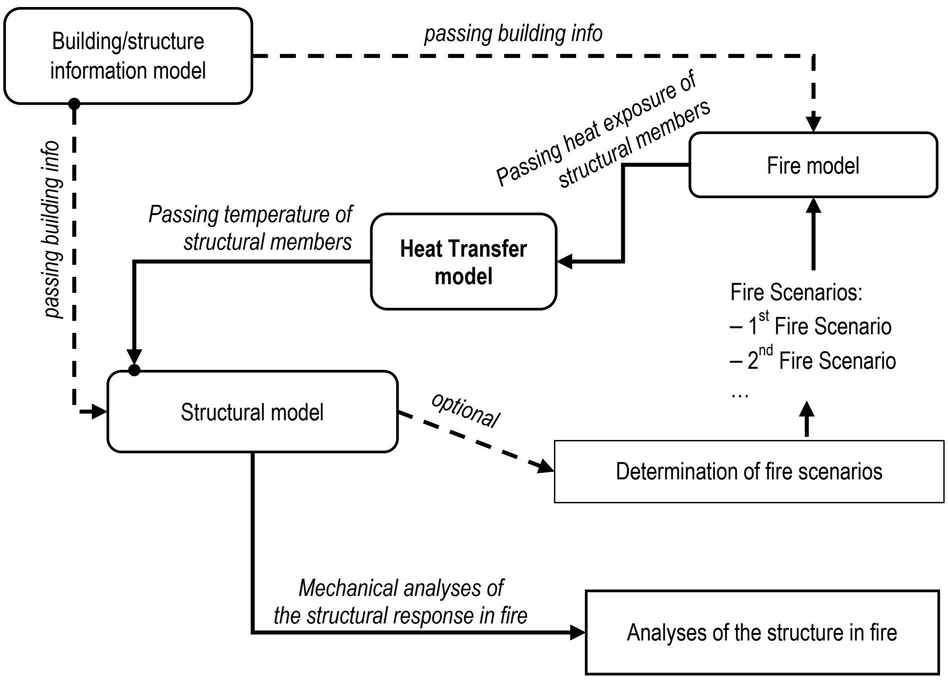


Figure 3–1 Integrated framework for analyses of structures in fire

3.1 Physical bases for heat exchange between the fire and the structure

Three fundamental mechanisms heat transfer are recognized: thermal convection, thermal radiation, and thermal conduction, see Figure 3–2. The heat between the fire environment and the structure exchanges on surfaces of a solid phase. The heat exchange is done by convection and radiation. After the heat enters the solid, it is then conducted inside the material. The rules of heat conduction are specified by Fourier's law.

From the structural point of view, the knowledge about the temperature distribution inside the members of an analysed structure is crucial. Hence, the thermal exposure determines the boundary conditions for calculations of heat flow inside the solid. More specifically, convective and radiative heat fluxes are the quantities which condition the development of the temperature field inside structural members.

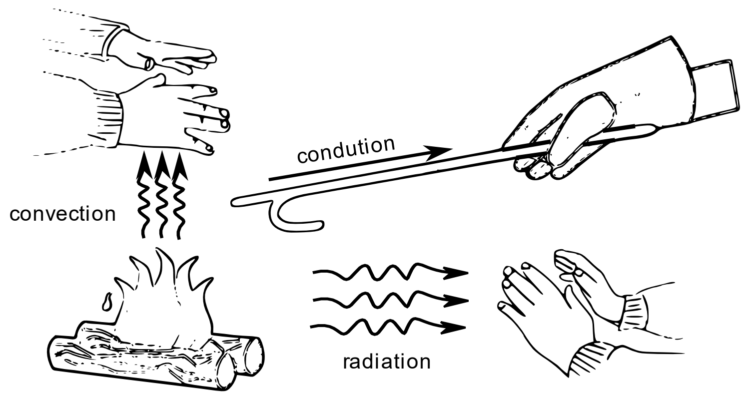


Figure 3–2 Illustration of the three fundamental heat transfer mechanisms

The heat flux is a relation between the elementary amount of energy exchanged, Q, and the time of heat exchange process t. The heat flux is represented by the symbol $\dot{q}$ and it is given by:

$$\dot{q} = \frac{dQ}{dt}, \tag{3–1}$$

whereas the heat flux density is defined with respect to the elementary (unity) area:

$$\dot{q}" = \frac{\dot{q}}{S} \cdot \boldsymbol{s}, \tag{3–2}$$

where:

$\dot{q}$	[W]	Heat flux;
$\dot{q}"$	[W·m^{-2}]	Heat flux over the elementary area;
S	[m^2]	Surface of the elementary area;
$\boldsymbol{s}$	[—]	Unit vector normal to the surface.

The net heat flux absorbed by the body is the sum of the convective, $\dot{q}_{con}$, and radiative part, $\dot{q}_{rad}$:

$$\dot{q}_{\text{net}} = \dot{q}_{\text{con}} + \dot{q}_{\text{rad}} \,. \tag{3–3}$$

A similar equation, but related to the equilibrium at the surface is defined as:

$$\dot{q}''_{\text{net}} = \dot{q}''_{\text{con}} + \dot{q}''_{\text{rad}} \,, \tag{3–4}$$

which is called the heat balance equation.

3.2 Convective heat flux

The convective heat flux density is proportional to the difference between the gas temperature and the surface temperature. At the interface between solid and gas phases, it is usually expressed by:

$$\dot{q}''_{\text{con}} = h_{\text{c}} \cdot \left(\theta_{\text{g}} - \theta_{\text{s}}\right) , \tag{3–5}$$

where:

$\dot{q}''_{\text{con}}$	[W·m−2]	Convective heat flux;
h_{c}	[W·m−2·K−1]	Coefficient of heat transfer by convection;
θ_{g}	[K]	Gas temperature;
θ_{s}	[K]	Surface temperature.

Hence, three quantities have to be resolved in order to get an appropriate value of the convective heat flux. Assuming the known value of the coefficient of heat transfer by convection, h_{c}, the value of the convective heat flux is then dependent on the temperature difference between the gas and the solid surface. The gas temperature is evaluated based on the energy transport equation, which is governed by the first law of thermodynamics written for a control volume, which is symbolically written as:

$$\dot{E} = \sum \dot{Q} + \sum \dot{W} + \dot{Q}_{\text{s}} \,, \tag{3–6}$$

where:

E	[W]	Rate of increase of the energy;
$\dot{Q}$	[W]	Net rate of heat added to the system;
$\dot{W}$	[W]	Net rate of work done by pressure and viscous forces;
$\dot{Q}_{\text{s}}$	[W]	Rate of heat added or removed by the heat source on the control volume, e.g. due to chemical reactions and/or radiation..

The above energy rate equation is often recalled in terms of enthalpy definition h for compressible flows, which is the sum of the total specific energy E and the pressure/density term. This problem is governed by the set of the Navier-Stokes equations consists of 6 flow-field variables and one field-dependent variable: the gas temperature, which is of particular interest in the computation of convective heat flux. The equation which closes the system is the equation of state, from which the gas temperature is directly obtained. More details can be found in section 2.3.2 and literature concerning field modelling.

Apart from the gas temperature, which is directly taken from the solution of Navier-Stokes equations, e.g. by CFD computations, special attention is paid to the coefficient of heat transfer by convection h_c. This coefficient highly depends on the fluid flow in the close neighborhood of the solid surface – the fluid-solid interface. The comprehensive study about the coefficient of heat transfer by convection can be found in several textbooks [17, 29–32]. According to these sources, the coefficient has to be evaluated separately for natural and forced convection. For natural convection, it is dependent on natural convection coefficient C and the difference between gas and solid surface temperature $|\theta_g - \theta_s|$. In forced convection conditions, which is the most common case in turbulent fires, the coefficient of heat transfer by convection depends on the conductivity of the gas k_g, characteristic length related to the size of the physical obstruction L, the Reynolds, Re, and Prandtl, Pr, numbers that characterize the gas flow that pass the obstruction. Generally, in fire dynamics computations, see [17, 32], the coefficient of heat transfer by convection h_c is taken as:

$$h_\mathrm{c} = \max\left\{\begin{matrix} C \cdot |\theta_\mathrm{g} - \theta_\mathrm{s}|^{\frac{1}{3}} \\ \frac{k_\mathrm{g}}{L} \cdot 0.037 \cdot \mathrm{Re}^{\frac{4}{5}} \cdot \mathrm{Pr}^{\frac{1}{3}} \end{matrix}\right\}. \tag{3–7}$$

In the case of an ordinary enclosure fires, the natural convection takes place just in the very beginning of the fire or in places far from the fire origin. Then, the natural convection coefficient C is taken equal to 1.52 for horizontal surfaces or equal to 1.31 for vertical surfaces [17]. The other parameters are the known physical quantities, like k_g; or the analysis parameters, need to be a priori known, like L; or are resolved during an analysis, like Re, Pr.

3.3 Radiative heat flux

Radiative heat flux is a key ingredient of a total heat flux for fully developed fires. This is due to its dominant role in heat transfer in large scale fires. Radiation is described by the vector field in the continuous media, governed by the electromagnetic waves that transfer the radiation. The radiative heat flux into the solid corresponds to the absorbed radiation resulting from the incident radiation incoming to the solid surface. The schematic view of this phenomenon is shown in Figure 3–3.

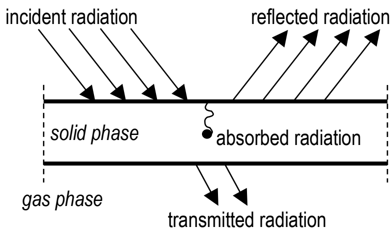


Figure 3–3 Effects of incident radiation on fluid-solid surface

The amount of radiation energy absorbed by the solid body $\dot{q}_{\mathrm{rad}}$ is by the definition the difference between the incident radiation $\dot{q}_{\mathrm{inc}}$ and the sum of reflected $\dot{q}_{\mathrm{reflc}}$ and transmitted radiation $\dot{q}_{\mathrm{transm}}$:

$$\dot{q}_{\mathrm{rad}} = \dot{q}_{\mathrm{inc}} - \dot{q}_{\mathrm{reflc}} - \dot{q}_{\mathrm{transm}} \quad . \tag{3–8}$$

In structural fire engineering, most of the time non-transparent bodies are considered. Then, the transmitted part is equal to 0, so the eq. (3–8) is reduced to:

$$\dot{q}_{\mathrm{rad}} = \dot{q}_{\mathrm{inc}} - \dot{q}_{\mathrm{reflc}} \quad . \tag{3–9}$$

Then, using the formula (3–9), and introducing the absorptivity of a solid surface, α_{s}, the equilibrium equation at the solid surface is formulated:

$$\dot{q}''_{\mathrm{rad}} = \alpha_{\mathrm{s}} \cdot \dot{q}''_{\mathrm{inc}} - \dot{q}''_{\mathrm{reflc}} \quad , \tag{3–10}$$

which describes the amount of radiative energy absorbed by the unit area of the solid surface in a unit of time. The radiant incoming heat flux vector $\dot{q}_{\mathrm{inc}}$, at the position described by vector $\boldsymbol{r}$, is calculated as an integral from the incident intensity $\boldsymbol{I}(\boldsymbol{r}, \boldsymbol{s})$, over the spherical domain of interest:

$$\dot{q}_{\mathrm{inc}} = \int_{\Omega} \boldsymbol{s} \cdot \boldsymbol{I}(\boldsymbol{r}, \boldsymbol{s}) d\boldsymbol{s} \quad , \tag{3–11}$$

where $\Omega = 4\pi$ for whole sphere, and $\Omega = 2\pi$ for integration over hemisphere around the particular direction $\boldsymbol{s}$. The amount of energy transferred by the incident intensity is spectrally dependent. On the solid-fluid interface, the integral (3–11) is evaluated over the hemisphere over the normal direction of the surface. So, the radiation incident to the unit surface becomes:

$$\dot{q}''_{\mathrm{inc}} = \frac{\dot{q}_{\mathrm{inc}}}{S} \cdot \boldsymbol{s} \quad . \tag{3–12}$$

The reflected radiant heat flux is equal to:

$$\dot{q}''_{\mathrm{reflc}} = \varepsilon_{\mathrm{s}} \cdot \sigma \cdot \theta_{\mathrm{s}}^4 \quad , \tag{3–13}$$

where ε_s [—] is the emissivity of the solid surface and σ is the Stefan-Boltzmann constant, and θ_{s} is the surface temperature (likewise in eq. (3–5)), given in Kelvin. In definition (3–13), the product $\sigma \cdot \theta_{\mathrm{s}}^4$ describes the black body radiation of a surface. The net radiant heat flux absorbed with respect to the unit solid surface $\dot{q}''_{\mathrm{rad}}$ is then calculated by inserting (3–13) into (3–10):

$$\dot{q}''_{\mathrm{rad}} = \alpha_{\mathrm{s}} \cdot \dot{q}''_{\mathrm{inc}} - \varepsilon_{\mathrm{s}} \cdot \sigma \cdot \theta_{\mathrm{s}}^4 \quad . \tag{3–14}$$

Since the absorptivity is equal to the emissivity, $\alpha_s = \varepsilon_s$, equation (3–14) is usually reformulated to the following form:

$$\dot{q}''_{\mathrm{rad}} = \varepsilon_s \cdot (\dot{q}''_{\mathrm{inc}} - \sigma \cdot \theta_s^4) \quad . \tag{3–15}$$

Note, that the calculation of the net radiant heat flux absorbed by the body requires the exact knowledge of the amount of radiative energy incident to a surface. So, the integral (3–11) has to be resolved. This is usually not the case in practical engineering problems, in which the radiative heat flux density is estimated using simplified formula or CFD solvers are used to resolve the field problems.

3.3.1 Shadow effect

The shadow effect is revealed in the reduction of radiation that reaches particular points of a cross-section's surfaces. Namely, some of the surfaces of an open cross-section are partly shadowed to radiation by other parts of the cross-section. This phenomenon is illustrated in Figure 3–4. The shadowed surfaces do not experience external radiation from the whole hemisphere around them but from a limited number of angles. So the incident radiation to these surfaces is reduced. The shadow effect is a geometrical effect. Hence, it is characteristic for a particular shape of a cross-section. There are various approaches used to consider the shadow effect.

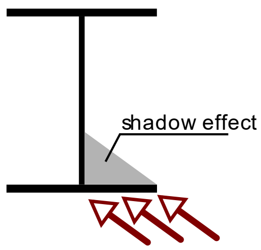


Figure 3–4 Shadow effect

3.4 Adiabatic surface temperature

3.4.1 Concept of adiabatic surface temperature

The concept of an adiabatic surface temperature (AST) turned out to be an efficient way to express the heat exposure of the solid surfaces both in a real experiments, using plate thermometers and in numerical analyses. The biggest advantage of the adiabatic surface temperature is the description of a thermal exposure of a surface with a single quantity called the adiabatic surface temperature (AST). So, it can be used as a single boundary condition when calculating temperature of structures exposed to fire. From a theoretical point of view, the adiabatic surface temperature is a temperature of an infinitely thin plate, made of a perfect conductor, lying on a perfect insulator, see Figure 3–5.

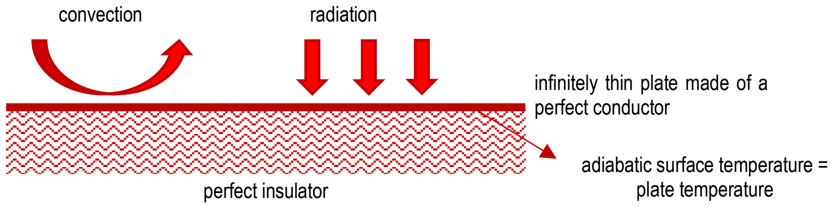


Figure 3–5 Physical model of an adiabatic surface

The above setup visualises the main feature of an adiabatic surface: it reflects all the heat reaching it. So, the net heat flux given by the heat balance equation (3–4) is, by definition, equal to zero. Thus, equation (3–4), enriched by equations (3–5) and (3–15), takes a form

$$\dot{q}''_{\text{net}} = h_{\text{c}} \cdot \left(\theta_{\text{g}} - \theta_{\text{AST}}\right) + \varepsilon_{\text{s}} \cdot \left(\dot{q}''_{\text{inc}} - \sigma \cdot \theta^4_{\text{AST}}\right) \equiv 0 \quad , \tag{3–16}$$

where θ_{AST} is the adiabatic surface temperature. Following the mathematical model of an adiabatic surface (eq. (3–16)), the adiabatic surface temperature is one of the roots of the fourth order polynomial, when the all other quantities appearing in eq. (3–16) are known.

The advantages of using the adiabatic surface temperature for the definition of boundary conditions in structural fire engineering problems are introduced hereafter. Assume the unknown quantity of the total net heat flux density reaching the solid surface (s) $\dot{q}''_{\text{tot,s}}$. It can be calculated in accordance with eq. (3–4) after simple substitutions:

$$\dot{q}''_{\text{tot,s}} = h_{\text{c}} \cdot \left(\theta_{\text{g}} - \theta_{\text{s}}\right) + \varepsilon_{\text{s}} \cdot \left(\dot{q}''_{\text{inc}} - \sigma \cdot \theta^4_{\text{s}}\right) \ . \tag{3–17}$$

Now, subtracting eq. (3–16), by definition equal to zero, from eq. (3–17), gives:

$$\dot{q}''_{\text{tot,s}} = h_{\text{c}} \cdot \left(\theta_{\text{g}} - \theta_{\text{s}}\right) + \varepsilon_{\text{s}} \cdot \sigma \cdot \left(\theta^4_{\text{AST}} - \theta^4_{\text{s}}\right) \ . \tag{3–18}$$

So, the total net heat flux consisting of both the convective and radiative part, is evaluated using the single quantity, the adiabatic surface temperature (AST). Note, in eq. (3–18), the adiabatic surface temperature is interpreted simultaneously as the effective black body radiation temperature, for the purpose of calculating the incident radiation, and as the gas temperature for the purpose of calculation of the convective heat flux. This feature is indicated as the biggest advantage of the adiabatic surface temperature concept. From the practical point of view, it allows us to decrease the amount of information that has to be provided to calculate the heat exchange between the gas and the solid, with no loss in accuracy. But, to get a value of the adiabatic surface temperature, the solution of fourth order polynomial equation (3–16) is required.

The closed-form analytical solution of eq. (3–16) has been introduced in [33]. The physical coefficients and quantities occurring in eq. (3–16) are used to define:

$$\begin{aligned} a &= \varepsilon_{\mathrm{s}} \cdot \sigma \\ b &= h_{\mathrm{c}} \\ c &= -\varepsilon_{\mathrm{s}} \cdot \dot{q}''_{\mathrm{inc}} - h_{\mathrm{c}} \cdot \theta_{\mathrm{g}} \end{aligned}, \qquad (3\text{–}19)$$

and subsequently:

$$\alpha_{\mathrm{M}} = \left(\sqrt{3} \cdot \sqrt{27 \cdot a^2 \cdot b^4 - 256 \cdot a^3 \cdot c^3} + 9 \cdot a \cdot b^2\right)^{\frac{1}{3}} \qquad (3\text{–}20)$$

$$\beta_{\mathrm{M}} = 4 \cdot \left(\frac{2}{3}\right)^{\frac{1}{3}} \cdot c\,, \qquad (3\text{–}21)$$

$$\gamma_{\mathrm{M}} = (18)^{\frac{1}{3}} \cdot a\,, \qquad (3\text{–}22)$$

which are used to define:

$$M = \sqrt{\frac{\beta_{\mathrm{M}}}{\alpha_{\mathrm{M}}} + \frac{\alpha_{\mathrm{M}}}{\gamma_{\mathrm{M}}}}\,. \qquad (3\text{–}23)$$

Finally, an analytical solution for the adiabatic surface temperature is given by:

$$\theta_{\mathrm{AST}} = \frac{1}{2}\left(-M + \sqrt{\frac{2 \cdot b}{a \cdot M} - M^2}\right)\,. \qquad (3\text{–}24)$$

The adiabatic surface temperature can be measured experimentally using a device called the plate thermometer. For furnace tests, the temperature of the furnace is controlled using plate thermometers and the temperature measured by the plate thermometers is effectively considered as the adiabatic surface temperature. Thus, the plate thermometer is considered as the device that measures the exposure of a surface both to convection and radiation. However, for experiments carried out in less controlled conditions (natural fires), the adiabatic surface temperature must be calculated based on the plate thermometer output. The adiabatic surface temperature can be calculated by modified equation (3–24). This is introduced hereafter.

3.4.2 Calculation of AST based on plate thermometer output

Plate thermometers are the devices used to measure the heat conditions in various types of fire tests. They are quite simple devices that consist of thin steel plate, an insulator and a thermocouple attached to a steel plate. The quantity that plate thermometers measure is the temperature of thin steel plate exposed to fire from one side and insulated from the other side, see Figure 3–6.

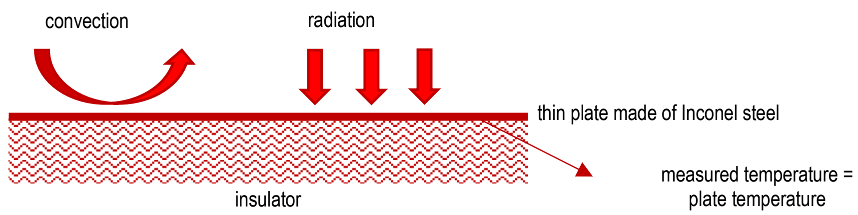


Figure 3–6 Scheme of the plate thermometer

The procedure for analytical calculation of the adiabatic surface temperature is used to compute the adiabatic surface temperature based on the plate thermometer output. The difference is in evaluation of the heat balance equation. Here, it is evaluated on the surface of the plate thermometer, see [32]:

$$\varepsilon_{\mathrm{PT}} \cdot \left(\dot{q}''_{\mathrm{inc}} - \sigma \cdot \theta_{\mathrm{PT}}^4\right) + h_{\mathrm{c}} \cdot \left(\theta_{\mathrm{g}} - \theta_{\mathrm{PT}}\right) + K_{\mathrm{PT}} \cdot \left(\theta_{\mathrm{g}} - \theta_{\mathrm{PT}}\right) = C_{\mathrm{PT}} \cdot \frac{\mathrm{d}\theta_{\mathrm{PT}}}{\mathrm{d}t} \quad , \tag{3–25}$$

where:

θ_{PT}	[K]	Plate thermometer temperature;
$\varepsilon_{\mathrm{PT}}$	[—]	Surface emissivity of the plate thermometer;
K_{PT}	[W·m⁻²·K⁻¹]	Heat conduction coefficient for the heat lost by conduction through the insulation pad plus along the Inconel plate;
C_{PT}	[J·m⁻²·K⁻¹]	Heat capacity of the Inconel plate plus a third of the heat capacity of the insulation pad (see plate thermometer description in [32]).

The other elements of eq. (3–25) have been introduced earlier. The values of the parameters of the standard plate thermometer are assumed to be constant and equal to: $\varepsilon_{\mathrm{PT}} = 0.9$, $K_{\mathrm{PT}} = 8.0$ W·m^{-2}·K^{-1}, $C_{\mathrm{PT}} = 4200$ J·m^{-2}·K^{-1}, see [32].

$$\begin{aligned} a_{\mathrm{PT}} &= \varepsilon_{\mathrm{PT}} \cdot \sigma \\ b_{\mathrm{PT}} &= \left(h_{\mathrm{c}} + K_{\mathrm{PT}}\right) \\ c_{PT} &= -\varepsilon_{\mathrm{PT}} \cdot \sigma \cdot \left(\theta_{\mathrm{PT}}^4\right)^i + \left(-h_{\mathrm{c}} - K_{\mathrm{PT}}\right) \cdot \theta_{\mathrm{PT}}^i - C_{\mathrm{PT}} \cdot \frac{\theta_{\mathrm{PT}}^i - \theta_{\mathrm{PT}}^{i-1}}{\Delta t} \quad . \end{aligned} \tag{3–26}$$

Then, successive parameters $\alpha_M, \beta_M, \gamma_M$, are calculated using formulae (3–20) to (3–22) and analogously to eq. (3–23) M_{PT} is defined as:

$$M_{\mathrm{PT}} = \sqrt{\frac{\beta_{\mathrm{M}}}{\alpha_{\mathrm{M}}} + \frac{\alpha_{\mathrm{M}}}{\gamma_{\mathrm{M}}}}. \tag{3–27}$$

The adiabatic surface temperature, calculated based on the plate thermometer output, is then obtained using eq. (3–24) with the only modification given in eq. (3–26):

$$\theta_{\mathrm{AST}}^{i}=\frac{1}{2}\cdot\left(-M_{\mathrm{PT}}+\sqrt{\frac{2b_{\mathrm{PT}}}{a_{\mathrm{PT}}\cdot M_{\mathrm{PT}}}-M_{\mathrm{PT}}^{2}}\right). \tag{3–28}$$

Note, equation (3–28) is a valid solution if, and only if, the finite difference method approximation of the time derivative works. So, the time step is sufficiently low and the curve describing the θ_{PT} is smooth. In the other case, the resulting value of the adiabatic surface temperature can be erroneous. Hence, the coefficient c_{PT} may become positive in the cooling phase, when an erroneous finite difference method approximation is obtained. So, the eq. (3–28) returns a nonreal solution (complex number). Therefore, the plate thermometer measurements should be sufficiently dense and smoothed.

3.5 Heat conduction

Heat conduction is the process occurring in a solid body that is phenomenologically recognized as the ability of a body to distribute the temperature over its volume. For a closed system and the infinite time, the body averages its temperature, so there is no temperature difference between any of the particles that the body consists of. The heat conduction process is governed by the well-known Fourier's law: "the heat flux, resulting from thermal conduction is proportional to the magnitude of the temperature gradient and opposite to it in sign", which mathematically is given by:

$$q''=-\lambda\cdot\nabla\theta\ , \tag{3–29}$$

where the nabla operator (gradient operator) $\nabla=\left[\frac{\partial}{\partial x},\ \frac{\partial}{\partial y},\ \frac{\partial}{\partial z}\right]$ arbitrarily defines the heat flux vector, assuming the isotropic characteristic of material, defined by the thermal conductivity λ. The mathematical model that describes the heat distribution in a solid is called the heat equation. It is a parabolic partial differential equation of the following form:

$$\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}+\frac{\partial^2\theta}{\partial z^2}=\frac{1}{\alpha}\frac{\partial\theta}{\partial t}\ , \tag{3–30}$$

which is often shortened to its equivalent form that uses the nabla operator: $\alpha\cdot\nabla^2\theta=\dot{\theta}$, or the Laplace operator: $\alpha\Delta\theta=\dot{\theta}$. The quantity α is then called thermal diffusivity, and it is equal to the thermal conductivity λ divided by the specific heat capacity at constant pressure c_{p} and the density ρ. So, the equation (3–30) is rewritten as:

$$\frac{\lambda}{\rho\cdot c_{\mathrm{p}}}\cdot\left(\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}+\frac{\partial^2\theta}{\partial z^2}\right)=\frac{\partial\theta}{\partial t}\ . \tag{3–31}$$

Comparing equations (3–29) and (3–31), the former consists of only the spatial derivatives, while the latter is time dependent. Nevertheless, for time dependent, transient problems, the heat flux defined by the equation (3–29) has to be understood as the instantaneous heat flux. Hence, it is defined as:

$$\dot{q}''=-\lambda\cdot\nabla\theta\ . \tag{3–32}$$

Equation (3–32) provides the mathematical description of the Fourier's law, when the transient nature of heat flux is considered. Notice, neither equation (3–31), nor equation (3–32) takes into account the heat source occurring during the heating process. They only explain the nature of heat propagation for given initial conditions. To take into account the external heat sources, boundary conditions are specified. Hence, the heat source, defined as the heat added to a system, may be specified in two ways: (1) by the direct definition of the time dependent boundary conditions and (2) by the specified inherent heat source.

In the case the direct definition of the time dependent boundary conditions, the time dependent heat flux is given at the boundaries. Here, it is calculated using the concept of the adiabatic surface temperature. In equation (3–18), the indication about the time dependence of its components is done. So, the boundary conditions at the domain's surfaces are:

$$\dot{q}''_{\mathrm{tot,s}}(t) = h_{\mathrm{c}} \cdot \left(\theta_{\mathrm{g}}(t) - \theta_{\mathrm{s}}\right) + \varepsilon_{\mathrm{s}} \cdot \left(\dot{q}''_{\mathrm{inc}}(t) - \sigma \cdot \theta_{\mathrm{s}}^4\right) \; , \tag{3–33}$$

where $\theta_{\mathrm{g}}(\mathrm{t})$ and $\dot{q}''_{\mathrm{inc}}(\mathrm{t})$ defines the time dependent conditions at the boundaries, or, equivalently:

$$\dot{q}''_{\mathrm{tot,s}}(t) = h_{\mathrm{c}} \cdot \left(\theta_{\mathrm{AST}}(t) - \theta_{\mathrm{s}}\right) + \varepsilon_{\mathrm{s}} \cdot \sigma \cdot \left(\theta_{\mathrm{AST}}^4(t) - \theta_{\mathrm{s}}^4\right) \; , \tag{3–34}$$

where $\theta_{\mathrm{AST}}(t)$ defines the time dependent conditions at the boundaries, and θ_{s} is the unknown temperature field that has to be resolved using eq. (3–31). In general, the coefficients h_{c} and ε_{s} can also be dependent on the physical phenomena occurring during the process of heat flow. The incident heat flux density $\dot{q}''_{\mathrm{inc}}$ is often replaced by the radiation temperature θ_{r} which is defined as

$$\theta_{\mathrm{r}} = \frac{\dot{q}''_{\mathrm{inc}}}{\sigma} \; . \tag{3–35}$$

In the specified inherent heat source, the heat is generated or delivered directly inside the solid under consideration. Then, the heat source is defined simply by including an appropriate function $\dot{q}(t, x, y, z)$ to the equation (3–31):

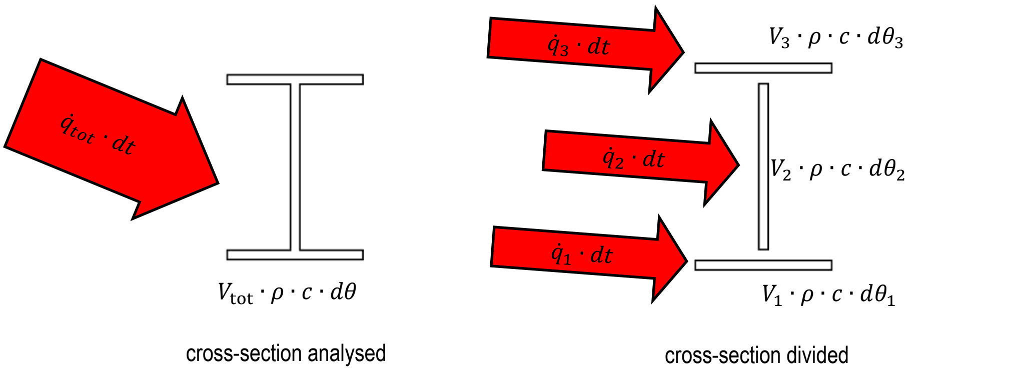
$$\frac{\lambda}{\rho \cdot c_{\mathrm{p}}}\left(\frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial y^2} + \frac{\partial^2\theta}{\partial z^2}\right) + \dot{q}(t, x, y, z) = \frac{\partial\theta}{\partial t} \; , \tag{3–36}$$

where $\dot{q}(t, x, y, z)$ is temporarily and spatially dependent.

3.6 Modelling approaches

3.6.1 Lumped capacitance model

The lumped capacitance model can be used for structures with cross-sections of relatively thin walls, e.g. steel and aluminium profiles. Here, the cross-section or its part is analysed based on the assumption that the total received heat is then stored inside the analysed component, see Figure 3–7, where $\dot{q}_{\mathrm{tot}} = \dot{q}_1 + \dot{q}_2 + \dot{q}_3$ is the total heat received by the body, $V_{tot} = V_1 + V_2 + V_3$ is the volume of the body and $d\theta$ is the temperature increment during the heating process which last for a time interval equal to dt. When the body is divided into several components, the heat balance equation is formulated separately for each analysed part. Parameters ρ and c are, respectively, density and specific heat of the material. Note, that heat balance equations for body divided into separate parts are decoupled, consequently $d\theta \neq d\theta_1 + d\theta_2 + d\theta_3$. Additional heat conductance equation would have to be applied in order to provide connection between θ_1, θ_2 and θ_3.



$$\dot{q}_{\mathrm{tot}} \cdot dt = V_{\mathrm{tot}} \cdot \rho \cdot c \cdot d\theta$$

$$\dot{q}_1 \cdot dt = V_1 \cdot \rho \cdot c \cdot d\theta_1$$

$$\dot{q}_2 \cdot dt = V_2 \cdot \rho \cdot c \cdot d\theta_2$$

$$\dot{q}_3 \cdot dt = V_3 \cdot \rho \cdot c \cdot d\theta_3$$

where:

$$\dot{q}_{\mathrm{tot}} = \dot{q}_1 + \dot{q}_2 + \dot{q}_3 \quad \text{and} \quad V_{\mathrm{tot}} = V_1 + V_2 + V_3$$

Figure 3–7 Heat balance expressions for a cross-section analysed using the lumped heat capacitance model, analysed as a whole and divided into three components

Eurocode EN 1993-1-2 proposed the lumped capacitance model for calculation of steel temperature development, both for unprotected and protected internal steelwork. The calculation procedure given in EN 1993-1-2 is summarized hereafter.

For an equivalent uniform temperature distribution in the cross-section, the increase of temperature $\Delta\theta_{\mathrm{a,t}}$ in an unprotected steel member during a time interval Δt is determined from:

$$\Delta\theta_{\mathrm{a,t}} = k_{\mathrm{sh}} \frac{A_{\mathrm{m}}/V}{c_{\mathrm{a}} \cdot \rho_{\mathrm{a}}} \dot{h}_{\mathrm{net,d}} \cdot \Delta t \ , \tag{3–37}$$

where:

k_{sh}	[—]	Correction factor for the shadow effect;
A_{m}/V	[m^{-1}]	Section factor for unprotected steel members;
A_{m}	[m^2]	Surface area of the member per unit length;
V	[m^3]	Volume of the member per unit length;
c_{a}	[kJ·kg^{-1}·K^{-1}]	Specific heat of steel;
ρ_{a}	[kg·m^{-3}]	Steel density;
$\dot{\mathrm{h}}_{\mathrm{net,d}}$	[kW·m^{-2}]	Design value of the net heat flux per unit area.

Note, that in literature, the heat flux per unit area is often called the heat flux density and it is described by the symbol $\dot{q}''$.

In EN 1993-1-2, the shadow effect is taken into account in a simplified manner. The shadow effect is considered by reducing the amount of energy reaching the cross-section, by inclusion of a so-called "boxed" section. This is due to fact that the cross-section can receive only as much radiant energy as the equivalent "boxed" section. However, this modification simultaneously reduces the amount of convective energy. But, because in fully developed fires, for which the Eurocode model is mainly used, the heat transfer is dominated by the radiation, this issue is to be neglected there. The correction factor for the shadow effect is determined from:

$$k_{\mathrm{sh}} = \begin{cases} 0.9 \cdot \dfrac{[A_{\mathrm{m}}/V]_{\mathrm{b}}}{[A_{\mathrm{m}}/V]} & \text{, for I} - \text{sections under nominal fire actions} \\ \dfrac{[A_{\mathrm{m}}/V]_{\mathrm{b}}}{[A_{\mathrm{m}}/V]} & \text{, for all other cases} \end{cases} \tag{3–38}$$

where $[\mathrm{A_m}/\mathrm{V}]_{\mathrm{b}}$ is the box value of the section factor. The geometric interpretation of quantities A_{m}, $A_{\mathrm{m,b}} = A_{\mathrm{m,box}}$, V is shown in Figure 3–8 and Figure 3–9.

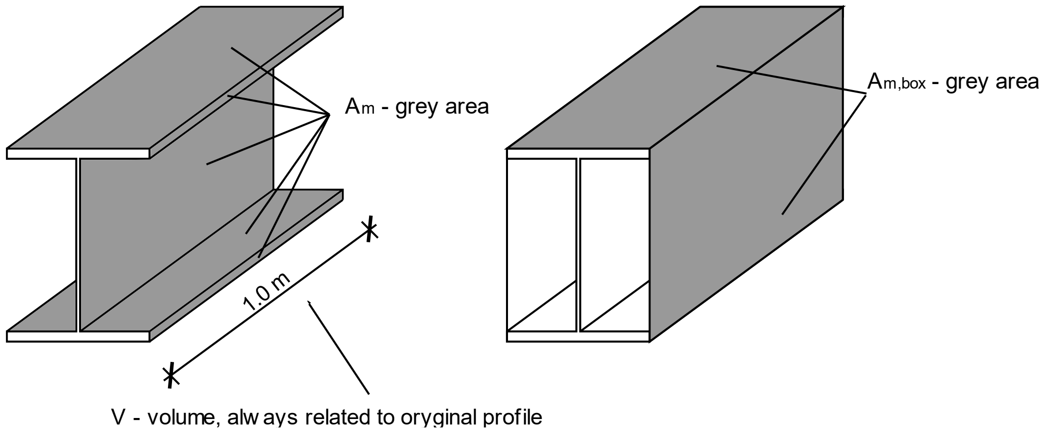


Figure 3–8 Interpretation of A_{m}, $A_{\mathrm{m,b}} = A_{\mathrm{m,box}}$, V for a cross-section exposed for fire from 4 sides.

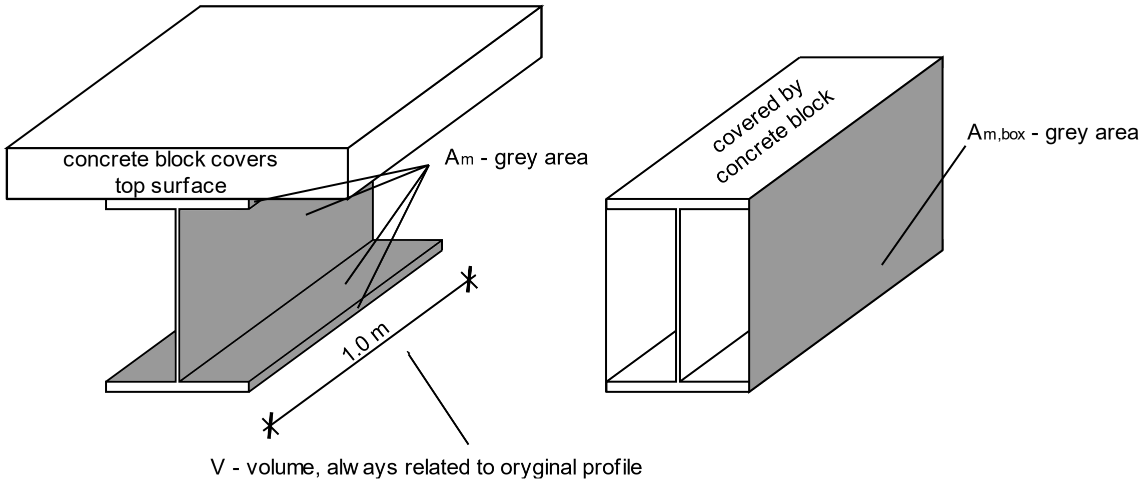


Figure 3–9 Interpretation of A_{m}, $A_{\mathrm{m,b}} = A_{\mathrm{m,box}}$, V for a cross-section exposed for fire from 3 sides.

The net heat flux is calculated taking into account both the convective component $\dot{h}_{\mathrm{net,c}}$ and the radiative component $\dot{h}_{\mathrm{net,r}}$ (see p.3.1 of EN 1991-1-2):

$$\dot{h}_{\mathrm{net,d}} = \dot{h}_{\mathrm{net,c}} + \dot{h}_{\mathrm{net,r}} \, . \tag{3–39}$$

The convective heat flux is calculated from

$$\dot{h}_{\mathrm{net,c}} = \alpha_{\mathrm{c}} \cdot \left(\theta_{\mathrm{g}} - \theta_{\mathrm{m}}\right) \ , \tag{3–40}$$

where:

α_{c}	[W·m⁻²·K⁻¹]	Convective heat transfer coefficient – 25 W·m⁻²·K⁻¹ for exposure to ISO 834 fire curve;
θ_{g}	[K]	Gas temperature (for standard fire exposure: ISO 834 fire curve, see p.3.2.1. EN 1991-1-2);
θ_{m}	[K]	Surface temperature (for steel profiles we assume $\theta_{\mathrm{m}} = \theta_{\mathrm{a}}$).

The radiative heat flux is given by:

$$\dot{h}_{\mathrm{net,r}} = \Phi \cdot \varepsilon_{\mathrm{m}} \cdot \varepsilon_{\mathrm{f}} \cdot \sigma \cdot \left[(\theta_{\mathrm{r}} + 273)^4 - (\theta_{\mathrm{m}} + 273)^4\right] , \tag{3–41}$$

where:

θ_{r}	[°C]	Radiation temperature (for nominal fire we assume $\theta_{\mathrm{r}} = \theta_{\mathrm{g}}$);
ε_{m}	[—]	Emissivity of the surface, for steel profiles equal to 0.7;
σ	[W·m⁻² K⁻⁴]	Stefan-Boltzmann constant equal to 5.67·10⁻⁸ W·m⁻² K⁻⁴;
Φ	[—]	Configuration factor = 1unless other than nominal fires are not considered;
ε_{f}	[—]	Emissivity of the surface = 1unless other than nominal fires are not considered.

Eurocode EN 1993-1-2 introduces also the method for calculation of temperature development in internal steelwork insulated by fire protection material. In such case, the formula for a uniform temperature distribution in a cross-section, the increase of temperature $\Delta\theta_{\mathrm{a,t}}$ of an insulated steel member during a time interval Δt is to be obtained from:

$$\Delta\theta_{\mathrm{a,t}} = \frac{\lambda_{\mathrm{p}} \cdot \left[A_{\mathrm{p}}/V\right] \cdot \left(\theta_{\mathrm{g,t}} - \theta_{\mathrm{a,t}}\right)}{d_{\mathrm{p}} \cdot c_{\mathrm{a}} \cdot \rho_{\mathrm{a}} \left(1 + \frac{\phi}{3}\right)} \cdot \Delta t - \left(\exp\left(\frac{\phi}{10}\right) - 1\right) \cdot \Delta\theta_{\mathrm{g,t}} \tag{3–42}$$

$$(\text{but } \Delta\theta_{\mathrm{a,t}} \geq 0 \text{ if } \Delta\theta_{\mathrm{g,t}} > 0),$$

with

$$\phi = \frac{c_{\mathrm{p}} \cdot \rho_{\mathrm{p}}}{c_{\mathrm{a}} \cdot \rho_{\mathrm{a}}} \cdot d_{\mathrm{p}}\left[A_{\mathrm{p}}/V\right] , \tag{3–43}$$

Equation (3–42) with respect to (3–37) consists of some additional parameters related to fire protection material and its placement around the structural member, these are: c_p – the temperature independent specific heat of the fire protection material, d_p – the thickness of the fire protection material, $\theta_\mathrm{g,t}$ – the ambient gas temperature at time t, $\Delta\theta_\mathrm{g,t}$ – the increase of the ambient gas temperature during the time interval Δt, λ_p – the thermal conductivity of the fire protection system, ρ_p – the density of the fire protection material.

Eurocode EN 1993-1-2 specifies the time interval Δt should not exceed 5 s for unprotected steel members and 30 s for insulated steel members. The sections factors A_p/V for steel members insulated by fire protection material should be calculated appropriately for contour and hollow encasement of steel profiles using rules given in Table 4.3 of EN 1993-1-2.

3.6.2 Semi-infinite solids and 1D heat transfer

The approach which uses the semi-infinite solid assumption can be used for estimation of temperature penetration in solid structural sections is detailed described in [32]. These type of approaches can be used in scenarios in which heat flow coming from different surfaces of a section does not significantly interfere with each other and the surfaces exposed to fire is not influenced by the limited depth of the section. In such cases, a solid may be assumed as semi-infinite. In practice, this is valid for concrete cross-section.

Wickström, in [32], gives a formulae for the maximum distance δ at which the only change of temperature at one point, i.e. surface point, influences the temperature at a given point:

$$\delta < 3 \cdot \sqrt{\frac{\lambda}{c \cdot \rho} \cdot t}\,, \tag{3–44}$$

where:

δ	[m]	Boundary layer thickness;
λ	[W·m^{-1} K^{-1}]	Conductivity;
c	[J·kg^{-1} K^{-1}]	Specific heat;
ρ	[kg·m^{-3}]	Density;
t	[s]	Time of fire exposure.

The coefficient “3” is proposed arbitrarily and can be modified with respect to assumed accuracy.

Under the condition of constant heat flux density received by a solid’s surface $\dot{q}_\mathrm{s}''$ and constant thermal properties of a material λ, c, ρ, at a point at a distance x from the exposed surface, the temperature $\theta(x,t)$ is equal to:

$$\theta(x,t) - \theta_\mathrm{initial} = \dot{q}_\mathrm{s}'' \cdot \left[\frac{2\sqrt{t}}{\sqrt{\pi} \cdot \sqrt{k \cdot \rho \cdot c}} \cdot \exp\left(-\frac{x^2}{4 \cdot \alpha \cdot t}\right) - \frac{x}{k} \cdot \left(1 - \mathrm{erf}\frac{x}{2 \cdot \sqrt{\alpha \cdot t}}\right)\right], \tag{3–45}$$

where θ_initial is the initial temperature of a solid, α is the thermal diffusivity, i.e. $\alpha = k/(c\rho)$ and erf is the Gauss error function.

Note that equation (3–45) is determined for a solid of a perfect material of constant thermal properties at constant heat exposure. However, in practice, it can be successfully used for estimation of temperature profile inside the real structural members. The more accurate calculations of temperature profile on the depth of the semi-infinite solid require numerical solution of the differential equation (3–35), which practically is a nonlinear equation due to nonlinearities coming from nonlinear material parameters and boundary conditions.

Nowadays, Finite Element Method (FEM) is the most commonly used method for solving heat transfer equations in solids. FEM allows to algebraize the differential equation (3–35) by discretizing the domain under consideration into several subdomains called finite elements. Then, the temperature in the analysed domain is calculated only at the nodes. The temperature field between the nodes is interpolated using the shape functions appropriate to selected finite element. In the finite element method formulation used in 1D heat transfer problems, the shape functions which interpolate temperature field between the nodes of a finite element are linear. The example of discretization of a 1D heat transfer model is given in Figure 3–10.

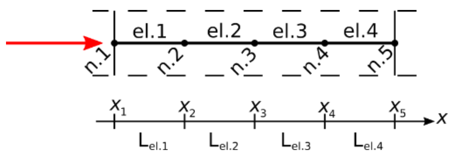


Figure 3–10 An exemplary 1D heat transfer problem. Domain discretized into 4 finite elements, the external heat flux is applied to node number 1.

The heat balance equation (3–35) can be determined for an arbitrary 1D finite element, see Figure 3–11, knowing the state of the element at current time step, i.e. the material parameters, nodal temperatures and nodal heat fluxes due to external actions change during the analysis of a transient process.

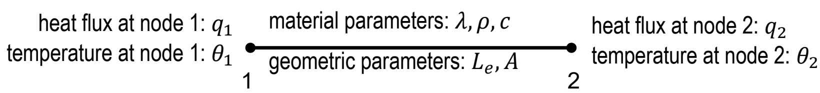


Figure 3–11 1D heat transfer finite element.

The heat balance, in the framework of FEM, for an arbitrary element is written in the following matrix form:

$$\boldsymbol{K}_{\mathbf{e}} \cdot \boldsymbol{\theta}_{\mathbf{e}} + \boldsymbol{C}_{\mathbf{e}} \cdot \dot{\boldsymbol{\theta}}_{\mathbf{e}} = \boldsymbol{Q}_{\mathbf{e}}\,, \tag{3–46}$$

where:

$$\boldsymbol{K}_{\mathrm{e}} = \frac{\lambda}{L_{\mathrm{e}}} \cdot \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}, \tag{3–47}$$

$$\boldsymbol{C}_{\mathrm{e}} = \frac{L_{\mathrm{e}} \cdot c \cdot \rho}{2} \cdot \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \tag{3–48}$$

$$\boldsymbol{Q}_{\mathrm{e}} = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}, \tag{3–49}$$

$$\boldsymbol{\theta}_{\mathrm{e}} = \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}, \tag{3–50}$$

$$\dot{\boldsymbol{\theta}}_{\mathrm{e}} = \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}. \tag{3–51}$$

The heat balance equations, for problems which consists of several finite elements, is build by aggregation of elements' matrices into global matrices, i.e. for the problem given in Figure 3–10 the heat balance equation is:

$$\boldsymbol{K} \cdot \boldsymbol{\theta} + \boldsymbol{C} \cdot \dot{\boldsymbol{\theta}} = \boldsymbol{Q}. \tag{3–52}$$

Using the notation where superscript indicates the element number and subscript indicates the position of component in element's matrix, i.e. k_{12}^3 means component 12 of conductivity matrix of finite element 3, we can specify for problem given in Figure 3–10:

$$\boldsymbol{K} = \begin{bmatrix} k_{11}^1 & k_{12}^1 & & & (0) \\ k_{21}^1 & (k_{22}^1 + k_{11}^2) & k_{12}^2 & & \\ & k_{21}^2 & (k_{22}^2 + k_{11}^3) & k_{12}^3 & \\ & & k_{21}^3 & (k_{22}^3 + k_{11}^4) & k_{12}^4 \\ (0) & & & k_{21}^4 & k_{22}^4 \end{bmatrix}, \tag{3–53}$$

$$\boldsymbol{C} = \begin{bmatrix} c_{11}^1 & & & & (0) \\ & (c_{22}^1 + c_{11}^2) & & & \\ & & (c_{22}^2 + c_{11}^3) & & \\ & & & (c_{22}^3 + c_{11}^4) & \\ (0) & & & & c_{22}^4 \end{bmatrix}, \tag{3–54}$$

$$\boldsymbol{\theta} = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \\ \theta_5 \end{bmatrix}, \tag{3–55}$$

$$\boldsymbol{Q} = \begin{bmatrix} q \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \tag{3–56}$$

$$\dot{\boldsymbol{\theta}} = \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_4 \\ \dot{\theta}_5 \end{bmatrix}. \tag{3–57}$$

Equation (3–52) is a nonlinear equation in the sense that parameters of the equation, eg. material properties, depend on the solution. Hence, the iterative solution procedures, like Newton-

Raphson method, can be used to reach equilibrium at each time step. However, in practical application of fire engineering, unless the very rapid heating is considered, any of Newmark methods with time step less or equal 5 s should give accurate results.

3.6.3 Intermediate models

For thin-walled steel cross-sections, e.g. hot-rolled, box and cold-formed sections, some intermediate heat transfer models can be used. Intermediate models utilize some of benefits of lumped capacitance model and/or 1D heat transfer models to determine temperature distribution in two-dimensional cross-sections. Here, two intermediate models are shown: (1) a model in which incoming heat flux is directly determined at the envelope of a cross-section, (2) a model which uses AST to determine conditions around the cross-section.

3.6.3.1 Direct determination of heat flux at a cross-section envelope

In this kind of approaches, the section temperature is calculated by taking into account both convective and radiative heat fluxes facing the particular section surfaces. Calculation of convective heat flux does not generate many problems as long as we consider convective heat flux is dependent only on the constant coefficient of the heat transfer by convection $h_c$and difference between fluid and surface temperature $(\theta_g - \theta_s)$, see eq. (3–5). The special concern, however, must be paid for the proper definition of radiation problem by recognition of radiation's directions. Here, helpful are so called face view angles defined as the lower and the upper limit of radiation direction angle that can reach particular point on the section surface (Figure 3–12). It is assumed that only the radiation along the direction β within α_1 and α_2 limits can reach particular point of interest on the section edge:

$$\alpha_1 < \beta < \alpha_2 \,. \tag{3–58}$$

The main disadvantage of this method is the necessity to collect and process a significant amount of data from a fire model. The collected data quantifies the incident radiation from all the direction around the cross-section. Afterwards, data must be processed to quantify the amount of radiation received by particular parts of a cross-section.

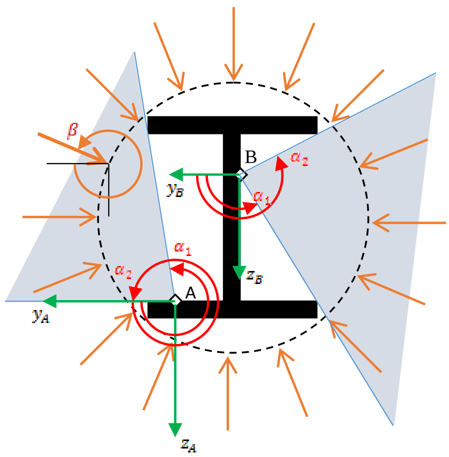


Figure 3–12 Geometrical visualization of view angles α_1 and α_2 for an example of points A and B and corresponding angle of radiation vector β.

The temperature is averaged in section temperature points, see Figure 3–13. The number of section temperature points depends on the required accuracy in calculated temperature distribution. Heat fluxes $\dot{q}_1$ and $\dot{q}_2$ are calculated by integration of the difference between incident and emitted radiation at the corresponding edges. It is assumed that the heat received is stored in part of a cross-section represented by analysed section temperature point. Hence, at particular section temperature point, the increase of temperature is calculated as:

$$\Delta\theta_i = \frac{\dot{q}_1 + \dot{q}_2}{h \cdot c \cdot \rho} \cdot \Delta t \,, \tag{3–59}$$

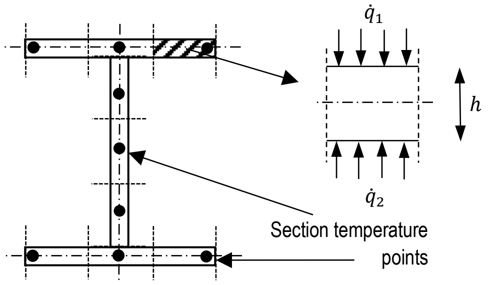


Figure 3–13 Section temperature points and related heat fluxes $\dot{q}_1$ and $\dot{q}_2$.

3.6.3.2 Using Adiabatic Surface Temperature (AST) to determine conditions around the cross-section

This approach is based on the following assumptions:

1. The thermal exposure of the cross-section of the structural element (Figure 3–14 a) can be specified at artificial surfaces creating the convex polygon surrounding the cross-section, called an envelope of receiving surfaces (Figure 3–3 b). The thermal exposure is then represented by the value of an *adiabatic surface temperature* (AST) at each surface, so it combines the effects of radiation and convection.
2. During the heat transfer analysis, when the radiation problem is resolved, artificial surfaces creating the envelope of receiving surfaces, act as the black body radiators (Figure 3–3 c).
3. Since a cross-section's walls are thin, the constant temperature throughout their thickness is assumed. However, the conduction across the cross-section could be taken into account.

The envelope of receiving surfaces is composed of artificial surfaces that play an important role in this approach. Note that the above assumptions do not enforce the envelope of receiving surfaces to have a rectangular section, like in (Figure 3–3 b, c). It can have any different shapes, depending on the shape of the cross-section it surround. Moreover, the number of artificial surfaces is not restricted. One can use an increased number of artificial surfaces when higher accuracy is required. Note that the artificial surfaces are only theoretical entities developed on the basis of adiabatic surface temperature concept and do not interfere the fire model.

Even though the artificial adiabatic surfaces are only theoretical entities, they refer to real devices, called plate thermometers (Figure 3–15 a). Plate thermometers are widely used in measurement of thermal exposures. The adiabatic surface temperature can be computed from plate thermometer output using a reformulated solution given in eq. (3–24). The temperature of the virtual surfaces is set to the adiabatic surface temperature (AST), Figure 3–15 a, b. Thanks to the use of AST, the temperature of the virtual surfaces can be used for specification of convective heat flux to the visible solid section surfaces. Therefore, the developed heat transfer model takes into account the thermal exposure both from radiation and convection. The virtual surfaces are placed only at the position of recognised heat exposure, i.e. for the steel profile that supports the concrete ceiling, the upper edge of the polygon does not contribute in heat transfer, see Figure 3–15 a, b.

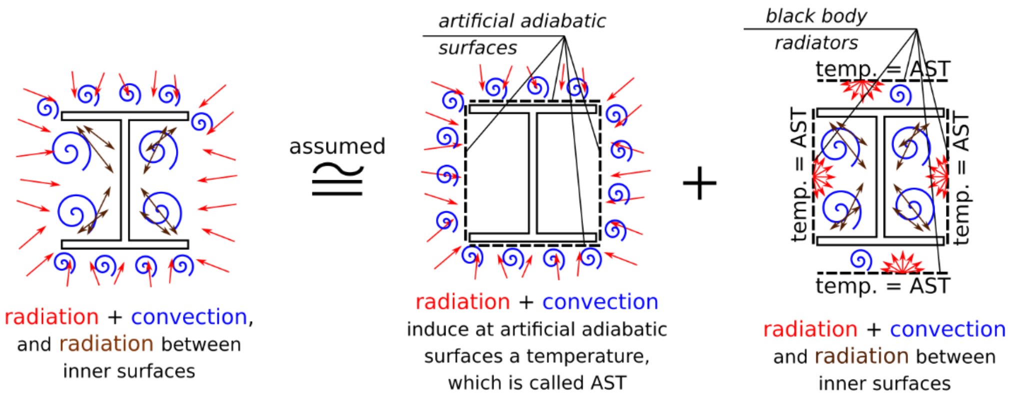


Figure 3–14 The idea behind the heat transfer approach for a thin-walled cross-section that uses AST: a) thermal exposure conditions; b) introduction of artificial adiabatic surfaces into the model; c) scheme of resolving the heat transfer problem within the thin-walled cross-section.

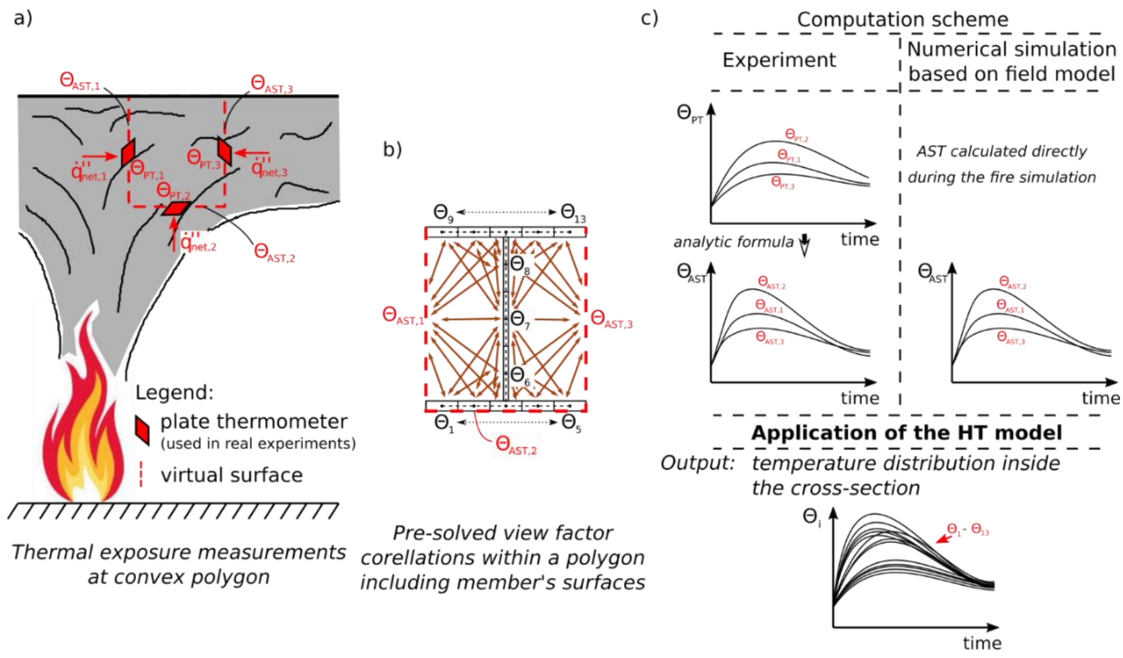


Figure 3–15 Visual representation of connection between the heat transfer approach, experiments and numerical simulations: a) visualization of the polygon inside the fire compartment that consists of virtual surfaces, b) co-radiating surfaces and temperature points inside the cross-section, c) computation scheme.

The temperature is calculated at section temperature points, as previously, however, the amount of information to be provided by fire model is limited to AST at receiving envelope surfaces. The quantities for convective $\dot{q}_{\mathrm{conv}}$ and radiative $\dot{q}_{\mathrm{rad}}$ heat fluxes are specified as the output of the heat transfer model and then substituted into equation for the increase of temperature at the temperature point:

$$\Delta\theta_i = \frac{\dot{q}_{\mathrm{conv}} + \dot{q}_{\mathrm{rad}}}{h \cdot c \cdot \rho} \cdot \Delta t \,, \tag{3–60}$$

An example of an I-section divided into 7 parts and enclosed by the receiving envelope is shown in Figure 3–16. The heat received at each of 7 temperature points is collected from corresponding to this point surfaces. The reciprocal radiation between the envelope's surfaces and cross-section's surfaces is to be resolved by the heat transfer model.

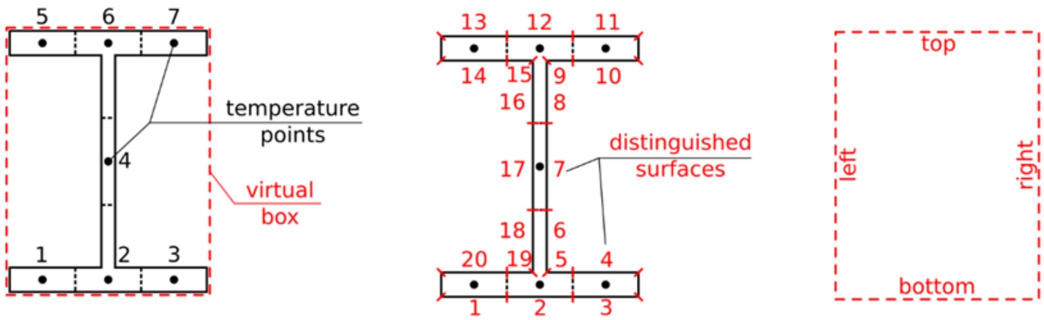


Figure 3–16 Cross-section divided into 7 parts and corresponding: 7 temperature points, 15 surfaces at section edges, 4 surfaces of receiving envelope.

Using this approach, it is possible to define a heat transfer model that allows the calculation of the temperature distribution in thin-walled sections to be more accurate and yet similarly simple and fast as the lumped capacitance Eurocode model. This is due to the fact that the model is based on a set of matrices, which are constant for a given geometry and given number of temperature points. These matrices play an analogous role as section factors $\mathrm{A_m}/V$ and correction factors for the shadow effect k_{sh} in the lumped capacitance Eurocode model.

3.6.4 2D heat transfer analyses using Finite Element Method

2D Finite Element Method is used for the heat transfer analyses in problems which require particular accuracy in calculation of temperature field in structural section. This is usually the case for concrete structures with complex cross-sections, e.g. the need for calculation of isotherm 500, Figure 3–17. However, from the physical and computational point of view, there is no limitation for use of 2D models for particular materials. The 2D FEM analyses of heat transfer allow to consider exact fire exposure of structural sections, as well as specific physical phenomena like reciprocal radiation of surfaces in voids, see Figure 4–1.

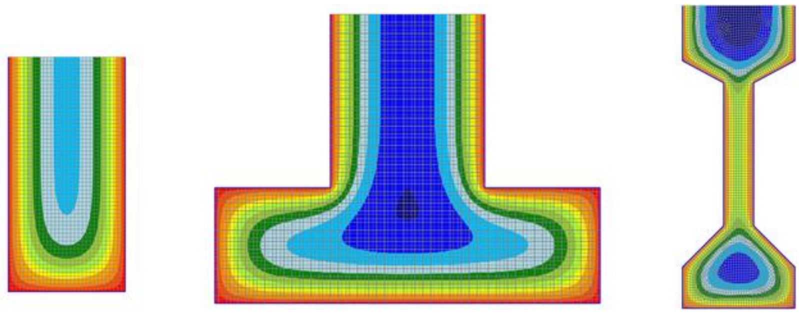


Figure 3–17 Colormaps representing different temperature profiles in concrete cross-sections.

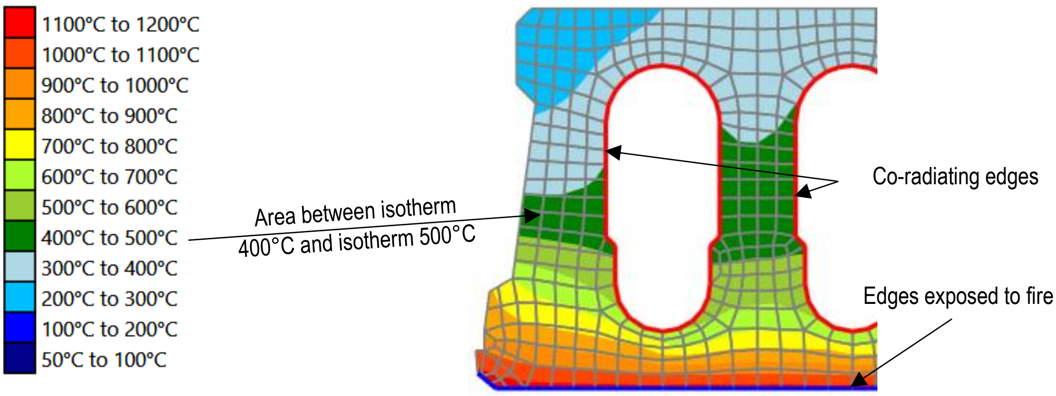


Figure 3–18 Representation of exact fire exposure and reciprocal radiation in section's voids on the example of concrete slab.

2D heat transfer analyses of structures in fire requires specialistic software which allows for definition of complex geometries, boundary conditions and thermal exposure. These kind of software must also provide solutions for transient nonlinear problems, which is crucial in fire engineering application.

4 THERMAL AND MECHANICAL RESPONSE CALCULATION MODELS

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Calculation models for simulating thermal and/or mechanical response of structures – structural models – can predict the response of structure such as deflection, elongation, etc., depending on the applied actions. In the context of advanced structural fire safety design structural modelling represents the final step in the estimation of the ability of the structure to withstand the effects of fire. The process of structural analysis for thermal effects is shown in Figure 4–1.

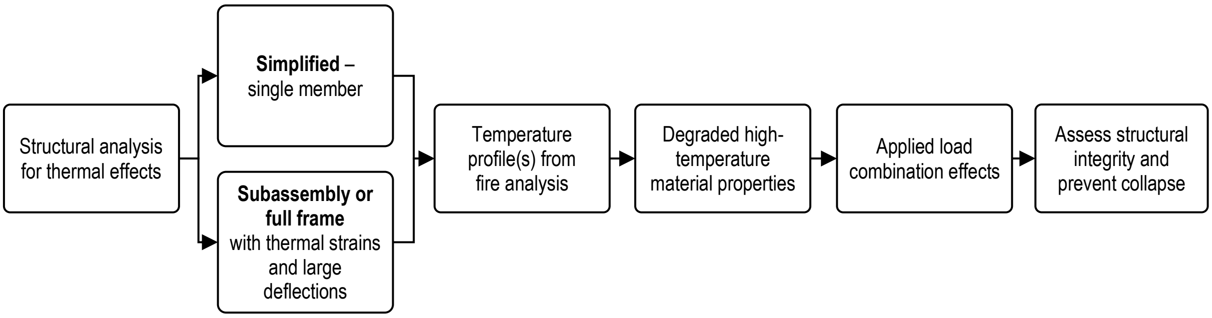


Figure 4–1 Schematic of structural analysis for fire effects, adapted from ch. 52 of [15].

Although the principles of the structural analysis for thermal effects remain the same, the approaches differ, depending on the type and complexity of the model. From this perspective, structural models may be categorised as follows:

- simplified structural fire resistance models;
- advanced structural models;
- integrated advanced structural models.

As with fire models, it does not mean that the greater complexity of a structural model warranties its accuracy. As the complexity of a model grows, user specifications and inputs become much more detailed. So for simpler problems, involving individual structural members, application of simplified structural models may be sufficiently accurate and appropriate. The individual model categories are briefly introduced and described in the following sections.

4.1 Simplified structural fire resistance models

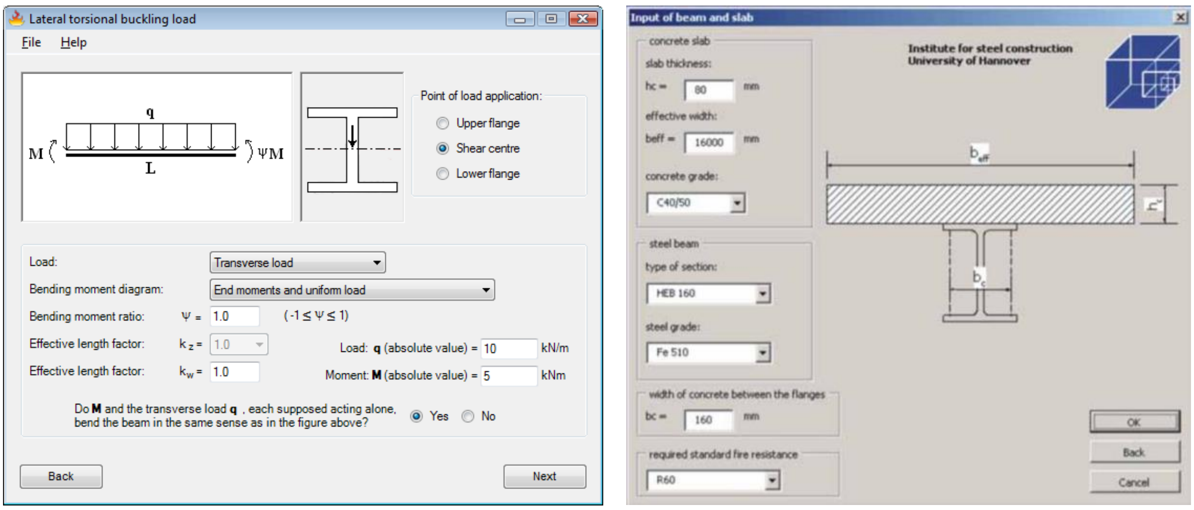
Simplified structural fire resistance models perform calculations for individual structural elements in isolation. The actual calculations represent simplified design methods; hence their field of application is quite limited, often only to a selected number of structural elements of particular type and/or shape. On the other hand, some of them offer the capability of predicting thermal actions based on nominal curves or user-defined input. Alternatively, these models as such may be incorporated into a zone or field model or coupled with them. An example of direct incorporation of such a structural model into a zone fire model is Ozone, described in section 2.3.1.3. An overview of simplified structural models is in Table 4–1. Examples of user interfaces are shown in Figure 4–2.

It should be noted, that simplified models, such as those listed above may be developed for specific purposes or a set of conditions. Hence, the user should always check the applicability of the model to the particular problem at hand. For example, restraint conditions play a critical role, or there may me time, temperature or other limits for the particular models. Particular care should be exercised when different than the standard time-temperature curve heat exposure is to be evaluated. Many of the analytical equations have been developed for this particular heating regime. Using a different one may render the results invalid.

If these models are a computerised representation of a standard and generally accepted procedure, e.g. equations from Eurocodes, the validation is not necessarily required. On the other hand, verification and the correct implementation of the equations should always be checked. If no official documentation of verification is available, then calibration calculations should be conducted and the results of the simplified model checked against results obtained from hand calculations or other verified models.

Table 4–1 Overview of simplified structural models for calculation of fire resistance [34].

Model	Country	Short description
AFCB	Luxembourg	Composite beam fire design according to Eurocode 4
AFCC	Luxembourg	Composite column fire design according to Eurocode 4
CIRCON	Canada	Fire resistance model for reinforced concrete columns with circular cross section
COFIL	Canada	Fire resistance of circular hollow steel section filled with plain concrete
Elefir - EN	Portugal/Belgium	Fire resistance of steel structural elements according EN version of Eurocode 3
Elefir	Belgium	Fire resistance of steel structural elements according Eurocode 3
H - Fire	Germany	Calculation of design resistance for composite members exposed to fire by using the simple calculation models of the EN 1994-1-2
INSTAI	Canada	Fire resistance of insulated circular hollow steel columns
INSTCO	Canada	Fire resistance of circular concrete-filled tubular steel sections
POTFIRE	France	Fire resistance of concrete filled hollow section – based on annex G of Eurocode 4
RCCON	Canada	Fire resistance model for reinforced concrete columns with rectangular cross section
RECTST	Canada	Fire resistance of insulated rectangular hollow steel columns
SQCON	Canada	Fire resistance model for square reinforced concrete columns
WSHAPS	Canada	Fire resistance of protected W-shape steel columns
Požární odolnost	Czech Republic	Fire resistance of steel elements based on EN 1993-1-2



Elefir–EN – steel structures per EN 1993-1-2

H-Fire – composite structures per EN 1994-1-2

Figure 4–2 Examples of user interfaces of simplified structural models for structural fire safety design.

4.2 Advanced structural models

The advanced structural models group covers primarily general-purpose finite element method (FEM) models for conducting finite element analysis (FEA). FEA is, along with the finite difference and finite volume methods, an approach for numerically solving the differential equations governing the phenomenon of interest. The structure (system) is subdivided into simpler discrete parts, which are called finite elements. These elements form a computational mesh with a finite number of points upon which the calculations are performed. For further information on FEA, the reader may refer to [35] or other specialised texts.

Typical elements used by FEM models for approximation of real objects are:

- 3D bulky solids;
- 2D shells;
- 1D beams.

The general purpose FEM packages, are able to simulate a wide range of phenomena including the heat transfer and structural problems. A list of available FEM packages is provided in Table 4–2; the list is not exhaustive. Since FEM packages usually contain a wide range of sub-models it is not possible to generalise their components and possible coupling. In general, they contain solvers for steady-state and transient problems and are able to take input from other programs, e.g. fire models. This input would usually take form of a text file with temporal, spatial coordinates followed by other variables of interest, e.g. temperature, heat flux etc. There are also specialised scripts and utilities available, such as the FireThermomechanical Interface (FTMI) which transfers the results from Fire Dynamics Simulator (see Section 2.3.2) to ANSYS [36].

Table 4–2 Overview of advanced structural models – extended from [34].

Model	Country	Short description of problems which can be solved:
ABAQUS	USA	Uncoupled heat transfer analysis, sequentially coupled thermal-stress analysis, fully coupled thermal-stress analysis, fully coupled thermal-electrical-structural analysis, adiabatic analysis, coupled thermal-electrical analysis, cavity radiation
ALGOR	USA	CFD including steady-state and transient heat transfer, steady and unsteady fluid flow and mass transfer
ANSYS	USA	Steady-State Thermal for the structural thermal response model can be use and Static Structural for the mechanical response model
COSMOS	USA	Temperature, convection, radiation, heat power: Thermal Stress, Heat Transfer - Steady State & Transient, Temperature Dependent Materials, Fluid Flow
MSC NASTRAN	USA	Conduction, convection, and radiation analyses: heat transfer and thermal stress analysis
LUSAS	GB	Steady-state, and transient thermal / field analyses: Prescribed temperature, Heat flux or rate of heat generation or absorption, Convection between surfaces or to the environment, Radiation between surfaces or to environment, Environmental or initial temperatures, Impermeable boundaries for seepage flow, Temperature dependent properties
MIDAS FEA	USA	Heat transfer, thermal stress and seepage-thermal stress analysis types
LS DYNA	USA	Heat transfer and coupled thermal-stress: Steady State Heat Transfer, Transient Heat Transfer, Thermal Stress

There are two approaches to coupling fire and structural models. One-way coupling only passes the information from a fire model to a structural model. Once the thermal effects of fire are established, i.e. the fire simulation is finished, then these data are appropriately passed and mapped into the structural model for further thermomechanical analysis. Therefore, potential deterioration of the structure, particularly for fire separating elements (walls and floor slabs), is not reflected in fire or heat spread. Coupling requires mapping of points for which is the information transferred from the fire model into the structural model. The principle of mapping is illustrated in Figure 4–2 and discussed in [37].

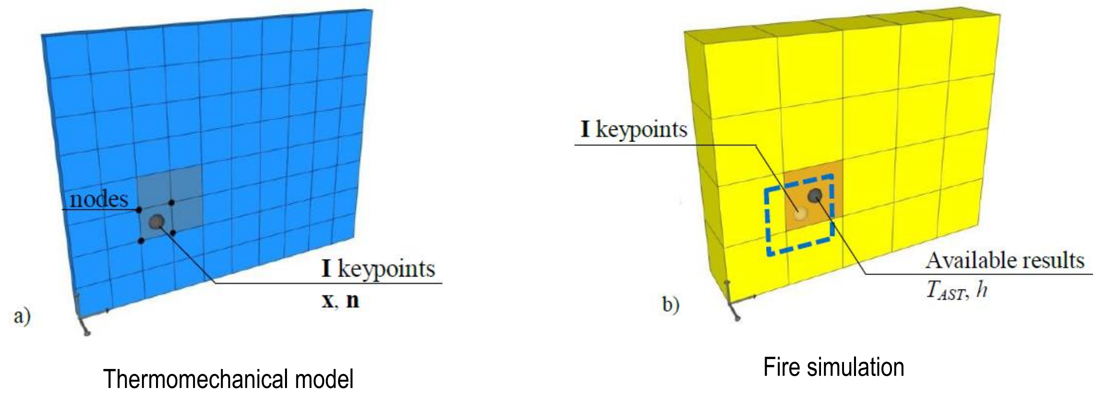


Figure 4–3 Illustration of the exposed surfaces and the mapping procedure.

Two-way coupling is a more advanced approach which the information is passed on only from the fire model to the structural model, but also in the opposite direction. This way the thermal feedback of the structure may be accounted for, as well as potential structure deterioration. While one-way coupling may be asynchronous, i.e. the information is passed once the fire calculation has been completed, two-way coupling requires time synchronisation. This means that the information must be passed in regular intervals as the calculation proceeds so that the fire calculation is regularly updated. This may require a series of iterations in order to reflect the adjustments from structural models. The general principle of this approach is shown in and discussed in [38].

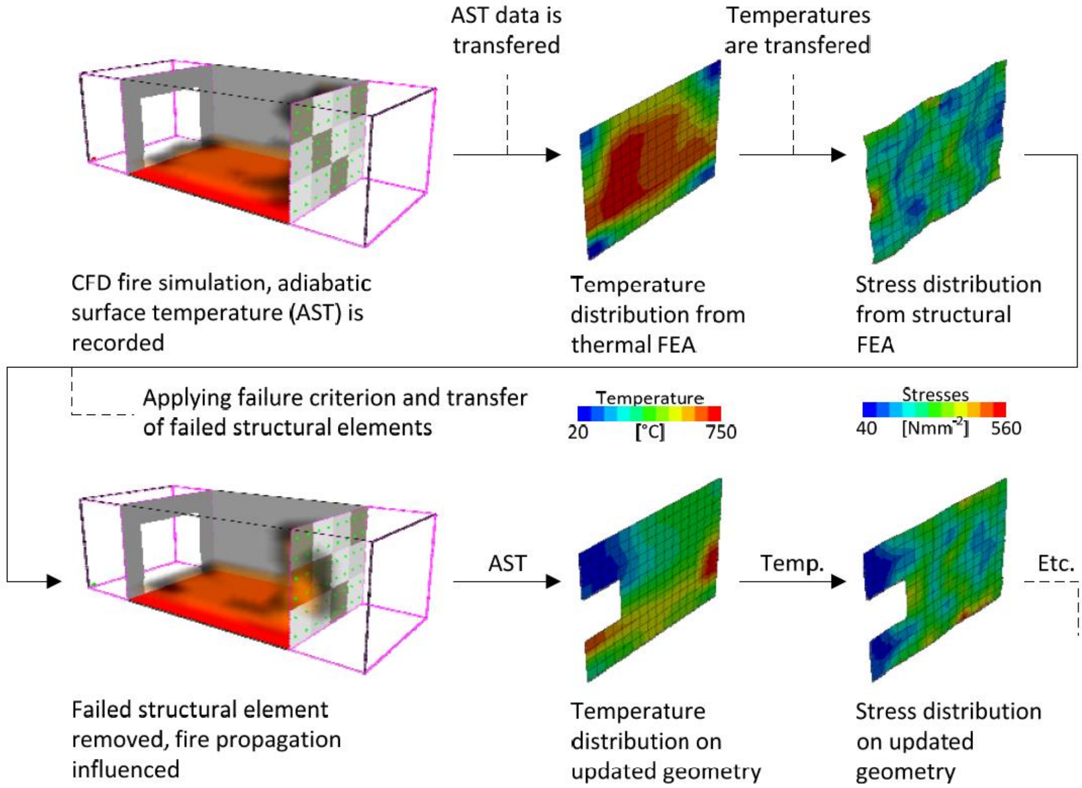


Figure 4–4 Two-way coupled fire to thermomechanical analysis using a stress-based failure criterion [38].

A comprehensive review of the evolution and capabilities of models for structural resistance may be found in [39]. An in-depth discussion on the fire and structural models coupling is in [40].

4.3 Integrated advanced structural models

Integrated advanced structural models are able to simulate both the fire as well as the thermal and mechanical response of structure. The fire, thermal, structural, and other models are coupled internally. An overview of integrated advanced structural models is provided in Table 4–3. Their complexity and application range varies from relatively simple models for specific types and/or shape of structural members (e.g. BoFire) to advanced FEM packages, e.g. SAFIR [41]. Even though there is some integration of fire exposure prediction, this usually covers the standardised time-temperature curves and user defined input. As with the general purpose FEM models (discussed in Section 4.2) there are various approaches for coupling the integrated models with fire models. Further information on this topic may be found in [40] and GENISTELA and GENISTRUC frameworks described in [42] and thesis [43].

Table 4–3 Overview of integrated advanced structural models [34].

Model	Country	Short description
BoFire	Germany	Transient, non-linear, incremental code based on FEM, with the implementation of ENV 1994-1-2
BRANZ-TR	New Zealand	Analysis of the fire resistance of reinforced or prestressed concrete floor systems
CEFICOSS	Belgium	Fire resistace model
COMPSL	Canada	Temperatures of multilayer slabs during exposure to fire
FASBUS	USA	Mechanical resistance model for structural elements exposed to fire
FIRES-T3	USA	Finite element heat transfer for 1, 2, or 3D conduction
HSLAB	Sweden	Transient temperature development in a heated slab composed of one or several materials
LENAS	UK	Mechanical behaviour of steel structures exposed to fire
SAFIR	Belgium	Transient and mechanical analysis of structures exposed to fire
SAWTEF	USA	Structural analysis of metal-plate connected wood trusses exposed to fire
SCIA ENGINEER	Belgium	Calculation of design resistance (FEM) of structures exposed to fire by using the simple calculation models of the Eurocode 3 and NEN6072 for thermal load
SISMEF	France	Mechanical behaviour of steel and concrete composite structures submitted to fire
STA	UK	Transient conduction in heated solid elements
STELA	UK	Three-dimensional finite-volume model, for calculating the thermal response of structural elements to fire gases
TASEF	Sweden	Finite element code for temperature analysis of structures to fire
TCSLBM	Canada	Two dimensional temperature distributions for fire exposed concrete slab/beam assemblies.
THELMA	UK	Finite element code for temperature analysis of structures exposed to fire
TR8	UK	Fire resistance of concrete slabs and floor systems
VULCAN	UK	Three – dimensional frame analysis program, which has been developed mainly to model the behaviour of skeletal steel and composite frames, including the floor slabs, under fire conditions.
WALL2D	Canada	Model for prediction heat transfer through wood-stud walls exposed to fire
Ocel požár	Czech Republic	Forms a part of static system FINE10, calculates resistance of steel elements exposed to fire based on the EN 1993-1-2

5 CONTROL

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5.1 Situation (structure & fire) representation

Even when the most advanced modelling techniques and tools are applied to a design problem, they are still only an approximation of real-world fire and structural behaviour. Every model incorporates simplifications and hence an appropriate representation of the situation to be analysed is necessary.

As discussed in section 2, representative fire scenarios are prerequisite for establishing the thermal effects of fire through design fires applied in fire models. Intrinsic variability, and hence uncertainty, associated with the prediction of fire behaviour makes this process rather complex.

The first step is, as with any engineering or performance-based analysis, the determination of requirements and objectives of the project. The primary goal is life-safety, which, from the structural standpoint, means that the ability of structural elements to bear loads and/or prevent fire from spreading will be maintained for a required time period. There may be further objectives such as property protection, business continuity or heritage protection (see case study in section 0). These objectives should then be translated into functional requirements, i.e. what function (load-bearing and/or fire separating) is required of which elements. Finally, the performance criteria, which indicate whether the functional requirements are met, are quantified. The details of these steps are covered in ISO 24679-1:2019 Fire safety engineering – Performance of structures in fire – Part 1: General [44], which should be used in conjunction with ISO 23932-1:2018 Fire safety engineering – General principles – Part 1: General [45].

Since it is often not practical or even possible to simulate the entire structure of a building relevant parts of the structure, or even individual elements, may be evaluated in isolation. EN 1991-1-2 allows the application of advanced calculation model in any type of design procedure, see also Figure 1–2 on page 12 of this guide. There are no "hard-and-fast" rules, but the selection of structural members, or parts of structure, is usually driven by their function and criticality, utilisation ratio, susceptibility to failure due to thermal expansion or shrinking, etc.

Hence, there will be some sort of preliminary assessment – qualitative and/or quantitative – required to identify the relevant scenarios, potential failure modes and their consequences. Part of this is an analysis of dependencies between structure members, parts of structure and structure of the entire building. The main question is, whether it is possible to safely isolate the critical part of structure or member for further analysis. For example, the car park case study presented in section 0 identifies the critical members of the structure and the most severe fire scenarios and then evaluates their combinations. Further examples may be found in ISO/TR 24679-6:2017 [46] and numerous research papers, e.g. [47, 48], and guides [49].

5.2 Sensitivity and uncertainty

When dealing with any type of fire and structural model, it is important to analyse the sensitivity of the model to input parameters and uncertainty associated with them as well as with the model itself. Only very few input parameters may be accurately represented as fixed values, e.g. the ambient temperature may be usually taken as 20 °C. A significant proportion of input parameters can attain their value from a range of observed or expected values. Hence, we observe variability in the input parameter. In some cases the range is relatively narrow and/or the value selection is driven by known circumstances which remain relatively stable or predictable over the entire range of evaluated scenarios. In other, the range may be quite wide and the actual value rather uncertain, e.g. the fire load for a multipurpose space such as a convention centre. To evaluate how the model results are affected by a change in input parameters sensitivity analysis is conducted.

Sensitivity analysis may be relatively straightforward for simpler calculations and independent variables. The equations forming the model usually indicate which parameters is the model more or less sensitive to. For example, the calculation of net radiative heat flux, see Equation (2–3), is strongly sensitive to the temperature of hot gases or emitting surface, since the 4th power of temperature is present in the equation. As such sensitivity analysis should help with the quantification of the magnitude of change in the outputs caused by the change in the inputs. Sensitivity analysis then sets priorities for further uncertainty analysis, which should primarily focus on the parameters which is the model most sensitive to.

When using a computer model, the sensitivity analysis usually takes a form of series of runs in which a single parameter is being changed across the entire range in desired steps or increments. For this approach a baseline scenario is required in which all the parameters have some default value. The potential caveat with this approach are the possible dependencies among the analysed parameters and their cumulative impact on results which may be not as significant when analysed individually. In this regard the insensitivity of a model to a certain input parameter should be treated as indicative only and not entirely conclusive. An example of such sensitivity analysis may be found in the appendix of [47].

Hasofer identifies two types of uncertainty in design [50]:

1. Knowledge uncertainty, which is due to lack of fundamental knowledge about the objects and the phenomena involved in the design. For example:
   a) lack of knowledge about the amount and type of combustible materials that will be present in a room when the fire starts,
   b) uncertainty about the accuracy of the fire modelling used,
   c) uncertainty about the acceptable heat dose on a person.
2. Stochastic uncertainty, which is due to the intrinsic variability of the phenomena involved in the design. For example, the fire growth rate over a class of buildings.

The knowledge or epistemic uncertainty may be reduced through detailed specification of the scenario(s) to be evaluated, both from the fire as well as structural, point of view. Since advanced modelling techniques are applied these require very case-specific information and data.

The other source of uncertainty is the inherent randomness of the fire phenomenon, which extends to a certain degree into the structural part of the analysis, also known as aleatory uncertainty. Two most common examples are the fire load and the variable load. Neither of these variables is a fixed value, but a selected characteristic (representative) value from an interval of distributed values. This value would usually be taken as the 85th or higher percentile of the interval, so that, only a small portion of values with small probability of occurrence is not represented.

As an example, Figure 5–1 shows the probability density and cumulative density functions of an arbitrary normal distribution of fire load whit μ = 70 kg·m^{-2}, σ = 12. Should the mean value of 70 kg·m^{-2} be selected, there would be a 50 % chance, that the fire load is exceeded, and a potential failure may occur. By increasing the characteristic (or representative) design value to 80 kg·m^{-2} about 80 % of potential values would be covered and to 85 kg·m^{-2} about 90%. Hence, the chance of underperformance due to underestimated fire load would be reduced to 20 % and 10 %, respectively. This approach could be considered the worst reasonable case approach to uncertainty treatment as per Pate-Cornell [51].

As an alternative to the above approach, which is based on conservative-enough values, the actual distributions may be inputs for the calculations. This obviously requires an appropriate sampling technique, e.g. Monte-Carlo, Latin hypercube, etc., and a sufficient number of iterations. An example of simple random sampling with various from the above described distribution of fire load is shown in Figure 5–2. It is clear that the true shape of the distribution, along with it is tails is captured better as the number of sampling point increases.

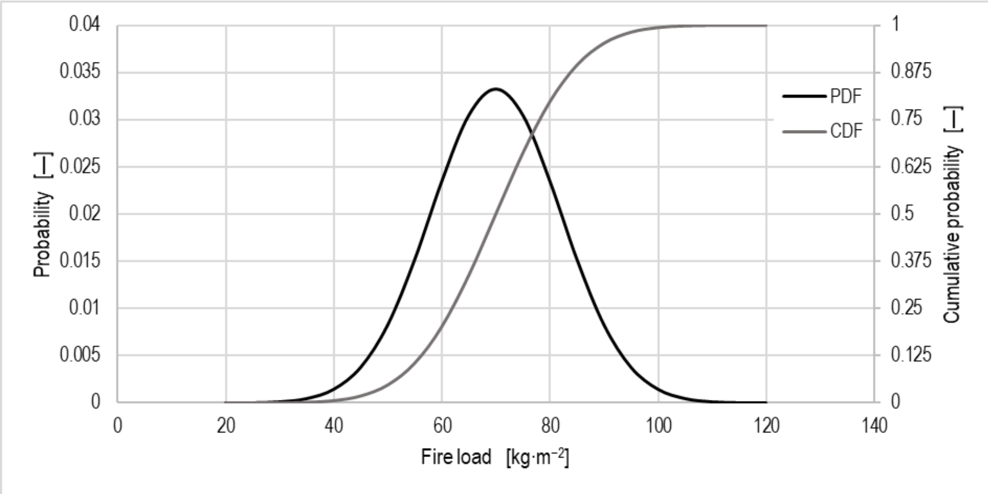

Figure 5–1 Exemplary PDF and CDF of an arbitrary fire load following normal distribution: μ = 70 kg·m^{-2}, σ = 12.

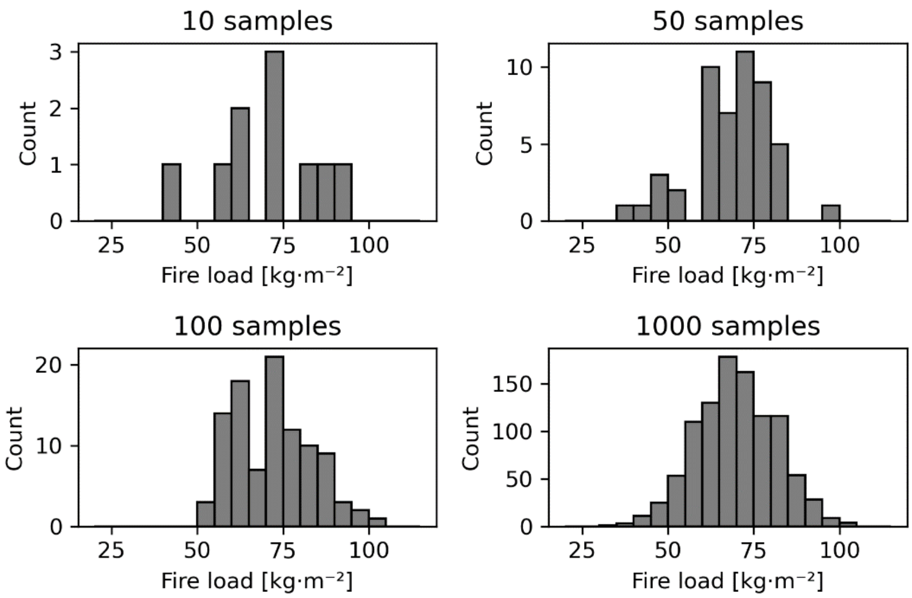

Figure 5–2 Example of simple random sampling from the arbitrary fire load distribution: μ = 70 kg·m^{-2}, σ = 12.

Subsequently, following the desired number of iterations with the sampled input(s), the results should be checked for convergence for example through the root mean squared error (RMSE) or other appropriate technique. Finally, the obtained result, e.g. average, is checked against the required value.

Alternatively, the distribution of the results (e.g. predicted times to member failure) may be checked against a required value or their distribution and the probability of failure determined and considered for tolerability or acceptability.

5.3 Verification and validation

Every model, in particular advanced computer models, should be properly verified and validated. ISO 16370-1:2015 Fire safety engineering — Procedures and requirements for verification and validation of calculation methods — Part 1: General defines verification and validation as follows [52]:

Verification – process of determining the degree to which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method.

Validation – process of determining that a calculation method implementation accurately represents the developer's conceptual description of the calculation method and the solution to the calculation method. The fundamental strategy of verification of computational models is the identification and quantification of error in the computational model and its solution.

The conceptual representation of verification and validation of models is shown in Figure 5–3.

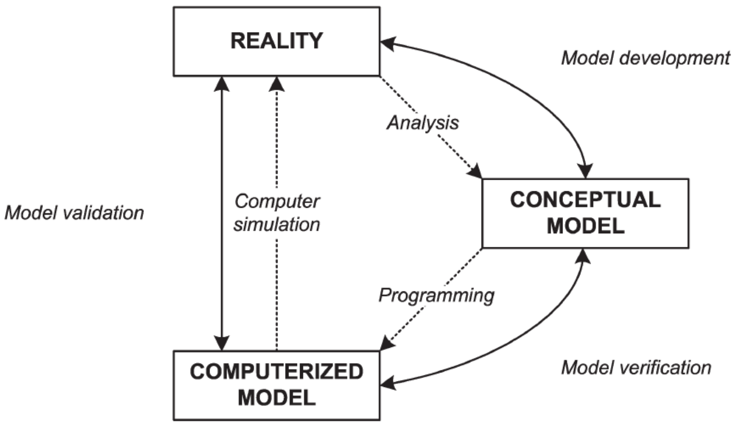

Figure 5–3 Conceptual representation of model verification and validation **[52]**.

It should be also noted that model validation against simulation results from other model, e.g. a zone fire model against a CFD fire model, is not an appropriate method.

Verification and validation (V&V) are usually not part of design process, i.e. application of the fire and/or structural models to a specific problems. Nonetheless, the user of any computer (or other) model should demonstrate due diligence and at least formally state the extent and form of verification and validation for selected models and provide references to documents containing information on them. As an example, both CFAST and FDS have their V&V documented in dedicated documents [10, 17, 18] and users may obtain the V&V model source files from their respective webpages.

Verification and validation statements are particularly important with regard to advanced and complex features of computer models that may have a significant impact on the results, e.g. direct suppression simulation when the suppressant actually interacts with the fire and/or cools the environment and constructions.

The formal procedure for V&V for fire safety engineering models may be found in the above mentioned ISO 16370-1:2015. This international standard is supplemented by a series of technical reports with examples for various types of models, including:

- ISO/TR 16730-2:2013 Fire safety engineering — Assessment, verification and validation of calculation methods — Part 2: Example of a fire zone model.
- ISO/TR 16730-3:2013 Fire safety engineering — Assessment, verification and validation of calculation methods — Part 3: Example of a CFD model.
- ISO/TR 16730-4:2013 Fire safety engineering — Assessment, verification and validation of calculation methods — Part 4: Example of a structural model.
- ISO/TR 16730-5:2013 Fire safety engineering — Assessment, verification and validation of calculation methods — Part 5: Example of an Egress model.

Further information on V&V may be found in various publications, e.g. general principles of V&V [53], FEM models V&V [54], fire models [55] to list a few. In addition a series of benchmark studies for numerical models in fire engineering may be found in [56, 57].

In addition to V&V documentation, the entire models should be sufficiently documented, both from the technical as well as user's perspective. In addition to the recommendations of ISO 16370-1:2015, guidance on documentation of fire models may be found in now withdrawn ASTM E1472-07 Standard Guide for Documenting Computer Software for Fire Models. As a follow-up document the SFPE has published an engineering guide titled Guidelines for substantiating a fire model for a given application [58].

5.4 Data and their sources

Data play a critical role in the accuracy and representativeness of any simulation. It should also be acknowledged that there will always be some approximated or extrapolated data to fill gaps where data are missing. Nonetheless any data used in simulations should:

- come from an authoritative and relevant source – e.g. when Eurocodes specify certain input values these should be used as the first choice.
- referenced and traceable – each piece of input data should contain clear indication where it is source from. This should not only be the title of a publication or a standard, but also a table, page or paragraph reference should always be provided where possible.
- justified and representative – where ambiguity may arise due to variability, uncertainty, or representativeness a commentary should be provided. This should offer clear reasoning and justification why a particular value or range of values is applicable in a given scenario / problem and whether any conditions or limitations are assumed.

In addition to data availability there may be limitations within the applied model that restrict input format. For example, specific heat or conductivity are temperature dependent. However, certain models, e.g., CFAST, only allow a fixed value input. Therefore, a representative value is required which will not affect the results adversely (primarily from the safety perspective). A sensitivity analysis is helpful in this regard as it may filter out parameters whose values do not significantly affect the outputs.

PD 7974-7:2003 [59] lists a series of key points that should be considered regarding data:

- Data applicability:
    - What is the set of cases that the data are drawn from?
    - What case are the data measuring?
    - How similar is my system to the cases considered?
    - If the data are from another country, will variations in statutory controls or design practices skew the data?

- Data quality
  - How old are the data (10 years is considered a typical cut off age for high quality data)?
  - Are corroborative data available?
  - Are the data from statistical studies or based on engineering judgement?
- Check study results
  - Do the answers look realistic?
  - How sensitive are the results to questionable data?

Although primarily relevant to probabilistic risk assessment parallels may be drawn for structural fire safety design.

6 CASE STUDIES

6.1 Industrial offshore hall

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6.1.1 General description of the structure

The analysed industrial hall is a part of an offshore structure factory located in Norway on the Nord Sea shore. The hall has the height about 21 m and dimensions in plan about 108x65 m, spanning over 16 axes in a longitudinal direction (numbers 1-16) and 4 axes in a transverse direction (letters A-D), see Figure 6–1. The main load bearing system consists of transverse frames every 7.2 m. The frames are composed of built-up steel columns that support crane girders, floors and roof trusses. The longitudinal stability is provided by the stiff, hollow section bracings in planes of walls and roofs. Figure 6–2 shows the geometry of a frame at 6th axis.

The structure has been previously designed for normal and operational conditions. The structure is designed according to Eurocode. The passive fire protection of main structural members has been proposed based on the calculation of critical temperatures of structural members. Critical temperatures are evaluated according to the simple calculation model given in Eurocode 1993-1-2, so they are obtained separately for each member. The goal of the performance-based analysis is to check the resistance of this structure to the natural fire, which may occur in an operating area of this hall. In this case, the fire is defined as a localised fire of a forklift truck operating in this hall. The fire resistance check utilises the methods proposed and developed in thesis [60].

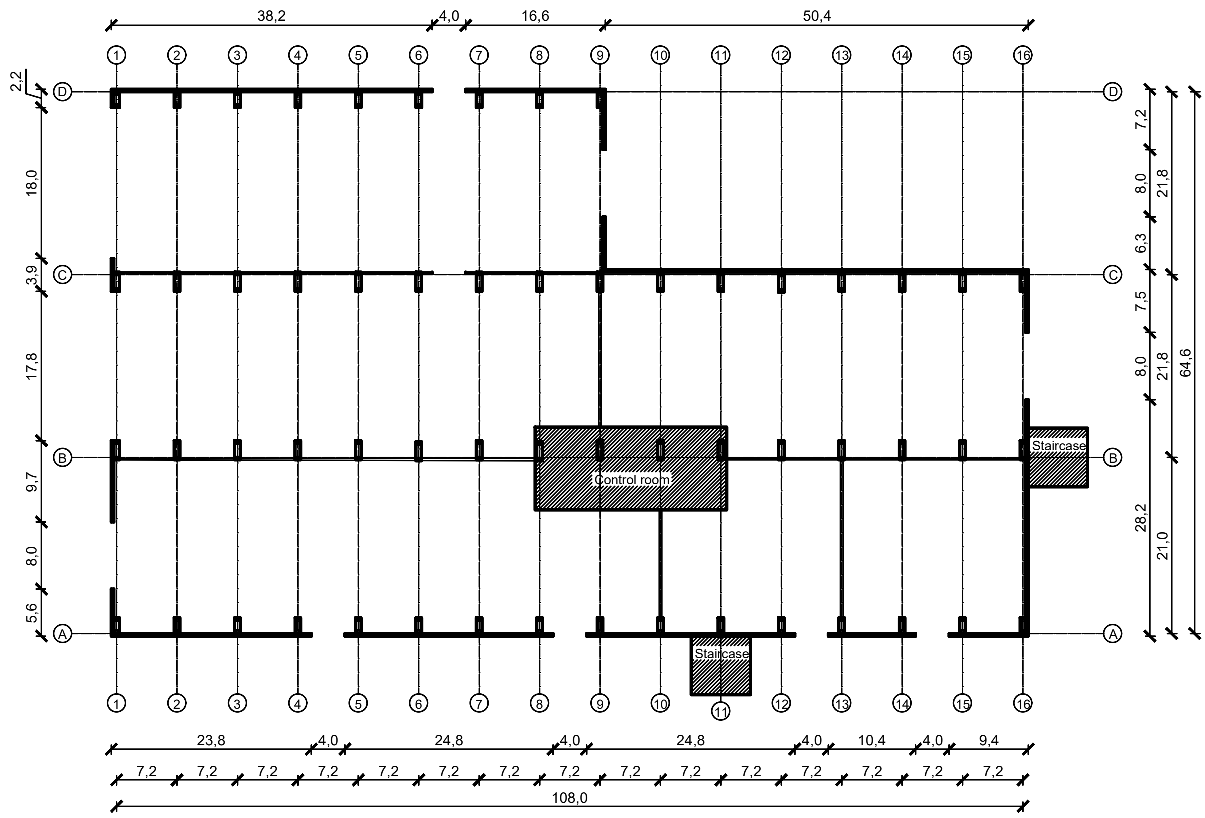


Figure 6–1 Sketch of ground floor plan.

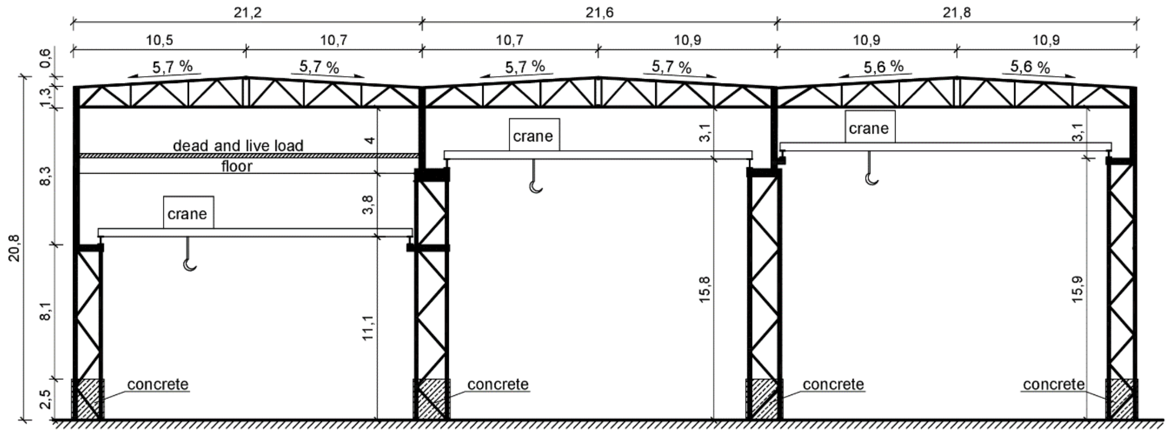


Figure 6–2 Sketch of frame no. 6.

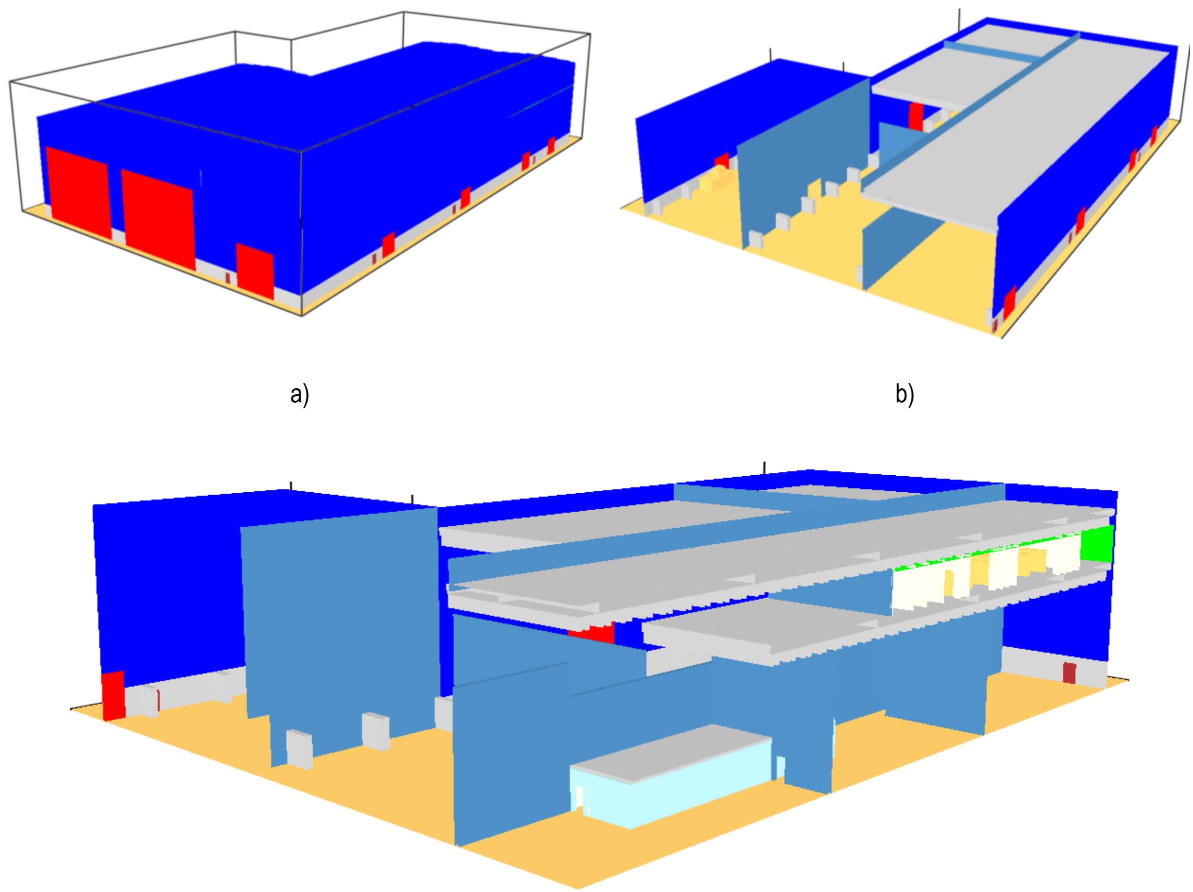
6.1.2 Numerical methods

Three numerical models are constructed: CFD fire model, heat transfer model and mechanical model. First, the fire simulation, based on CFD fire model, is executed. Then, heat transfer analyses are done using the developed heat transfer model. Finally, mechanical analyses of the structure in fire are performed. The theoretical bases for a CFD simulation of a fire and mechanical analysis of a structure in fire are given in [60]. The physical bases of the heat transfer between the fire environment and the structure are introduced in Section 3.6.3.2 of this guide. The heat transfer model is developed and comprehensively explained in [60, 61]. It is developed for an arbitrary cross-section, so no more insight is necessary referring to the given calculation example. Hence, only the related CFD fire model and FEM mechanical model are introduced hereafter.

6.1.3 CFD fire model

The CFD model (Figure 6–3) is created in a Fire Dynamics Simulator (FDS). The geometry of the building is modelled with the highest possible level of accuracy. This means all the compartmentations are included, like walls and ceilings, gates and doors, and massive structural elements. However, the steel structural members are not reproduced inside the CFD model. The numerical model is based on the 20 cm grid of cuboid finite volume elements. The computational domain is about 110,0 m × 65,0 m in plane and 27,0 m height. It is appropriately extended over the building envelope to avoid unphysical flows at the building's openings. The volume of the computational domain is equal to 189 112,3 m^3, and the total number of elements is equal to 23 639 040. Because of the size of the model, the domain is divided into 56 meshes, so the multithreading computations on 56 threads are possible.

On the external boundaries of the domain the ambient boundary conditions are set. So, the free inflow of fresh air and free outflow of fire gases into the atmosphere are established. For all the solid phase sections, appropriate material properties are set. Material properties are temperature dependent, so the heat loss into the solid is suitably incorporated into the model. Hence, four intrinsic material properties are set: conductivity, specific heat, density, and surface emissivity, plus one necessary geometric parameter: thickness of a layer of a material. There are total of 7 solid sections defined that incorporate 6 materials.



a) b)

c)

Figure 6–3 Plot of CFD model: a) external view, b) and c) cross-sections.

Burning of the polyurethane is the chemical reaction used for combustion. While the fire source (forklift truck) consists of several materials, the assumption of polyurethane is chosen for a conservative reason. The stoichiometry of a combustion reaction is based on the chemical compound of polyurethane provided in [62]. The soot yield coefficient is set to 0.05, which means the 5% of the mass of the combusted fuel is transformed into the soot.

Structural steel members are not directly reproduced in the CFD model because of the significant differences between the mesh size of the CFD model and the actual dimensions of these elements. Thus, there is no possibility to specify the actual thermal boundary conditions on structural element surfaces since they do not exist in the CFD model. Therefore, external coupling is used. The coupling approach is based on the heat transfer model developed within [61]. The main output from the CFD analyses is in the form of histories of an adiabatic surface temperature at the particular points of the computational domain. Then, they are used as boundary conditions in a solution of the heat transfer problem. The AST output is set in points corresponding to the middle points of each finite element. Therefore, a total of 59046 output points are selected. At each output point, AST is collected separately from four directions. Each direction corresponds to the normal direction of a receiving surface used in the heat transfer model.

6.1.4 FEM mechanical model

The behaviour of the structure in fire is examined using 3D finite element modelling in Abaqus software. The 3D plot of the model is shown in Figure 6–4, and the exemplary frame is shown in Figure 6–5. All structural elements are modelled as nonlinear beam elements in a 3D space with local stiffness matrices integrated at each step of analysis. This means the global stiffness matrix is updated at each load/time increment, taking into account the non-uniform distribution of material parameters within the cross-section. This approach is necessary when a non-uniform temperature field within the cross-section is taken into account. Hence, the temperature influences the yield strength, the Young's modulus, as well as the thermal elongation of material.

Abaqus provides several types of beam finite elements. The one used here is the element called B31. It is a 3D Timoshenko beam finite element, with two nodes, formulated to take into account both large axial strains as well as large rotations. The exception is the nominal torsional strain, where the quadratic terms are neglected (compared to unity), and the torsional shear strain is calculated with the assumption of small axial strain. The length of finite elements is kept at about 20 cm, which corresponds to the size of the CFD model grid. The displacements field on the finite element is approximated using linear shape functions.

In the Abaqus model, the sectional stiffness of the beam finite element is integrated using the Simpson method in 13 and 16 section integration points, respectively for I-sections and BOX-sections. The temperature at each section integration point is interpolated based on the temperature values provided at given temperature points.

Mechanical analysis of the structure in fire takes into account both geometrical and material nonlinearities. Boundary conditions are specified in terms of fixed displacements at the base of columns, external nodal forces resulting from load combination, and the history of the temperature field at each node of the model. The temperature history is provided by an external user-defined Fortran subroutine. This subroutine reads and processes the output from the heat transfer model implemented in the Matlab environment. The coupling procedure between CFD and FEM analyses is the core of the performance-based framework developed in [60, 61].

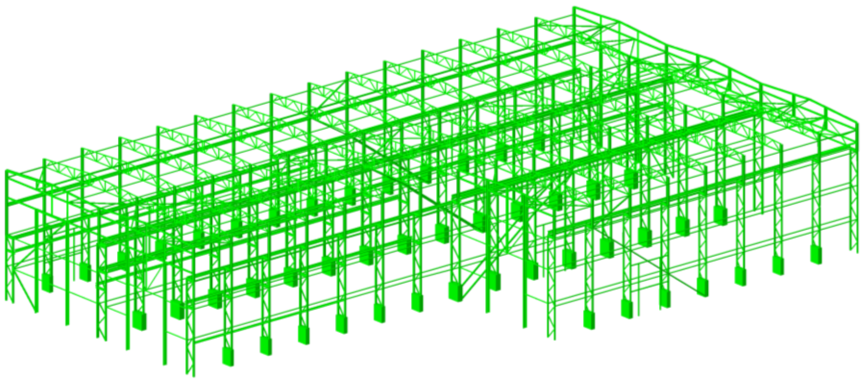


Figure 6–4 Plot of a 3D Abaqus model of the structure (beams' cross-section rendered).

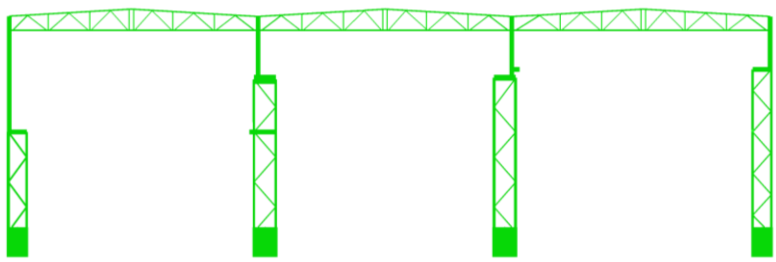


Figure 6–5 Plot of an exemplary frame from a 3D Abaqus model of the structure (beams' cross-section rendered).

6.1.5 Fire scenario determination

The performance of the structure is checked for the fire scenario determined using the method developed in Chapter 4 of the thesis [60]. The placement of the localised fire is justified according to that method. The fire is placed in the vicinity of a structural element, where failure results in the most severe overall damage of the structure. The type of the fire source (forklift truck fire) determines the choice of the method's variables.

6.1.6 Results

The environmental conditions in fire are represented here by the distribution of gas temperature. Figure 6–6 shows exemplary gas temperature distribution in the compartment. Whereas for many fire protection applications equally important to gas temperature are such indicators like smoke distribution or hazardous gases distribution, the structural response depends on the convective and radiative heat fluxes that reach the solid surfaces. However, structural steel members are not included inside the CFD model, since they are too small compared to the CFD grid. Therefore, the choice of gas temperature maps is assumed meaningful to represent environmental conditions of the structure in fire. The gas temperature fundamentally controls the convective heat flux and is partly the source of radiation coming into the solid surfaces (hot gases radiates to colder solid surfaces). The only lacking component here is the radiation from the fire source, which spreads over the whole fire compartment. Note that the adiabatic surface temperature, which is also a scalar quantity, takes into account both the convection and radiation influences. However, it is dependent not only on the spatial coordinates, but also the measurement direction. So, being a great quantity to represent the thermal boundary conditions at solid surfaces, adiabatic surface temperature is impossible to be visualised by the same reason as heat flux at fire-solid interface (structural steel members do not exist in a CFD model).

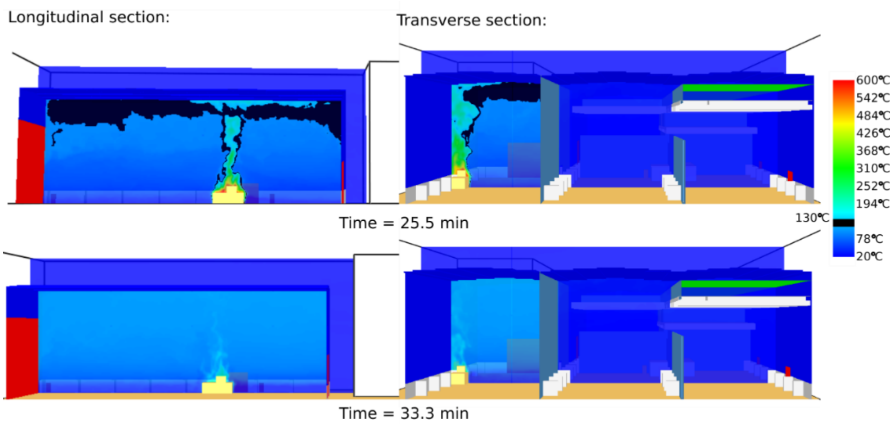


Figure 6–6 Gas temperature distributions in longitudinal and transverse cross-sections.

Table 6–1 and Figure 6–7 show the members selected for analysis, together with and cross-section details. Figure 6–8 and Figure 6–9 show temperature distributions inside hollow steel sections and I -sections. Figure 6–10 and Figure 6–12 show global view of the structure with mean section temperatures, and displacements measured between selected points, shown in Figure 6–11.

Table 6–1 Types of cross-sections used in the presentation of heat transfer results.

CS1	CS2	CS3	CS4	CS5
RHS 200×200×8	RHS 150×100×4	RHS 200×200×8	WI400-10-20×320	WI400-8-20×300
CS6	CS7	CS8	CS9	CS10
RHS 100×60×4	RHS 180×60×4	RHS 120×120×6	HEA 450	HEA 450

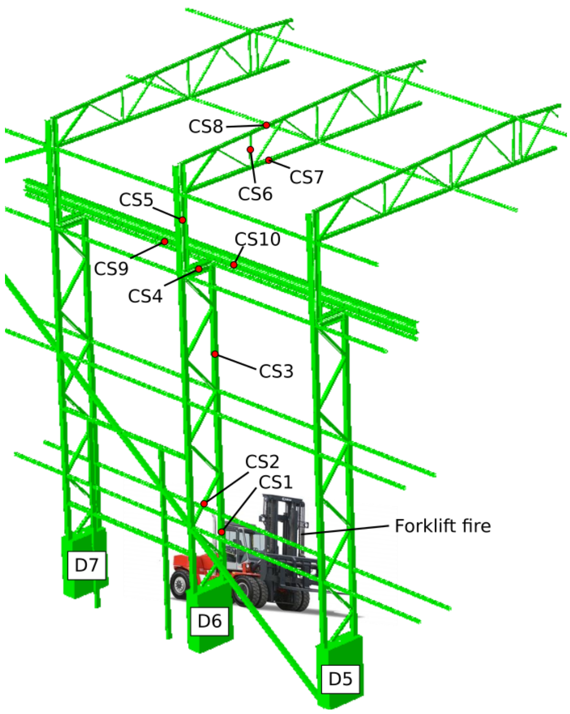


Figure 6–7 Members selected for the verification of a performance.

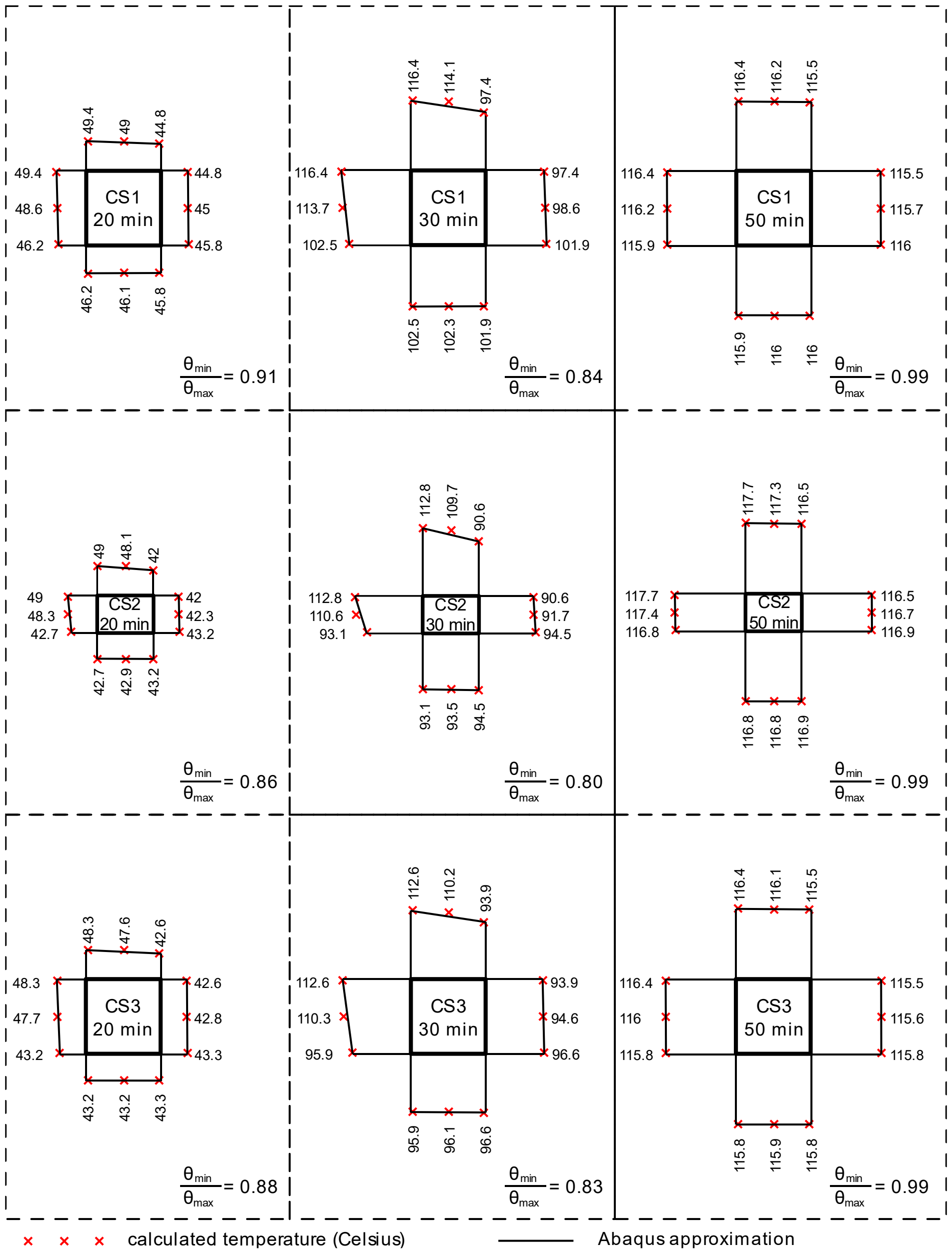


Figure 6–8 Temperature profiles at selected BOX-sections in a design fire and Abaqus approximation.

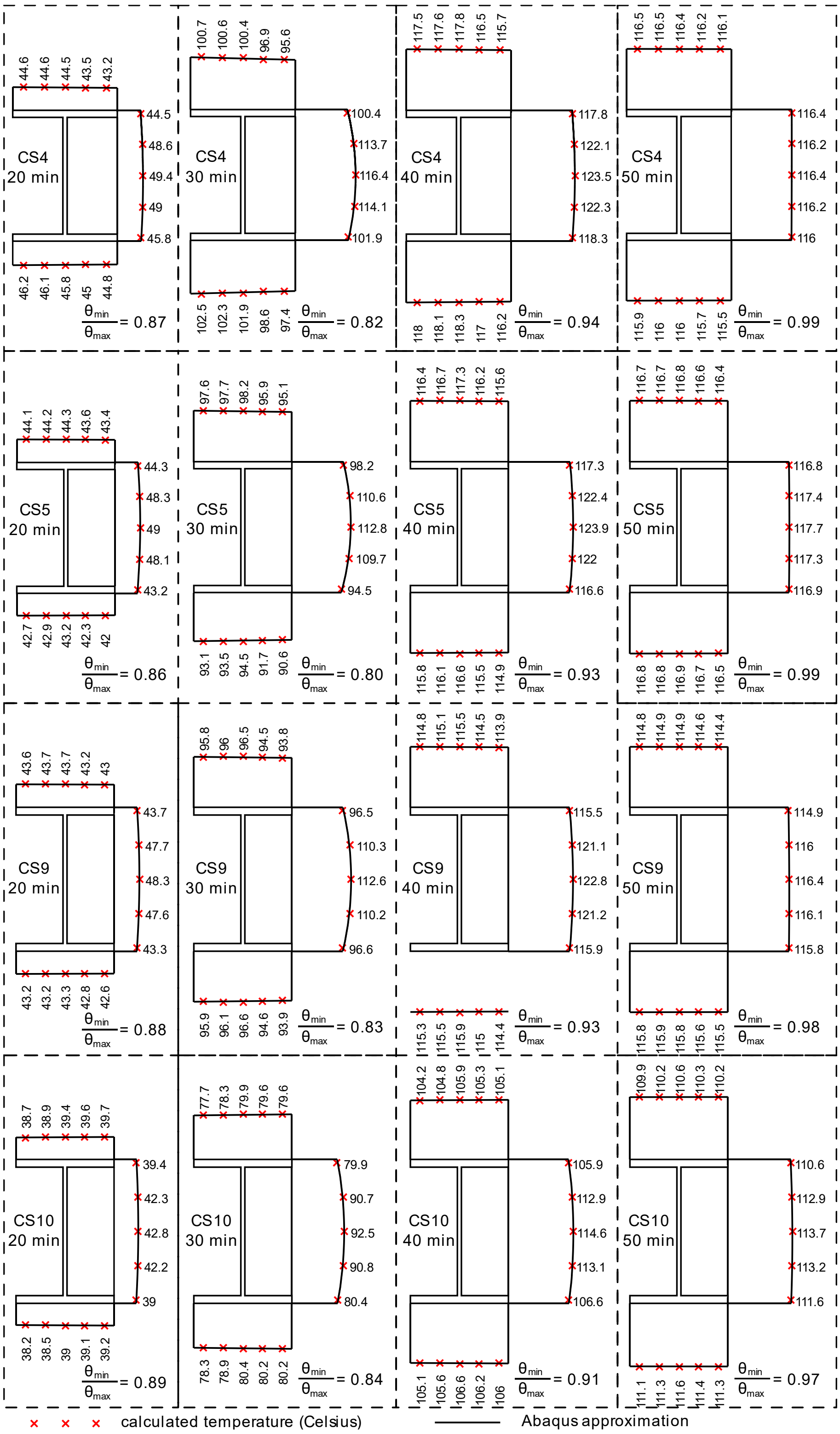


Figure 6–9 Temperature profiles at selected I-sections in a design fire and Abaqus approximation.

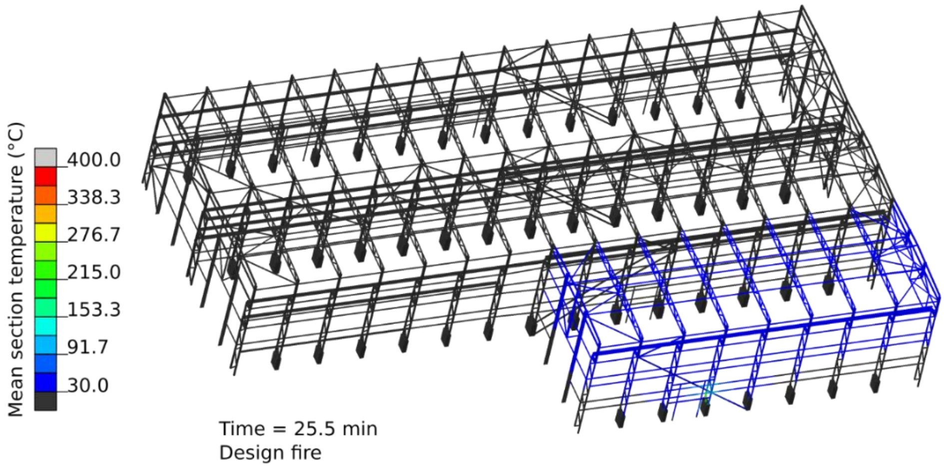


Figure 6–10 Mean section temperatures for the structure exposed to design fire at time 25.5 min.

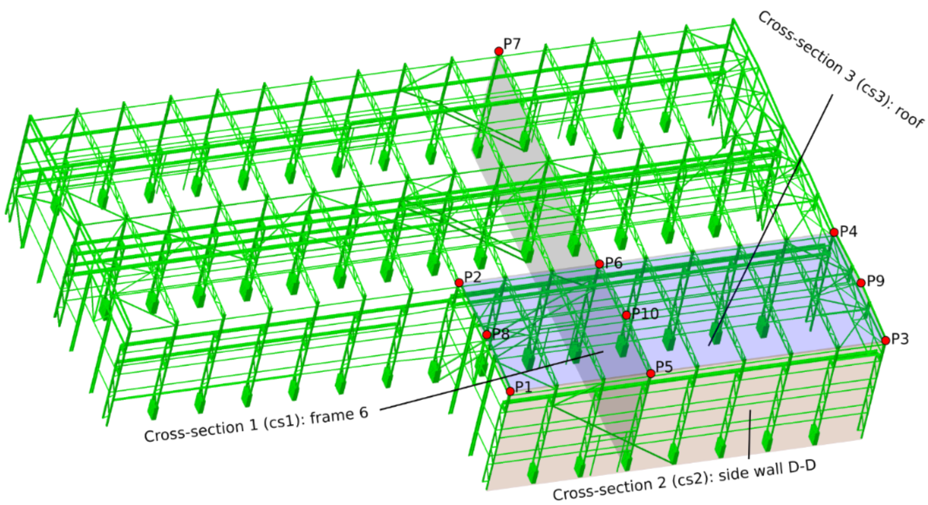


Figure 6–11 View of the structural model with displacement measurement points and cross-section being analysed.

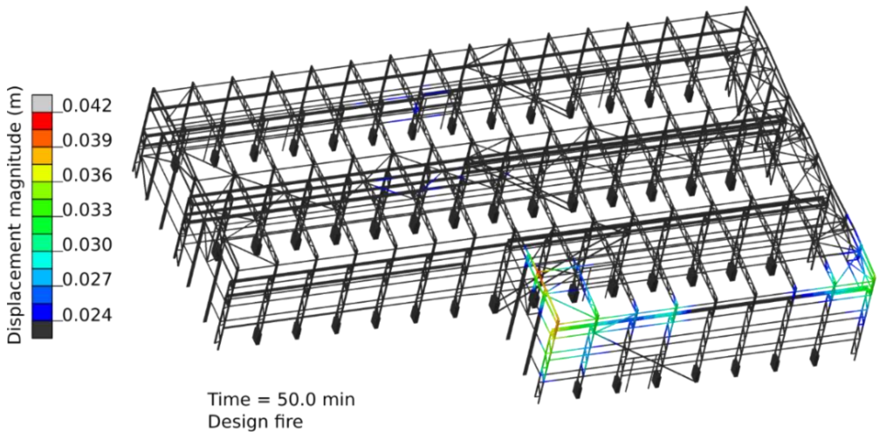


Figure 6–12 Displacement development at time 50 min for structure exposed to design fire.

The maximum transverse and longitudinal deformations are observed around 60 min of fire (Figure 6–13), whereas the maximum vertical displacement (at point P5) is visible after about 40 min of fire (Figure 6–13). This corresponds to the time at which maximum values of temperature are observed respectively in roof trusses and the column D6. However, the vertical displacements at points placed far from the fire source (P1, P3, P9, P8) are also delayed to 50 min (globally highest temperature distribution). Moreover, P10 vertical displacement in the amplified fire case rises more rapidly than it does for the design fire. This is due to the direct exposure of the roof truss above the fire to the flames. It confirms that the history of deformation is driven by the thermal expansion resulted from the localised fire, which has the most tremendous effect on the neighbouring structure.

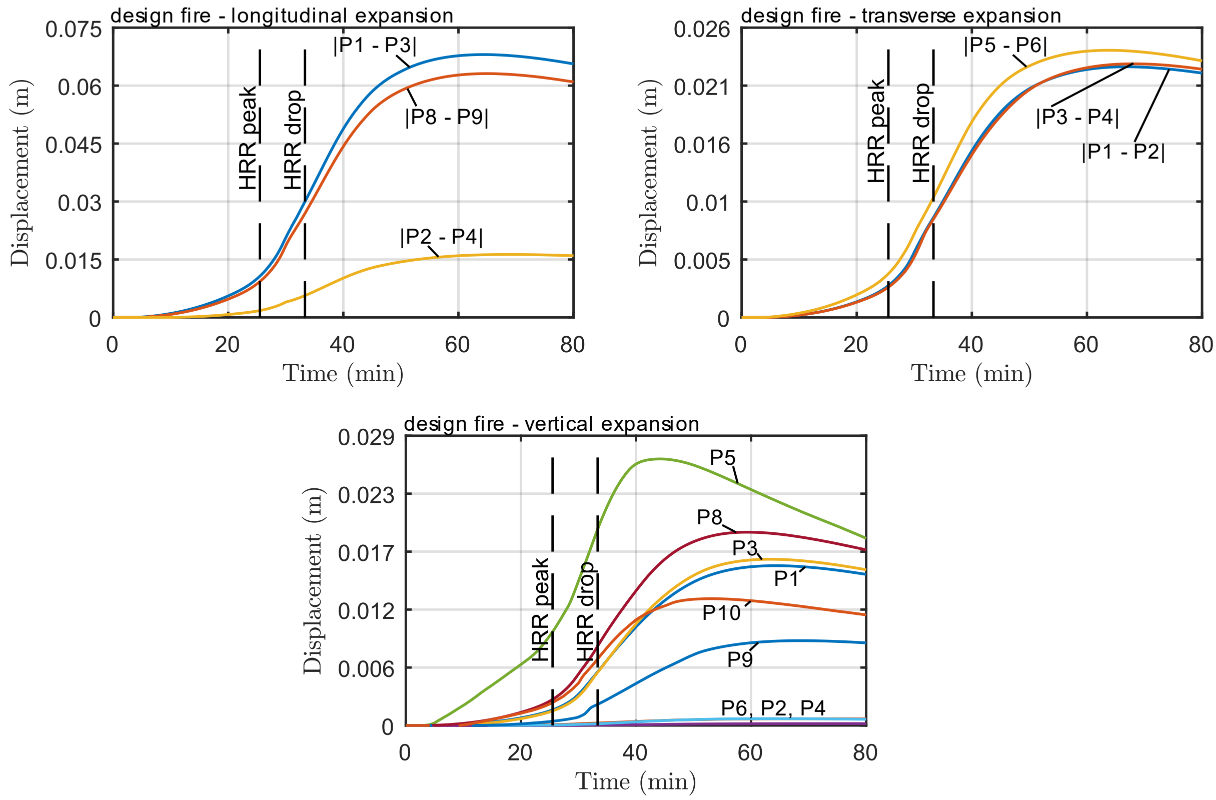


Figure 6–13 Longitudinal, transverse, and vertical expansion measured between selected points (see Figure 6–11).

Two types of environmental influences on the structure in localised fire are observed. The first is the local radiation from a convection column. The second is the heat flux from the hot gases reservoir below the roof. Hence, the heating, at the highest rate, of parts of the structure far from the fire source is delayed by about 10 minutes with respect to the heating of the structure close to fire. The time at which the structure is the most heated globally does not correspond to the time when the local temperature is the highest. Nevertheless, the maximum observed temperature in the structure is noticed locally in the structural members located in the vicinity of the fire.

Nevertheless, there is no overall structural collapse observed. The structure occurred to be robust enough to withstand the fire, even if the fire is amplified 5 times with respect to the design fire (the temperature of structural members oscillates at about 500–600°C, with the local values of mean section's temperature reaching almost 800°C). The part of the structure not affected by fire is a sufficient restraint for the part of the structure directly exposed to fire. On the other hand, the influence of the fire-affected part on the unaffected part of the structure is limited.

However, the effects of fire are irreversible. The relative displacements at the end of the fire do not go back to zero. In the design fire case, the longitudinal expansion after 80 min is about 6,0 cm, the transverse expansion is about 2,0 cm, whereas the vertical displacement is from 1,0 cm to 1,8 cm. However, the structure was not analysed up to the complete cool down. On the other hand, in a case of the amplified fire, the extensive plastic deformation is observed, so eventually the structure is unable to maintain its function after fire. The expansion at the end of the fire is respectively: about 33,0 cm in the longitudinal direction, 12,0 cm in the transverse direction, and from 5,0 cm to 9,0 cm in the vertical direction.

Locally, the effects of fire on the structure are more complex. The distribution of fire induced forces is implicitly observed. It is demonstrated by the pulling up of colder D5, D7 columns by a hotter D6 column during heating and the pulling down of column D6 when its plastic capacity is reached. Then, developed thermal strains are directly transformed into plastic strains. Similar effects are observed at the level of nonuniformly heated restrained cross-sections. There, hotter fibres take over the load bearing up to the yielding point. The load is then redistributed to other fibres of this cross-section which are colder and not fully utilized yet.

6.2 Refurbishment and converting the old industrial Eiffel-hall into Workshop and Rehearsal Centrum for the Opera

Horváth László István, Takács Lajos; *Budapest University of Technology, Hungary*

The Eiffel-hall – which was functioned as a workshop for locomotives for the Hungarian Royal State Railways – was built between 1883 and 1886 in Budapest, presumably designed by János FEKETEHÁZY, not by the Eiffel Office as it was generally thought. A few years ago the hall closed and became empty, later the change of the function of the hall was requested, finally the workshop and rehearsal centrum of the Hungarian State Opera have been placed in the building. The building has been fully renewed and transformed. The old lightweight load-bearing steel structure of the hall had to fulfil the requirements according to the present National Fire Safety Code (NFSC) and the design codes (Eurocode) containing the fire requirements. The paper introduces the structure and the advanced fire design steps including fire and structural simulations. The general and architectural design has been carried out by the KÖZTI Architects & Engineering Zrt. Different BME Departments were also involved into the structural and fire safety design [63].

6.2.1 Introduction

The Eiffel Hall (Figure 6–14 and Figure 6–15) is the largest industrial hall in Hungary which is registered and protected monument. The 214 m long, 96 m wide, brick side-walled hall building is divided into five longitudinal bays. The central part of the basically arranged cross-section is the saddle roofs covered 3 main bay, to which on two sides lower side-bays are connected with a half-saddle roof. The main girder is a light lattice steel structure, the distance between the main girders is 10 and 12 m. The height is 12,4–16,4 m.

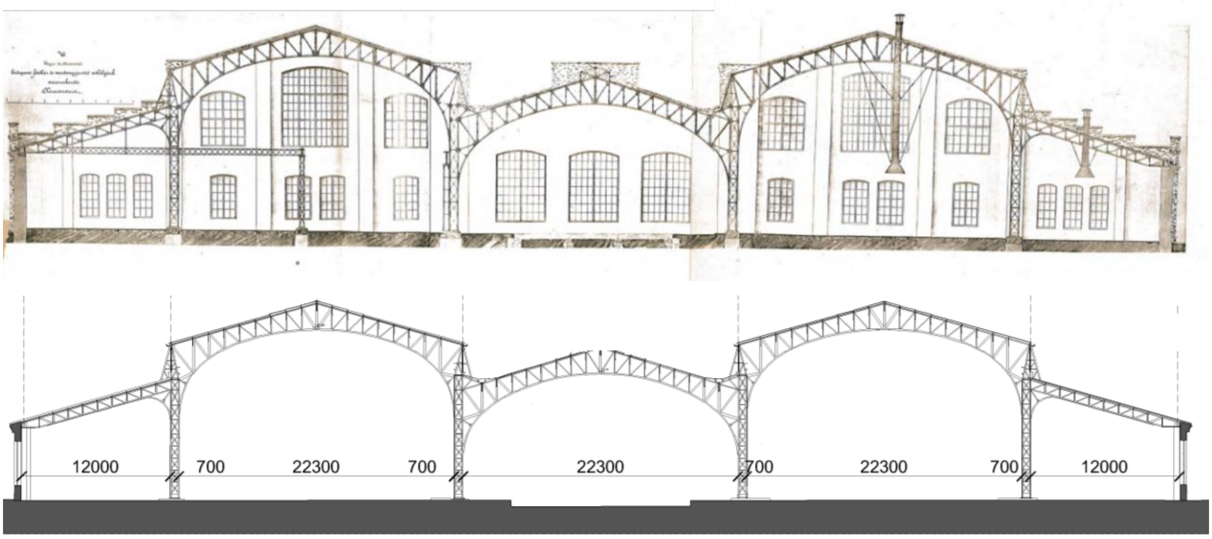


Figure 6–14 The original cross-section drawing of the hall **[64]**, and the main steel structure..

The public spaces, the lobby, the small theatre, the home stage, the rehearsal room and service rooms of the orchestra, and the railway history showroom have been established in the SW part. In the north-eastern tract of the hall are located the different workshops: painting and set-up operations, carpenter sewing rooms etc. Here are the storage places for the scenery. The inner garden on the 2nd floor and the gymnasium are important places for the employees.

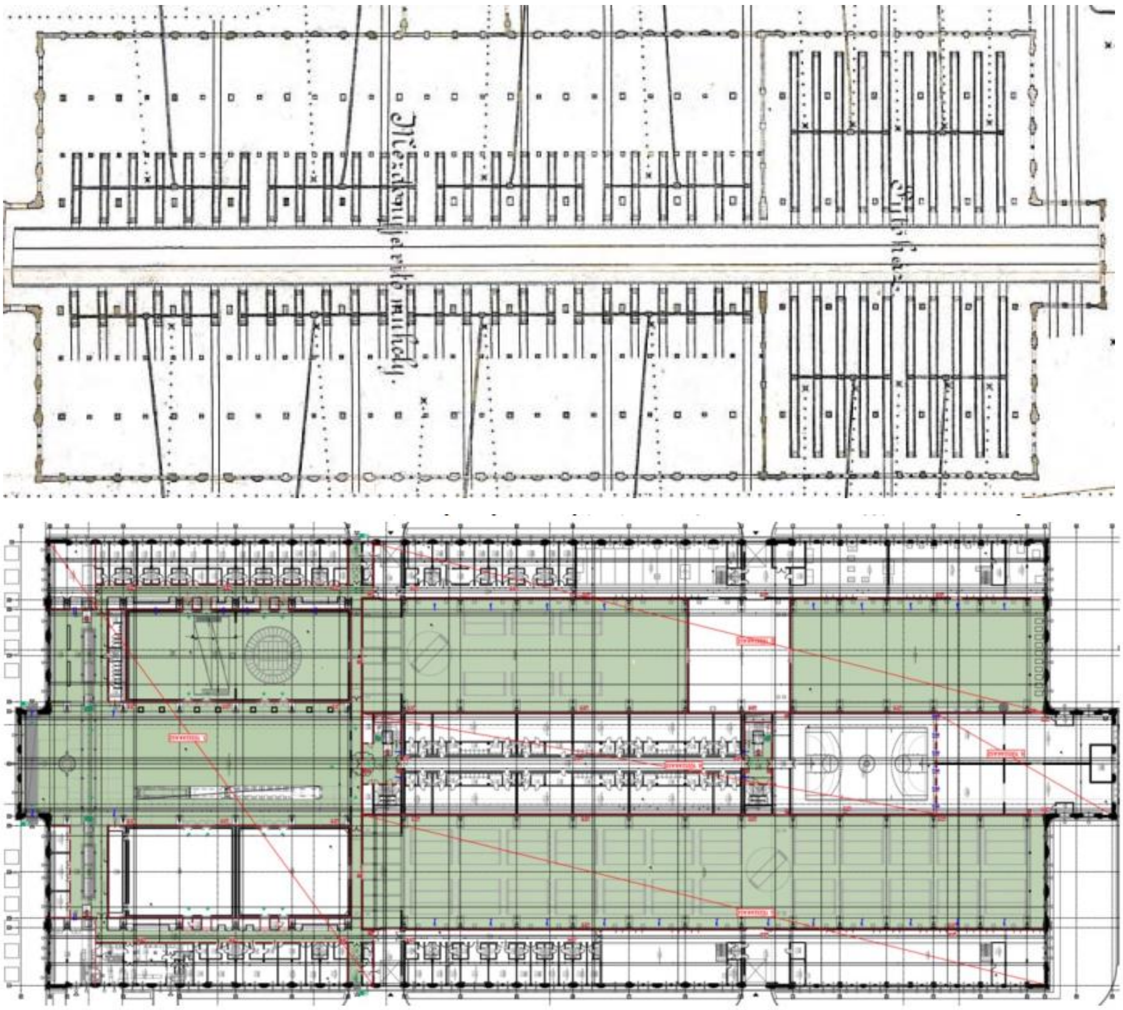


Figure 6–15 The original floor plan drawing of the hall **[64]**, and the new layout.

6.2.2 The load-bearing steel structure of the Eiffel-hall

The steel structure of the hall is an extremely slender, riveted lattice steel structure according to the practice of contemporary steel construction (Figure 6–16).

Figure 6–16 The steel structure and typical profiles of the main girder.

The steel structure of the two-side bay supported on the side walls, sliding on steel plates. The purlins are simple lattice structures, their chords and columns are made of hot rolled angle steel, and the diagonals are made of flat steel. The chords and columns of the main girders are made of 2 or 4 angle sections, where necessary extended by riveted flat profiles.

Complex statical examination has been performed including the measuring of the structural dimensions, checking the material properties, detailed inspection of the current structural condition (deterioration, corrosion…). Based on this data the structure has been checked taking into account loads and requirements of the relevant Eurocodes. The results of the fire design were also necessary for the design of the necessary strengthening. The main idea was, that the original structural behaviour should be kept as far as it is possible.

6.2.3 Fire safety design

There are basically two different ways of fire safety design: prescriptive method or engineering methods. At prescriptive method, simple tabular or empirical requirements are used from legislative provisions and in Hungary, there are fire safety guidelines consisting the acceptable best practices compliant with the ongoing regulation which can be easily used at simple and traditional buildings. Prescriptive methods can hardly be used at complicated, large scale buildings or at heritage buildings where existing structures often cannot fulfil the ongoing fire safety requirements. In contrast to the prescriptive methods, at engineering methods more complicated calculations, simulations are used requiring more engineering knowledge and work, special software and especially at numerical fire simulations, extensive hardware too. At the Opera Workshop Centre, fire safety requirements were determined with prescriptive methods but the smoke and heat ventilation was designed using fire simulation using FDS and PyroSim software from the beginning, and the evacuation was designed using Pathfinder software at the late stage of the design.

At the numerical fire simulations, the three-dimensional model of the building – its structures, fixtures, and interior spaces enclosed by structures – is divided into finite elements that form a network of cells or meshes. In the building model, besides the definition of flammable materials and building structures, fire scenarios can be determined at different locations as well. The operation of the models is characterised by the numerical solution of gas flow, heat, and mass transfer equations prescribed for cells. These can be used not only to determine, but also to visualise the behaviour of the building and its fire safety equipment in the case of a fire. Cell models are suitable not only for the fire safety design of buildings, but also the evaluation regarding the cooperation of the active fire safety systems (fire detection and alarm systems, smoke and heat ventilation system, built-in fire extinguishing system), and last but not least also for the precise determination of the temperature-to-time curves during fire on the load-bearing structures.

Main fire safety characteristics of the Opera Workshop Centre are the following:

- Design risk classification of the building is MR (Middle Risk) according to the risk classification of the National Fire Safety Code.
- Total floor area of the building is 26.697,0 m^2 consisting of five fire compartments.
- Fire safety requirements of the primary loadbearing structures are A2, R60 (REI 60) except the separating structure of the roof where the requirements are A2, REI 30.
- The building is equipped with built-in fire detection and alarm system and built-in fire extinguishing system (traditional sprinkler using wet sprinkler heads).
- Rooms with a floor area of over 1,200 m^2 are equipped with smoke and heat ventilation systems, where the extraction is ensured by a natural exhaust system, i.e. smoke exhaust duct lines built in the roof, and the air supply is ensured partly in a natural way, but mostly mechanically due to the protected status of the facade.

The numerical fire simulation was necessary for the following reasons:

- to demonstrate that visibility, temperature, and radiation in the tested areas accessed by large numbers of people are adequate for safe evacuation within the necessary evacuation time of three minutes; the evacuation time permitted by the NFSC would be 1.5 minutes without fire modelling (Figure 6–17 and Figure 6–18;
- to examine the efficiency of the heat and smoke ventilation in the warehouse and the roof garden with the designed natural smoke and heat ventilation and mechanical air supply system, without smoke barriers (Figure 6–19 and Figure 6–20);
- to determine the gas temperature exposure of the load-bearing structure and envelope components of the roof structure, particularly taking into account the changes in relation to the ignition temperature of the flammable thermal insulation materials of the roof sandwich panels;
- and to investigate that the cooperation of certain active fire protection equipments – especially the sprinkler system and smoke and heat ventilation system – do not undermine the efficiency of individual systems.

In the test period, requirements set out in the Hungarian Fire Protection Technical Guideline Fire Smokespread and Evacuation Modelling, as well as evacuation are as follows:

Within the evacuation time limit:

- Within the evacuation time limit, sight distance shall not fall below 15 m along the whole route of escape (for such 15-metre test, testing the toxic gases may be dispensed with).
- During escape, persons shall not be exposed to a temperature higher than 60 °C.
- During escape, persons shall not be exposed to density of radiation heat flux higher than 2,5 KW·m^{-2}.
- To test the evacuation time, a visible route length and temperature test plane has been taken at a height of Z = 2 m for each fire scenarios or Z = 3 m for the benefit of safety due to the features of some cell mesh. For the sake of clear interpretability, the scale belonging to the given test are repeated in all figures and the test condition is made black (see the figure below). In case of the evacuation time, the 15 m sight distance is made black. The date of test has been also indicated on the figures. To test radiation, point radiation detectors of cca 10 m × 10 m spacing have been placed near to each fire source on a plane at a height of Z = 2 m (Z = 3 m). Time distribution of the radiation near to the fire location is represented.

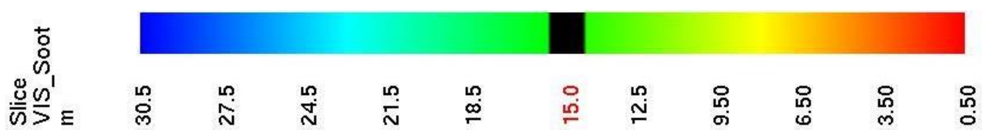


Figure 6–17 Visibility scale at the evacuation period. Blue colour means a better visibility, while red does the worse from 0 to 30 m.

Within the fire-fighting intervention time:

- At a distance of more than 25 meters from the location of the fire source, visibility shall not be less than 5 meters at the time when the firefighter commences the intervention.

- This criterion shall be met in such a way that the fire source is reachable by fire-fighting units of sufficient number and equipment (this is not included in the TvMI on Computer simulation of the spread of smoke and fire and escape).
- For testing the existence of intervention conditions, a visible route length test plane was defined for each fire source at a height of Z = 2 m. For the sake of clarity, the relevant scale for the test is repeated in each figure, and the test condition is highlighted (see the figure below). For testing the existence of intervention conditions, the visibility of 5 m is highlighted. The figures also indicate the time of the test.

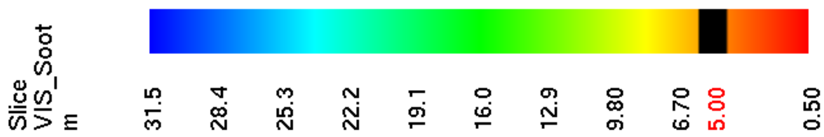


Figure 6–18 Visibility scale at the fire-fighting intervention period. Blue colour means a better visibility, while red does the worse from 0 to 30 m.

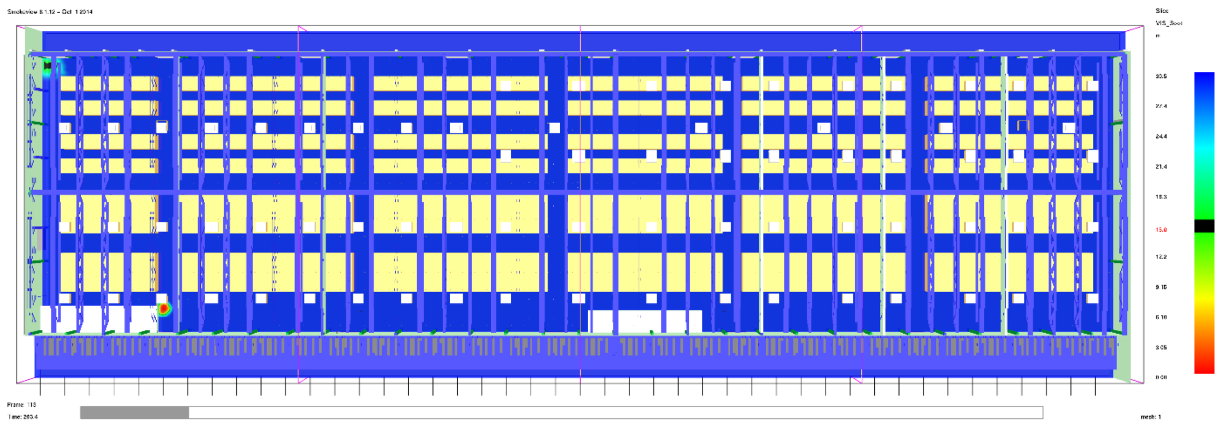


Figure 6–19 Length of visible route on a 2 m high plane at the end of a detection time and evacuation time limit in the large set scene storage of the Opera Workshop Centre. The black line indicates the boundary of visibility of less than 15 m.

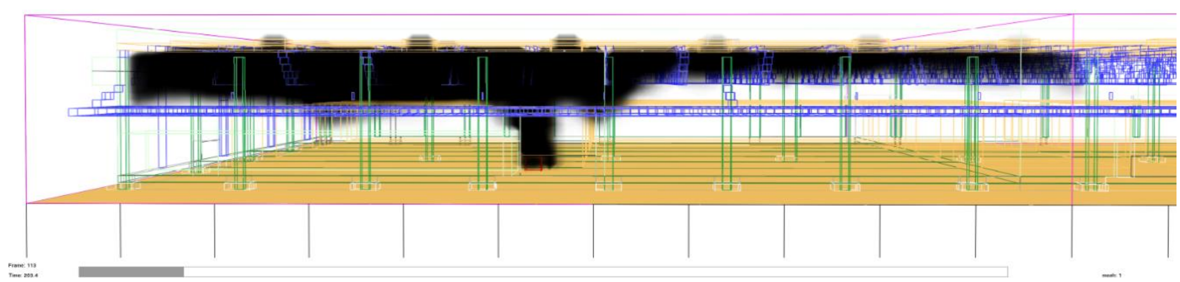


Figure 6–20 Smoke spread at the end of a fire detection alarm time and evacuation time.

Fire fighting intervention period must be calculated based on the followings:

1. Fire detection and transmission time;
2. Time to exit from the fire station;

3. Run time (see Figure 6–21);
   - in built-up area at an average speed of 30 km/hour
   - outside a built-up area at an average speed of 60 km/hour
   - in industrial zone at an average speed of 30 km/hour
4. time of detection and hose assembly time.

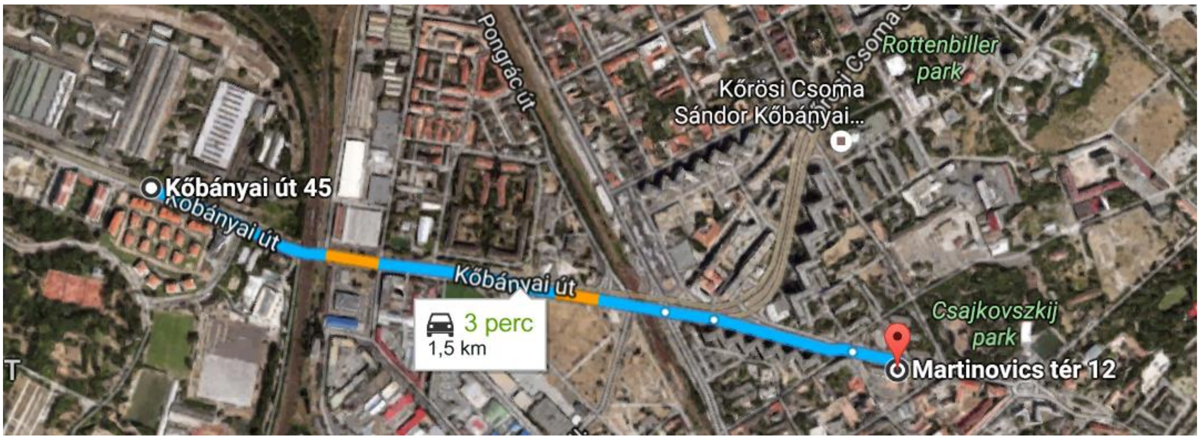


Figure 6–21 Run of fire-fighting brigades from the closest fire station to the Opera Workshop Centre.

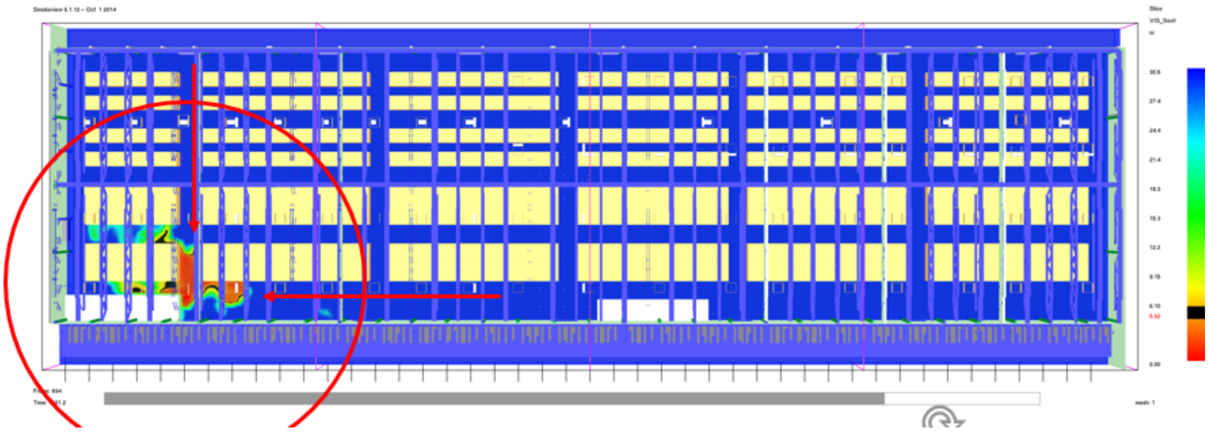


Figure 6–22 The length of visible route on a 2 m high plane at the beginning of the fire fighting intervention in the large set scene storage of the Opera Workshop Centre. The red circle connotes a 25 m radius. The red arrows indicate the possible directions of intervention.

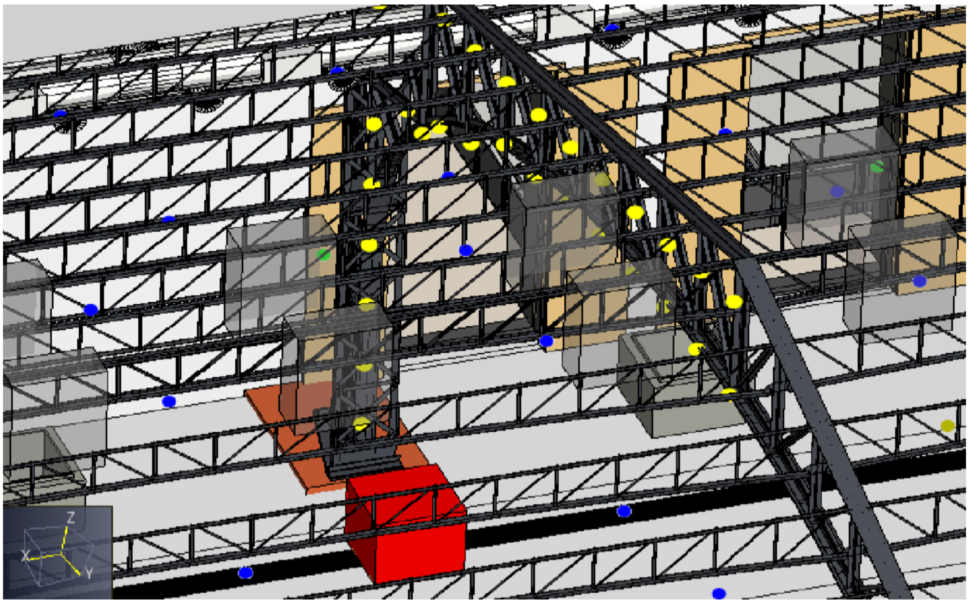


Figure 6–23 Temperature measuring devices around the structure over a fire scenario.

6.2.4 Checking of the steel structure against fire load

The fire effect on the steel load-bearing structure was based on the report [65]. Numerous fire scenarios were run, tested and evaluated to determine the most dangerous situations from structural point of view. Load-bearing calculation was performed on each of them, and we determined the locations where strengthening is needed, the locations and structural members where fire protection, as well as the critical temperature of the steel structure.

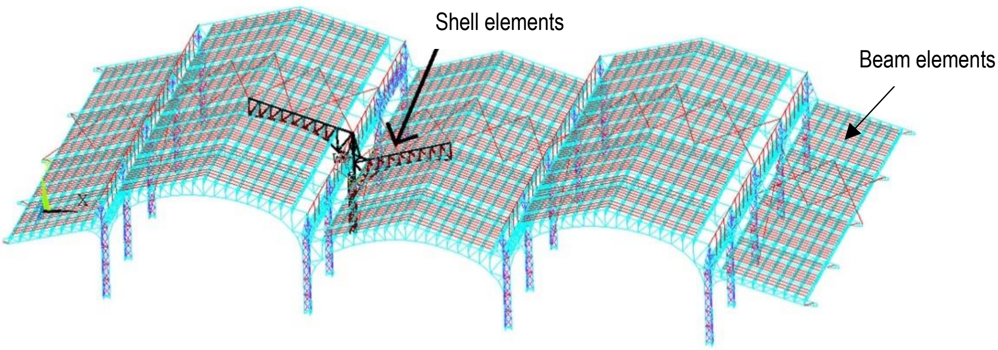


Figure 6–24 The combined shell-beam model in ANSYS.

For the structural analysis we developed a mixed bar-shell structural model in ANSYS 14.5 general finite element software, which can be seen in Figure 6–24. Given the dimensions of the building and the number of bars in the structure, we constructed partial model including five main frame from the entire structure, complete with lattice elements and longitudinal stiffening beams located between them. A numerical simulation-based method involving geometric imperfections and material nonlinearity (GMN and GMNI) was used in the calculations. We simulated the behaviour of the structure under fire load, refined the necessary strengthening, and finally verified the structural performance.

For each fire scenario, the size of the heat-affected zone and the temperature values within it were applied based on the results of the numerical fire simulation. The temperature values given in the temperature diagrams were divided into zones and the temperature of each zone was used. The mechanical properties of the steel structure were modified within the zones according to the specified temperature values (modulus of elasticity, yield strength).

The hall consists of extremely filigree elements that heat up quickly. In case of fire, the stresses are also strongly rearranged, some of the previously tensioned elements become pressed. According to our calculations, here the temperature of the steel structure exceeds 350°C, the stability of the structure cannot be verified. Therefore, it is necessary to apply a fire protection coating there, which does not allow the steel structure to heat up to more than 350°C. It shows, that the simple application of the minimum critical steel temperature from Eurocode 1993-1-2 [66] as 400°C can be inadequate solution. A critical part of the structure proved to be the upper part of the column-beam connection between the lower middle ship and the higher ships. Here it was also necessary to strengthen the steel structure.

Detailed calculations were performed for the critical fire scenarios. As an example, we present the fire scenario in the Scenery Depot studies. The temperature – time curves in different heights is illustrated in Figure 6–25.

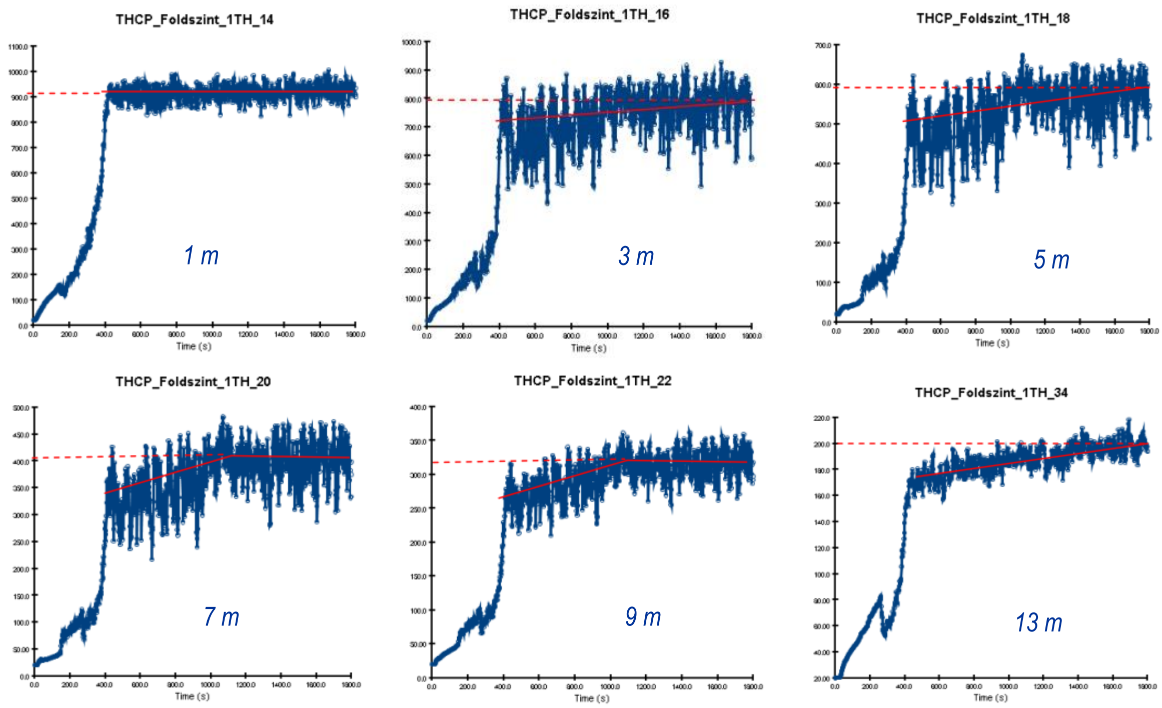


Figure 6–25 The temperature distribution over the example fire scenario in different heights.

Due to the cooling effect of the sprinkler system, which control the heat release rate of the fires, the temperature exposure of the structural members is generally lower than the usual ISO 834 cellulose temperature-to-time curve. The support structure rises above the fire source due to thermal expansion, about to “bulge out” (Figure 6–26). The fire source is close to the lower part of the column, therefore a fire protection intumescent coating is required up to 9 m in addition to reinforcing the lower part of the column. No protective coating is required on the column sections, beams and slabs above this.

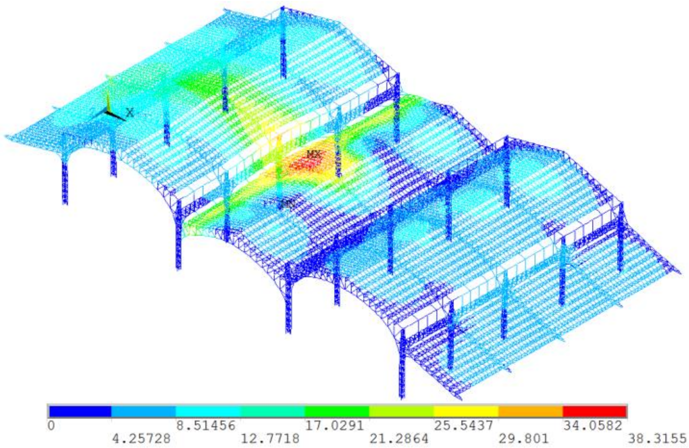


Figure 6–26 The deformation of the steel structure of the example fire scenario.

6.2.5 Summary

The refurbishment and converting the old industrial Eiffel-hall into Workshop and Rehearsal Centrum for the Opera was a real challenge. Contrary to the unfavourable passive fire safety features of the Eiffel Hall, with using advanced fire safety design methods, active fire safety systems such as sprinklers, smoke and heat ventilation and using fire simulations it was possible to perform the fire design with minimal necessary strengthening and fire protection. In addition to the minimized area of the intumescent painting, it has been stated that for the roof sandwich panels in some places not only mineral wool core material can be applied. This application shows the advantages and benefits of the application of the advanced methods of the performance-based fire safety design.

6.3 Car park

Lucia Figuli, Paulína Magdolenová; *University of Žilina, Slovakia*

6.3.1 Description

The advanced numerical fire model in the carpark building using the Computational Fluid Dynamics (CFD) method was created. Overall, three scenarios are created as open, semi-open and closed carpark in order to testify the simulation ability to incorporate different boundary conditions. Models are created in software Fire Dynamics Simulator (FDS) to obtain structural element temperatures during fire. Obtained data are compared to structural temperatures evaluated by simplified normalized approach [66] using the standard fire curve. The simulation results represent the input data for a follow-up advanced structural model (generally a Finite Element Method model) to determine the element fire resistance time. The created scenarios are modelled according to software user guide [16] rules and instructions.

The modelled geometry conforms with the dimensions of a five-store carpark building that was designed with 256 parking lots, 64 for each storey, according to all national requirements. The floor area of one storey is 56 m × 33 m, see Fig. 1, and the ceiling height is 3 m. According to STN 92 0201-2, the fire resistance of loadbearing elements of this building should be minimum 30 minutes (R30).

The parking house is designed as a 5-storey non-basement building in the area of the city of Žilina with floor plan dimensions of 33,0 m × 56,0 m with a construction height of 3,0 m. The load-bearing structure of the building is designed as a composite reinforced concrete slab with beams (ribs) of rolled steel H-profiles. The columns are designed steel from rolled H-profiles. Parking space is designed on the 1st - 5th floor, the roof is considered impassable and without the possibility of parking. The use of the building is designed exclusively for parking cars, provided that the building is connected to the adjacent building for users of the building on each floor. Ramps enabling car access to individual floors are considered as statically independent structures and their static analysis is not part of the dissertation. There are two external travel ramps – for driving upwards and for driving downwards (Figure 6–27).

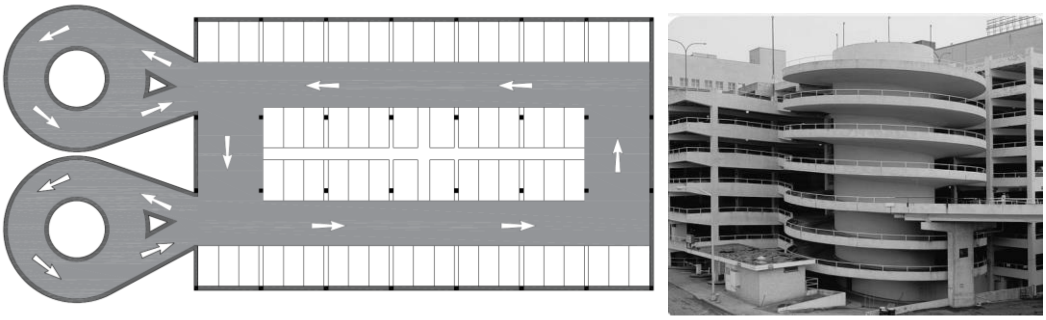


Figure 6–27 The floorplan and a photo of a similar existing carpark.

On one floor there were 67 parking spaces for the group of cars designed, see Figure 6–28. All stands are designed with perpendicular shifting (angle of the stand to the lane is 90 °), standard dimensions 2,50 m × 5,0 m. Of the total number of spaces, four are reserved on the floor for persons with reduced mobility and orientation, thus meeting the condition of the standards for a minimum number reserved for the total number of spaces. The dedicated spaces are positioned so that each has a handling space at least 1,4 m wide (Figure 6–28).

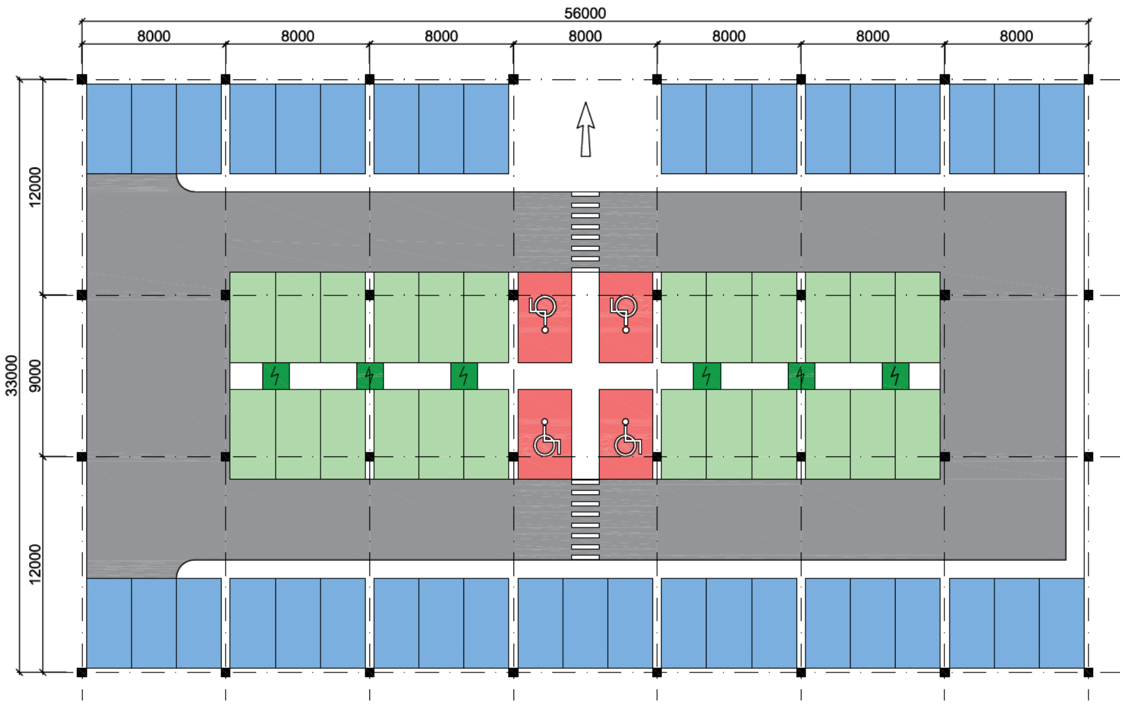


Figure 6–28 Floorplan of the modelled part of the carpark.

6.3.2 Fire modelling

The created fire scenarios are modelled in order to obtain the surface temperatures of chosen unprotected steel beam. The chosen element is 12 m long and is designed as a HEB500 cross-section of a S355 steel grade according to national Eurocode design requirements for standard room temperature 20°C. The position of the chosen beam is shown in Figure 6–29 with red colour.

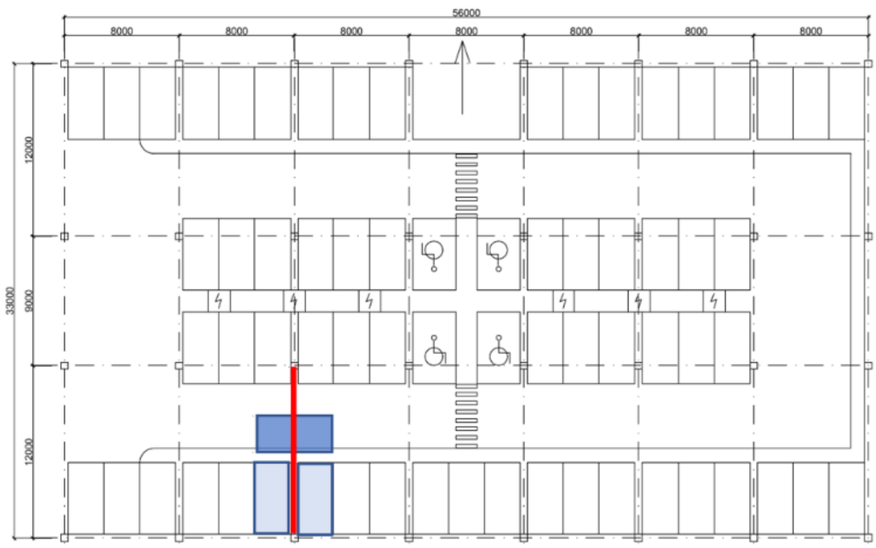


Figure 6–29 Floor plan of designed carpark with burning cars and analysed beam position.

In Figure 6–29, the burning cars of created fire scenarios are highlighted with blue colour. This layout of burning cars was chosen to represent the fire load that would contribute to obtaining highest temperatures of the chosen beam. The fire scenario is based on previously studied carpark fire assumptions that the fire spread between two gasoline cars with average parking distance (70 cm) is 12 minutes and at most 3-4 vehicles on fire at the same time should be considered [67–69]. This leads to the fire scenario where the first burning car is placed under the middle of the chosen beam where the element bending moment has the highest value (dark blue colour in Figure 6–29). The car fire starts in simulation time t = 0 seconds. The position of this car enables to spread the fire to two adjacent cars at the same time. According to the mentioned assumptions, these two cars start burning after 12 minutes at the time of simulation t = 720 seconds and their position is shown with light blue colour in Figure 6–29.

Before modelling the scenario, single car fire model was created in order to carry out the mesh sensitivity analysis. The geometry of the modelled car (Figure 6–30 left) is based on combination of a simple car FDS model by Markert and Guiliani [67] and an advanced model by Heinisuo and Partanen [68]. The car fire heat release rate (HRR) is defined as a time-depending function to conform the reference curve experimentally defined by Joyeux et al. [70] which was also used in mentioned studies [67, 68]. The burning area (red colour in Figure 6–30 left) with prescribed HRR can be characterized as a pool fire [71] inside the non-combustible car frame, taking into account all combustible materials inside a car [72–76]. The reference curve is shown in Figure 6–30 (right) together with the results of the mesh sensitivity analysis carried out for mesh cell size 100 mm, 200 mm and 300 mm.

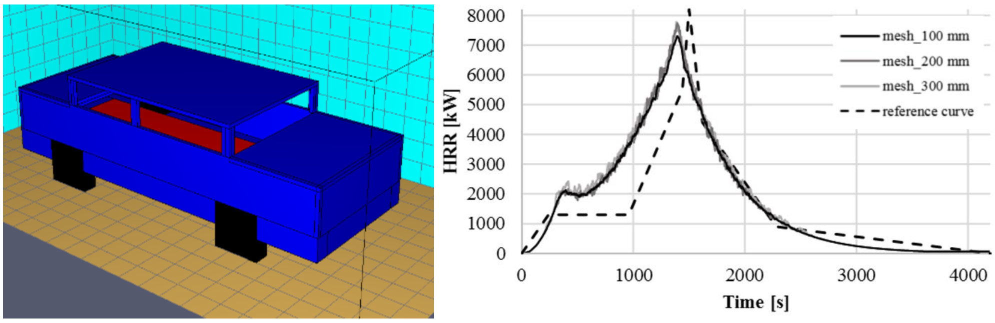


Figure 6–30 Geometry of modelled car (left) and mesh sensitivity analysis (right).

According to the mesh sensitivity analysis results, the mesh sell size 300 mm is chosen for the modelled scenario. To reduce the simulation time, half of the parking storey area is modelled and is divided into 6 meshes with, overall, 103 400 cells. The geometry, material characteristics and boundary conditions are modelled to represent the designed building properties. The proposed fire scenario is simulated with three different venting boundary conditions – as open, semi-open and closed building envelope walls.

The temperatures of the analysed beam are measured with FDS measuring devices (&DEVC) placed on the cross-section web and flange every 600 mm along the beam. The measuring quantity of the devices is the adiabatic surface temperature which already takes into account the material heat transfer coefficient and can be used as the input for potential follow-up FEM analysis [77].

The total simulation time of all three scenarios is 60 minutes (3600 seconds). The simulations were computed in FDS version 6.7.0 on the computing cluster at University of Žilina.

An asumptions based on previous studies were made. Parked cars distance was considered 600 mm, fire spread of 12 minutes, and 3-4 cars on fire. Three fire scenarios were applied on beam, girder, column. An example car layout for a column fire scenario is shown in Figure 6–31; another example of beam fire scenario is shown in Figure 6–32.

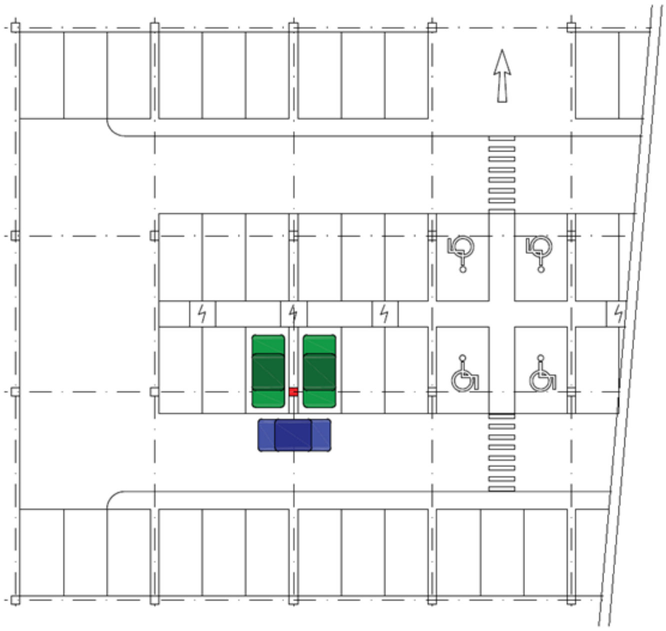


Figure 6–31 An example of a fire scenario for CFD fire modelling.

Four simulations for each fire scenario were made with various natural ventilation border conditions (without fire protection), see also Table 6–2:

- open carpark;
- semi-open carpark;
- closed carpark.

Additional simulations were conducted with active fire protection using sprinkler system.

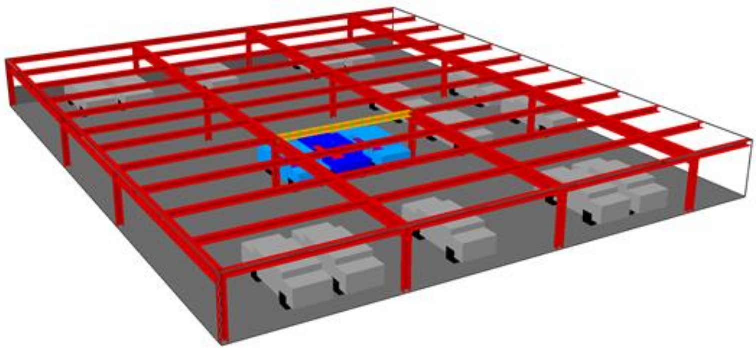


Figure 6–32 Visualisation of fire simulation in Fire Dynamics Simulator – analysed beam highlighted.

Table 6–2 Fire scenarios for CFD modelling.

Ventilation conditions	Scenario for analysed element		
	Girder	Beam	Column
Open	Scenario 1P	Scenario 1T	Scenario 1S
Semi-closed	Scenario 2P	Scenario 2T	Scenario 2S
Closed	Scenario 3P	Scenario 3T	Scenario 3S

The following Figure 6–33 shows the chosen representative simulation results as temperature-time curves of the beam section with the highest obtained temperatures (middle) and lowest obtained temperatures (end section towards floor area centre). Plotted curves show the beam flange temperatures for open, semi-open and closed carpark simulation scenarios and the flange temperature if exposed to standard fire curve ISO 834.

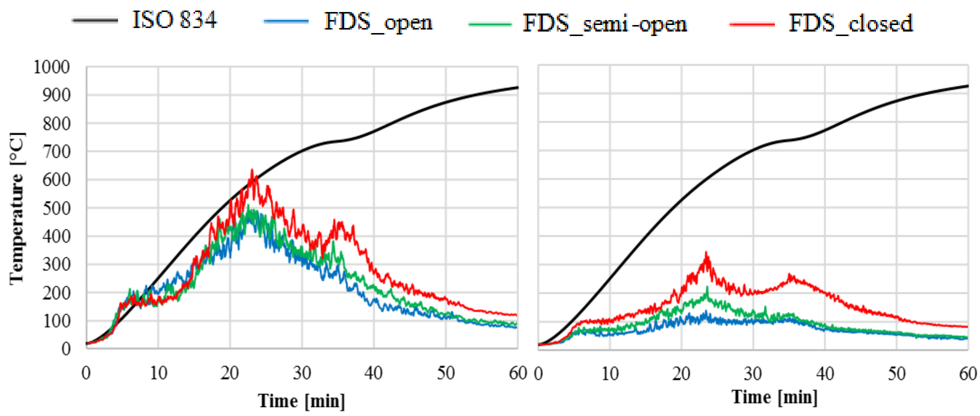


Figure 6–33 Obtained steel beam surface temperatures in middle section (left) and end beam section (right).

The results presented in Figure 6–33 show that obtained steel temperatures with CFD simulation are lower comparing to the standard curve approach during the fire development phase. The difference is more significant in the end beam section. The CFD output temperatures copy the modelled fire development which consists of the first burning car fire growth, its afterburning phase, fire spread to the two adjacent cars, its fire growth and afterburning phase. On the other hand, the temperature obtained with nominal approach develops according to the standard fire curve and represents only fire growth phase for the whole analysed time.

The obtained steel temperatures are compared with steel temperatures for the case of the beam exposure to the standard fire curve. The results are presented for the middle beam section, with the highest temperatures, and end beam section, with the lowest temperature values.

In both cases, obtained temperatures are lower than standard approach temperatures during the fire growth. As assumed, at the end section the difference is more significant. During the afterburning phase the difference grows in both sections as standard fire curve (ISO 834) does not take into account the afterburning phase. This verifies the assumption that numerical approach would provide not only more realistic fire development but is also efficient if the unprotected steel structure is designed. The presented results also show temperature differences for individual CFD scenarios. As assumed, the temperature values are lower while the ventilation rate rises. Therefore, the ability of CFD models to represent different boundary conditions is proved.

6.3.3 Structural modelling

Vertical elements (columns)position limits the driving and parking of cars. Their distribution determines the lengths of the span of the horizontal elements (beams) of the structure. The beams, which are the first to take over the load of the ceiling slab, are designed in the longitudinal direction in the length of 8,0 m (Figure 6–34) within the mutual axial distance of 3,0 m. The transverse load-bearing beams are oriented transversely within the floor plan and are designed to be 12,0 m long in the edge fields and 9,0 m in the middle fields.

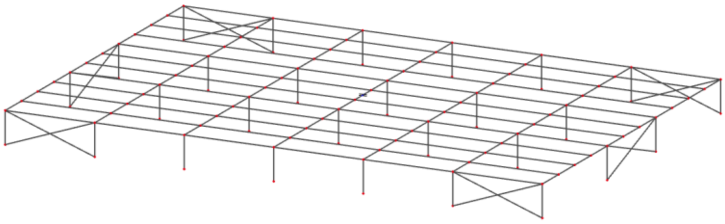


Figure 6–34 Beam structural model of one floor of parking house.

A 3D model of the load-bearing structure was created in the SCIA Engineer program in version 21.0, shown in Figure 6–35. The model of the structure serves to more accurately determine the internal forces of the structure, as it considers the interaction of individual elements. Ceiling slabs and roof slabs are modelled as composite reinforced concrete slabs. Horizontal beams are modelled as ribs of coupled plates with articulated support at both ends. The anchoring of the columns is modelled at the floor level of the 1st floor as the wedging of the bar elements.

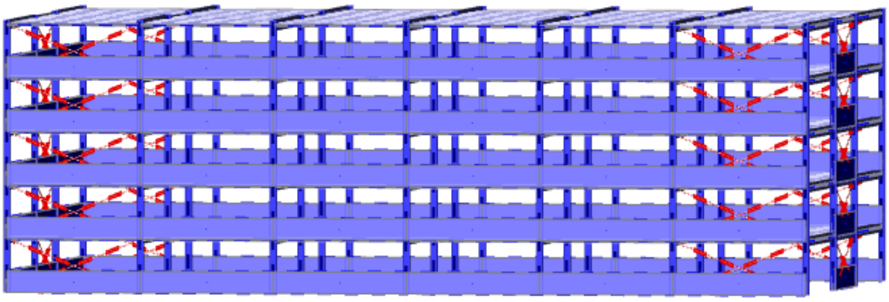


Figure 6–35 Three dimensional model of the parking house – side view.

Based on the utilization, location and design service life of the building (considered 50 years), the load cases were defined and classified into load groups (Table 6–3). In the case of load cases from the selected category, the load on the structures is applied in several ways. For individual elements the one that induces the most unfavourable internal forces in a given element is selected. In this way, the applied imposed load of the roof panel and the imposed load of the parking area (ceiling panels) are applied.

Imposed load of the roof was considered according to the standard STN EN 1991-1-1 for the category of loaded surface H: roofs inaccessible, except from the regular maintenance. Load values are according to the standard specified as uniform load q_k = 0,4 kN/m^2 and isolated force Q_k = 1,0 kN, and for roof structures, their behaviour have to be verified independently. In the group of imposed loads of roof, following load cases were applied:

- surface load of roof slab q_k (LC19),
- force Q_k applied in the centre of roof transversal beam (LC20) and roof beam (LC21).

After determining the value of the imposed load, we can classify the ceiling slabs of the parking house in the category of traffic areas F, which are designed for movement and parking of light vehicles (with a total weight of not more than 30 kN and the number of seats, excluding driver, less than or equal to 8). Values of imposed load of surface of category F are surface load q_k = 2,5 kN·m^{-2} and force load Q_k = 20 kN. In this case effect of these loads have to be considered together, because q_k is determined for the general effects of loads and Q_k for local effects. For this reason, belongs to the own load group.

Table 6–3 Load cases and load groups.

Load group			Load case			
Title	Description	Type	Title	Description	Type	Applied on
LG1	self-weight	standard	LC1	self-weight (without concrete slab)	permanent	all
			LC1_SB	self-weight of concrete slab - hardened concrete	permanent	celling slabs, roof slab
			LC2	roof	permanent	celling slabs, roof slab
			LC3	floor	permanent	celling slabs, roof slab
LG2	building phase	standard	LC1_CB	self-weight of concrete slab - fresh concrete	variable	celling slabs, roof slab
LG3	equipment	standard	LC4	banister - railing	permanent	loading panel
			LC5	air-conditioning system and lightening	permanent	celling slabs, roof slab
LG4	Cars – imposed surface load	selection	LC6	checker pattern 1	variable	celling slabs
			LC7	checker pattern 2	variable	celling slabs
			LC8	checker pattern 3	variable	celling slabs
			LC9	checker pattern 4	variable	celling slabs
			LC10	checker pattern 5	variable	celling slabs
			LC11	checker pattern 6	variable	celling slabs
			LC12	checker pattern 7	variable	celling slabs
LG5	Cars – imposed isolated force	selection	LC13	axle load – transversal beam in centre	variable	celling transversal beam
			LC14	axle load – transversal beam in support	variable	celling transversal beam
			LC15	axle load – beam in centre	variable	celling beam
			LC16	axle load – beam in centre	variable	celling beam
LG6	snow	standard	LC17	snow load	Variable	celling slab
LG7	wind	standard	LC18	wind load	Variable	
LG8	roof – imposed load	standard	LC19	imposed load of the roof - surface	variable	roof slab
			LC20	imposed load of the roof – isolated force on transversal beam	variable	roof transversal beam
			LC21	imposed load of the roof – isolated force on beam	variable	roof beam

In the load group of the surface imposed load of the ceiling, 7 load cases (LC6-12) were created, which include a uniform and checkerboard arrangement of the area load. All are schematically shown on the floor plan of the ceiling structure in Figure 6–36.

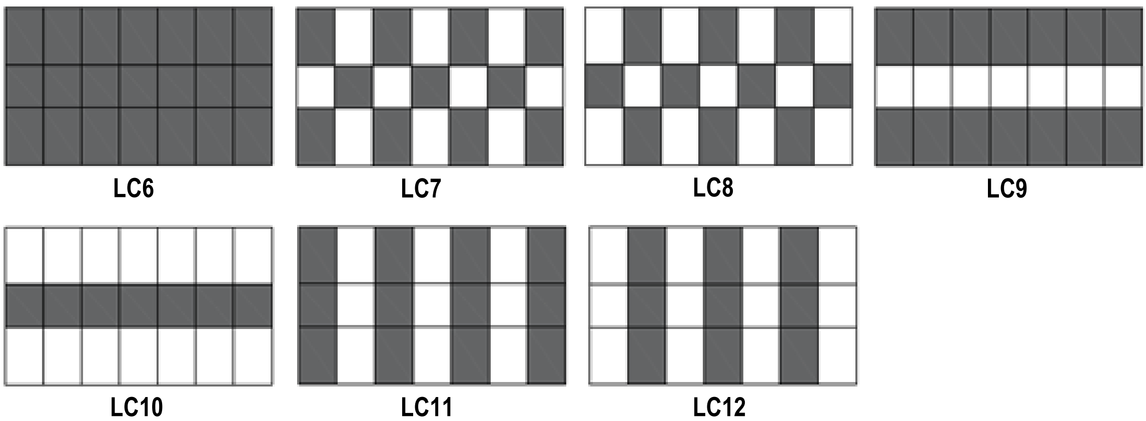
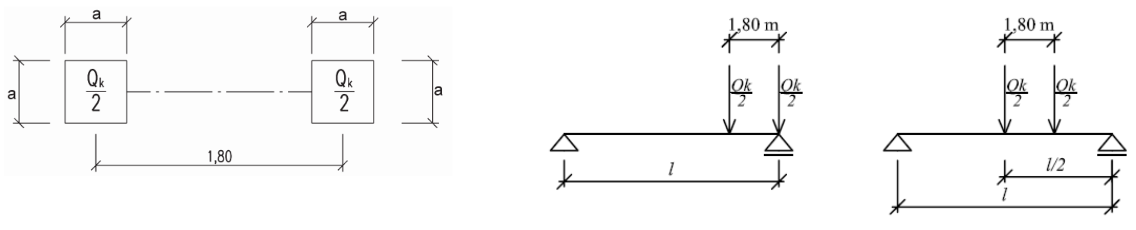


Figure 6–36 Forms of a checker pattern arrangement of the applied surface traffic load with respect to the axis of the main bearing elements.

The concentrated load Q_k has to act as an axle load applied with two square contact surfaces with side a = 100 mm for surface category F, see Figure 6–37 a). At the same time, it should be applied to the structure in such possible positions as to cause the most adverse effects of the load. This means that load cases have been created within the load group:

- by placing one of the load surfaces in the transversal beam support and in the beam support to induce the maximum reaction in the support (Figure 6–37 b),
- with one of the load surfaces placed at the centre of the cross member and at the centre of the beam to induce the maximum bending moment (Figure 6–37 c).



a) axle contact-point model   b) axle load on beam support   c) axle load on middle of beam

Figure 6–37 Load schemes.

Load combinations were created for:

- permanent design situations (final phase);
- temporary design situations (building phase);
- accidental design situations (fire).

In total, 5 combinations were created in SCIA model.

For analysis of fire resistance 3 representative category of structural elements were selected (Table 6–4). Based on the 3D model of the structure and the automatic selection of the most unfavorable combination of load cases, it was possible to determine the most stressed element in each category.

Table 6–4 Structural elements of fire resistance analysis

Chosen element	Element characteristics	Cross-section	Lenght	Internal forces for fire resistance determination
BEAM	internal ceiling beam	composite concrete slab 130 mm and rolled steel profile HEB 500	12 m	max. bending moment $M_{fi,Ed}$ = 879,990 kNm
				max. shear force $V_{fi,Ed}$ = 73,289 kN
GIRDER	internal ceiling girder	composite concrete slab 130 mm and rolled steel profile HEB 240	8 m	max. bending moment $M_{fi,Ed}$ = 154,471 kNm
				max. shear force $V_{fi,Ed}$ = 1,650 kN
COLUMN	internal 1st floor column	rolled steel profile HEA 400	3 m	max. normal force $N_{fi,Ed}$ = -2212,320 kN
				max. bending moment $M_{fi,Ed}$ = -1,790 kNm

Fire resistance requirement was set to R30 as per the Slovakian national requirements. Three design alternatives were considered:

- unprotected steel structure
- steel protected by intumescent paint
- steel protected by fireboards

Due to the extent only the unprotected steel evaluation is presented in this case study. Fire resistances of unprotected steel elements calculated through the simplified EN 1993-1-2 method are shown in Table 6–5. Significant increase in steel profile size is apparent.

Table 6–5 Fire resistances of unprotected steel elements – simplified calculation as per EN 1993-1-2.

Element	Normal temperature design		Fire resistance R30 design (UNPROTECTED STEEL)	
	Steel	Cross-section	Steel	Cross-section
beam	S 355	HEB 500	S 355	**HEM 900**
girder	S 355	HEB 240	S 355	**HEB 260**
column	S 355	HEA 400	S 355	**HEM 500**

Subsequently, individual structural elements were modelled in ANSYS. The dimensions of elements are as follows: HEB 500 (girder) a HEB 240 (beam). Celling concrete slab is modelled in the thickness of 130 mm as shown in Figure 6–38.

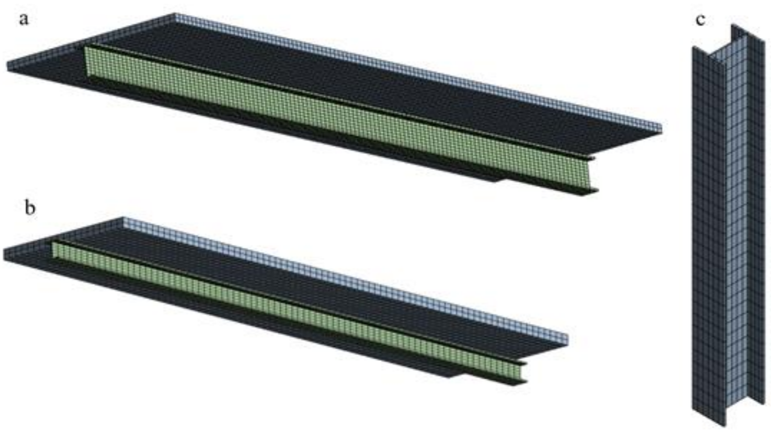


Figure 6–38 Models of structural elements in ANSYS – a) girder, b) beam, c) column.

For the analysis of the thermal response, the steel beams of the created models were longitudinally divided at the same intervals. The outputs from the CFD models of the fire, namely the adiabatic temperature of the structure (AST) and the heat transfer coefficient (HTC), were subsequently applied to these parts. The temperature data are applied separately to the flange parts and the wall parts by the respective values as a function of time. The total thermal response analysis time is 1800 s (30 minutes), which corresponds to the R30 requirement of the analysed fire resistance. The maximum deflection and the rate of deflection were observed to establish whether the limit states had been exceeded. An example of a girder deflection under thermal exposure is shown in Figure 6–39.

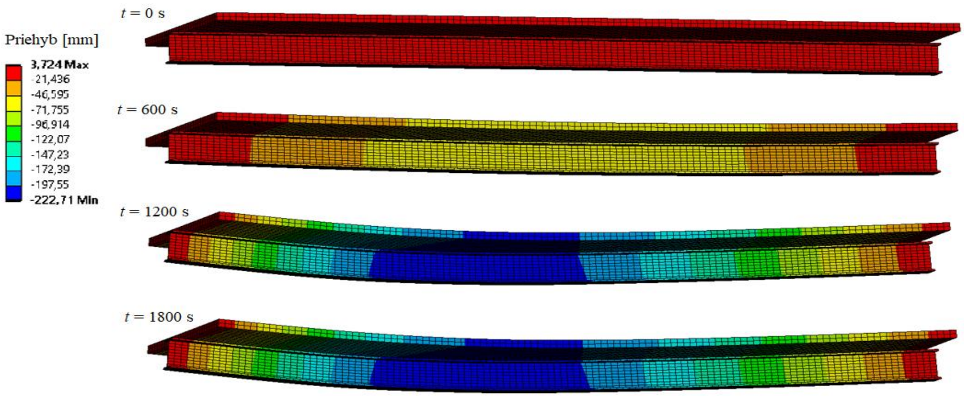


Figure 6–39 Example of the development of girder deflection under thermal exposure – scenario 2P.

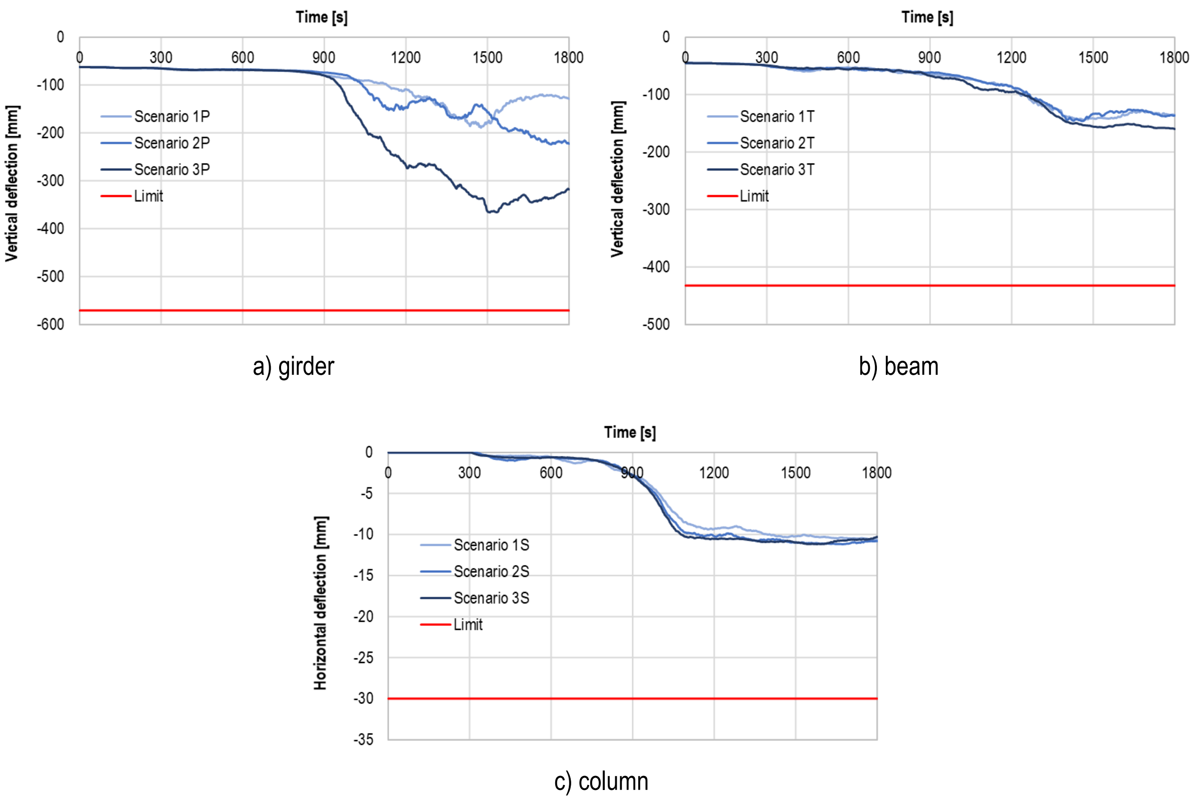


Figure 6–40 Structural modelling results – deformation – for the analysed construction members.

As the results in Figure 6–40 indicate the unprotected steel construction members did not exceed deflection limits when exposed to the thermal effects of the simulated fire. Given the considered scenarios it may also be concluded that the closed construction – no direct ventilation – represents the most severe conditions, particularly for horizontal elements – girder and beam. Hence, the unprotected steel construction elements with ambient-temperature profile sizes would withstand the effects of fire for the required period of 30 minutes. It should also be noted, that a subsequent evaluation would be required to establish the fire resistance of joints and other critical details.

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Annex – Brief summary on establishing fire resistance requirements in V4 countries and the partner country

Czech republic

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The combination of legislative regulations (laws, decrees) and Czech technical standards creates basic rules for designing fire safety of buildings. Laws and decrees (implementing legislation) are binding. Technical standards are generally not obligatory in the Czech Republic (they are recommended), but they can be obligatory if required by a decree (especially in the case of protection of the public interest, such as thermal protection, acoustics or fire safety). Fire design standards (series of standards CSN 73 08xx) and some other associated standards are binding because they are ordered by Decree 23/2008 Coll. The calculation methods and requirements are found exclusively in the technical standards of the ČSN 73 08xx series (fire safety of buildings), in part specific requirements are given in Decree 23/2008 Coll. However, with regard to the age of the Decree, the requirements are translated into the current versions of the standards [A1].

The fire safety design system is prescriptive. A different procedure (perfomance based design) is allowed by law (133/1985 Coll., § 99) [A2] and the framework methodology is then very briefly defined by the fundamental standards CSN 73 0802 [A3], resp. CSN 73 0804 [A4] (non-production or production objects) in the informative appendix. Acceptance criteria are not defined in national regulations.

The basic categorization in the field of fire safety designing is created by 2 fundametal standards for non-production buildings (CSN 73 0802, residential and civil buildings) and production buildings (CSN 73 0804). The general content of the master standards is given in the previous section. This categorization is complementary to other project standards (CSN 73 08xx series) for specific constructions and operations (assembly areas, housing, accommodation, alterations to buildings, medical buildings, social care, postal operations, telecommunications links, agricultural buildings, warehouses).

Fire resistance requirements

Fire resistance requirements are based on a fire resistance grade, which is determined from a combination of the following:

- construction system type based on the combustibility and combination of load-bearing and fire-separating construction elements, see Figure A–1;
- fire risk – expressed by calculated fire load or equivalent fire duration (calculated fire load is in principle the same value as equivalent fire duration – standard furnace exposure);
- building height – from the floor level of the ground level storey to the floor level of the uppermost storey.

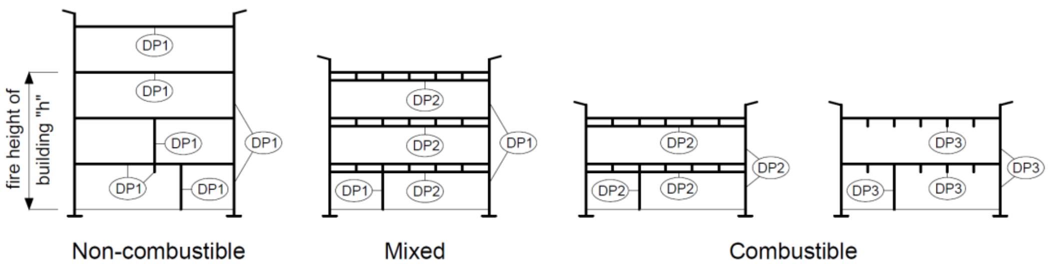

Figure A–1 Classification of construction system types

Classification of construction element types is based upon the reaction to fire class of their individual components as shown in Figure A–2.

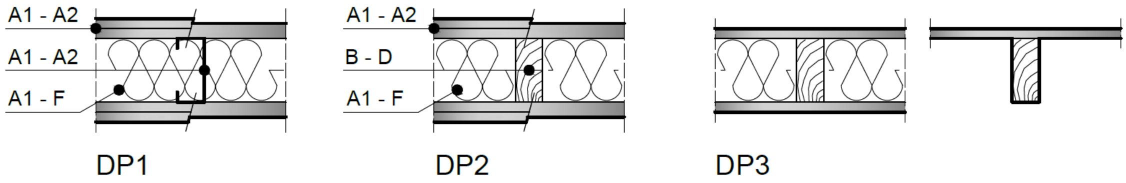

Figure A–2 Classification of construction element types

The fire risk value is calculated for each compartment and counts in variable and fixed fire load, fuel type (fire growth rate) and ventilation conditions. There are a series of calculations, which are different for non-industrial and industrial buildings.

Once the three parameters listed above are calculated then the fire resistance grade is established from a series of tabulated values, an example for non-industrial building is reproduced in Figure A-3.

Construction system (CS) of building	The highest factored fire load (p_v [kg/m²]) in fire compartment (FC)	The lowest fire resistance grade (FRG) in fire compartment						
		I.	II.	III.	IV.	V.	VI.	VII.
		Fire height of building h [m]						
Non-combustible	15	12	30	60	without limit			
	30	O	12	30	without limit			
	45	O	6	22,5	45	without limit		
	60	O	6	12	30	45	without limit	
	90	O_a	O	6	12	30	45	
	120	N_1	O_a	O	6	12	30	45
	above 120[1)]	N_1	N_1	O_a	O	6	12	30
Mixed	10	6	12	12	18	22,5	N_2	N_2
	25	O	6	12	18	22,5	N_2	N_2
	35	O	6	12	18	22,5	N_2	N_2
	50	O_a	O	6	18	22,5	N_2	N_2
	75	N_1	O	6	12	22,5	N_2	N_2
	100	N_1	O	6	9	15	N_2	N_2
	above 100[1)]	N_1	N_1	O	6	12	N_2	N_2
Combustible	10	4	9	12	12	12	N_2	N_2
	20	O	4	9	12	12	N_2	N_2
	30	O	4	9	12	12	N_2	N_2
	40	O_a	O	4	9	12	N_2	N_2
	60	N_1	O	4	4	9	N_2	N_2
	80	N_1	O_a	O	4	9	N_2	N_2
	above 80[1)]	N_1	N_1	O_a	O	4	N_2	N_2

Example:
- block of flats
- h = 21 m
- non-combustible CS
- FC = flat
- p_v = 45 kg/m²

▶ **III. FRG**

Table legend:
- **N** = FRG must not be applied
- **O** = FC in one-storey buildings only

Figure A–3 Determination of fire resistance grade

Subsequently for each relevant type of construction element the duration of fire resistance rating is established from a series of tabulated values; an example for non-industrial building is reproduced in Table A-1. The fire resistance criteria, e.g. integrity, insulation, etc. is defined by the ČSN 73 0810 standard [A5] and depend on the function of the particular construction element.

Table A–1 Fire resistance requirements for non-industrial buildings.

Ref.	Construction	Fire Resistance Grade (FRG) of Fire Compartment (FC)						
		I.	II.	III.	IV.	V.	VI.	VII.
		Fire Resistance of construction and required type						
1	Fire walls and ceilings:							
	a) in basement	30 DP1	45 DP1	60 DP1	90 DP1	120 DP1	180 DP1	180 DP1
	b) in upper floors	15	30	45	60	90	120 DP1	180 DP1
	c) in upmost floor	15	15	30	30	45	60 DP1	90 DP1
	d) between buildings	30 DP1	45 DP1	60 DP1	90 DP1	120 DP1	180 DP1	180 DP1
2	Fire openings:							
	a) in basement	15 DP1	30 DP1	30 DP1	45 DP1	60 DP1	90 DP1	90 DP1
	b) in upper floors	15	15	30	30	45 DP2	60 DP1	90 DP1
	c) in upmost floor	15	15	15	30	30	45 DP2	60 DP1
3a	External walls load-bearing:							
	a) in basement	30 DP1	45 DP1	60 DP1	90 DP1	120 DP1	180 DP1	180 DP1
	b) in upper floors	15	30	45	60	90	120 DP1	180 DP1
	c) in upmost floor	15	15	30	30	45	60 DP1	90 DP1
3b	External walls non-load-bearing:	15	15	30	30	45	60 DP1	90 DP1
4	Load-bearing elements of roof	15	15	30	30	45	60 DP1	90 DP1
5	Load-bearing elements inside Fire Compartment							
	a) in basement	30 DP1	45 DP1	60 DP1	90 DP1	120 DP1	180 DP1	180 DP1
	b) in upper floors	15	30	45	60	90	120 DP1	180 DP1
	c) in upmost floor	15	15	30	30	45	60 DP1	90 DP1
6	Load-bearing elements outside building	15	15	15	30	30 DP1	45 DP1	60 DP1
7	Load-bearing elements of independent building part inside Fire Compartment	15	15	30	30	45	45 DP1	60 DP1
8	Non-loadbearing elements inside Fire Compartment	-	-	-	DP3	DP3	DP2	DP1
9	Stairways, excl. PEW	-	15 DP3	15 DP3	15 DP1	30 DP1	45 DP1	45 DP1
10a	Evacuation and fire elevator shafts and shafts in buildings higher h > 45 m:							
	1. fire separation elements	According to line 1						
	2. fire openings	According to line 2						
10b	Other shafts:							
	1. fire separation elements	30 DP2	30 DP2	30 DP1	30 DP1	45 DP1	60 DP1	90 DP1
	2. fire openings	15 DP2	15 DP2	15 DP1	15 DP1	30 DP1	30 DP1	45 DP1
11	Roof facing	-	-	15	15	30	30 DP1	45 DP1
12	One-storey building:							
	a) fire walls	30 DP1	45 DP1	60 DP1	90 DP1	-	-	-
	b) fire openings	15 DP1	30 DP1	30 DP1	45 DP1	-	-	-
	c) vertical fire barriers in external walls between buildings	15 DP1	30 DP1	30 DP1	45 DP1	-	-	-

Literature

[A1] Decree No. 23/2008 Coll. on technical conditions of fire protection of buildings

[A2] Act no. 133/1985 Coll. on fire protection

[A3] CSN 73 0802:2020 - Fire protection of buildings - Non-industrial buildings

[A4] CSN 73 0804:2020 - Fire protection of buildings - Industrial buildings

[A5] CSN 73 0810:2016 - Fire protection of buildings - General requirements

Hungary

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In Hungary, fire safety requirements are regulated by legislative provision called National Fire Safety Code issued by Ministerial Decree 54/2014 (XII. 05.) BM as amended by Ministerial Decree 30/2019 (VII 26) BM [A6]. This is much shorter than its predecessors, consisting only the basic fire safety design principles, the required safety level and the detailed fire safety requirements.

Besides the legislative provision, there are altogether 14 Fire Protection Technical Guidelines including Fire Protection Properties for Building Constructions [A7]. Accepted technical solutions, Best Practice examples and standard applications are included in the Fire Safety Guidelines. There are no extracts or parts from EU related and valid standards, but practical solutions how to fulfil the required safety level using the standards. For instance, the required fire safety performances are included in the NFSC, calculation methods are included in the Eurocode standards [A8] and the accepted fire safety design processes of loadbearing structures are shown in the Fire Protection Technical Guideline: Fire Protection Properties for Building Constructions.

Figure A–4. Different Fire Protection Technical Guidelines

Advantage of the guidelines are the followings: easy – to – use, free download, regular overwiev is simpler than at the standards or at the legislative provisions. Fire Protection Technical Guidelines are completed by comittees of professionals but issued by the Headquarter of National Disaster Recovery.

Fire safety design of the structures

According to the NFSC, Article 6, when designing building products and building structures, they shall be selected in a manner to ensure that

- supporting structures retain their load-bearing capacity and dividing structures retain their integrity and thermal insulation capacity for a period of time specified in this Decree taking into account the expected impact of fire,
- building structures and building products designed to achieve a fire protection related objectives fulfil their role and remain functional for a period of time specified in this Decree and respond to the presence of fire effectively,
- they block, render more difficult or direct the propagation of fire and its concomitants in line with their function, and

- the volume of heat, smoke and combustion products they give off is kept to a bare minimum.

According to the NFSC, Article 7, initial parameters of fire protection design:

- the fire protection solutions of a building shall be designed and dimensioned taking into account the harmful effect of a single fire starting at any location inside the building at any time,
- the building is used according to its designated purpose when the fire starts,
- the number of people exposed to threat and their capacity to escape match the designated purpose,
- the fire covers a single fire compartment including the location where it started, and
- no simultaneous event occurs at the time of the fire, such that would pose a threat or risk or would render fire safety solutions inoperable.

Fire protection requirements shall be established on the basis of the fire hazard category of substances, the risk category of units of hazard and the standard risk category of independent building sections and special structures. To determine the risk that influences fire protection requirements, the following shall be specified:

- the units of hazard in a building and in an independent building section, the related risk categories and in turn the standard risk category of the building and the independent building section, and
- the risk category of special structures.

The unit of hazard may be:

- a unit with independent designated purpose,
- a group of adjacent units with independent designated purpose as defines in Article 11,
- a special structure or
- a part of the building, the independent building section or special structure identified by the person responsible for preparing fire safety documentation by taking the provisions of paragraph (3) into account.

Risk classifications of the different risk units and the design risk classification can be determined according to the followings:

- Based on the risk unit's highest floor level (+7,0 m below: VLR, between +7,01-+14,0 m: LR, between +14,01-+30,0 m MR, above 30 m: HR)
- Based on the risk unit's lowest floor level (between ±0,00 - -4,00: VLR, between- -4,01 - -7,00 LR, between - 7,01-+14,0 m: MR, below -14 m: HR).
- Based on the risk unit's room of maximum capacity (under 50 persons: VLR, between 51-300 persons: LR, above 300 persons: MR – there is no HR classification based on the room's capacity).
- Based on the escaping abilities of the users (escaping on their own: VLR,)
- Based on the stored objects, goods or materials (non combustible materials: VLR, combustible materials included maximum 100 kg or 100 l explosive materials: LR, combustible materials included maximum 300 kg or 300 l explosive materials: MR, explosive materials: HR).
- Based on the industrial technology (according to list of examples from the Fire Protection Technical Guideline Risk Classification [A9])

Classified by the degree of risk, buildings, independent building parts and units of hazard may belong to the design risk category of

- Very Low Risk or VLR,
- Low Risk or LR,
- Medium Risk or MR,
- High Risk or HR.

Notwithstanding the provisions of paragraph (4), the standard risk category of buildings, independent building sections and special structures shall be identical to the most severe risk category assigned to their units of hazard.

The supporting structure elements ensuring the structural stability of structures must comply – depending the standard or design risk classification - with the requirements set forth in the Table A–2 below:

Table A–2 Reaction-to-fire and resistance-to-fire requirements of the building structures

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	**Design risk classification**		**VLR**	**VLR**	**VLR**	**LR**	**LR**	**LR**	**MR**	**MR**	**MR**	**HR**	**HR**	**HR**
2	Number of levels of the building or building part		1-2 Industrial, agricultural, storage functions 1-3 residential function	3 Industrial, agricultural, storage functions 1-3 Public func-tions	4	1-2	3-4	5-6	1-2	3-6	7-15	1-2	3-15	>15
3	**Building structures**	**Criterion**	**Required resistance-to-fire and reaction-to-fire performance**											
4	Except of the bearing building structures, the slabs and the top floor's cover-ing structures – EI criteria concerns for walls with role against fire propagation – reaction-to-fire requirement of basement structures is at least A2, resistance-to-fire requirement is at least R30	R	15 D	30 D	60 D	30 D	30 C	60 A2	30 A2	60 A2	90 A2	60 A2	90 A2	120 A2
5	Above basement level, between floors, below attic and loft slabs – EI criteria concerns for structures with role against fire propagation – reaction-to-fire requirement of floor slabs above the basement is at least A2, resistance-to-fire requirement is at least R30	R	15 D	30 D	60 D	30 D	30 C	60 A2	30 A2	60 A2	90 A2	60 A2	90 A2	90 A2
6	Roof slabs and the loadbearing structures of the top floor's – concerning to the structure EI criteria can be skipped, if the structure' bust and through-heating do not risk the structure's surroundings and the sturcture's either part's flaming up does not come with the risk of the fire's major extension to the roof – reaction-to-fire requirement of the structure is D according to the Chart, but maximum C, if the structure is separating from the outdoor area non built-in attic or spaces not suitable for human habitation – - only reaction-to-fire requirement concerns on the loadbearing structure of the skylights	REI	15 D	15 D	30 D	15 D	15 D	30 A2	30 D	30 A2	60 A2	30 A2	60 A2	60 A2
7	Separating structure of the top floor's, not bearing structure below 80 kg/m^2 specific surface mass – over 80 kg/m^2 specific surface mass, requirement of the previous row must be fulfilled – concerning to the structure EI criteria can be skipped, if the structure' bust and through-heating do not risk the structure's surroundings and the sturcture's either part's flaming up does not come with the risk of the fire's major extension to the roof	REI	15 D	15 D	15 D	15 D	15 D	15 A2	15 D	30 A2	30 A2	30 A2	30 A2	60 A2

	– concerning to the structure REI criteria can be skipped, if the structure' bust and through-heating do not risk the structure's surroundings and the sturcture's either part's flaming up does not come with the risk of the fire's major extension to the roof and the collapse of the structure does not come with the risk of the stability of the primary loadbearing structures													
8	Loadbearing structures of internal stairs and landings and supporting structures of their tread serving as escape routes	R	15	30	60	30	30	60 A2	30	60	90 A2	60	90 A2	
9	Supporting structure of open stair serving as an escape route	-	A2											
10	Fire wall	REI	120 A1						180 A1			180 A1		
11	Fire compartment border wall and floor slab – EW criteria can be applied instead of EI at fire compartment border walls at least with B reaction-to-fire classification, over 2,10 m measured from the floor level of adjoining circulation or escape route – EW criteria can be applied instead of EI at external fire rated bordering wall, if not increase the fire spread hazard	EI (EW)	30 A2		60 A2	30 A2	30 A2	60 A2	30 A2	60 A2	90 A2	60 A2	90 A2	120 A2
12	Barrier against fire propagation		the requirement is at least the same as the adjoining floor slab or wall, but maximum A2, R 90 A2											
13	Fire rated partition wall – EW criteria can be applied instead of EI over 2,10 m measured from the floor level of adjoining circulation or escape route	EI (EW)	15					30						
14	Fire doors in fire walls	EI_2 C	90											
15	Fire doors in fire compartment walls and fire- compartment slabs	in slabs: REI_2 C	30			30		30	30	60		60	90	
16	Fire rated closure system	EI												
17	Lift shaft door, if it was made for protection against fire spreading		according to the related technical standards											
18	Fire-rated gap filling - closure system, fire retardant linear joint sealing	EI	the resistance-to-fire requirement is at least the same as the adjoining or connected structure but maximum EI 90											
19	Floor covering of the escape route		D_{fl}-s1			D_{fl}-s1		C_{fl}-s1	D_{fl}-s1	B_{fl}-s1		B_{fl}-s1		
20	Floor covering of the escape route in staircase									B_{fl}-s1	$A2_{fl}$-s1	B_{fl}-s1	$A2_{fl}$-s1	
21	Wall covering, suspended ceiling, ceiling cladding		D-s1, d0			D-s1, d0		C-s1, d0	D-s1, d0	B-s1, d0	A2	B-s1, d0	A2	
22	Thermal and sound insulation applied on the escape routes, with or without cladding		B-s1, d0			B-s1, d0		A2-s1, d0	A2-s1, d0			A2-s1, d0		
23	Raised floor of the escaping route	REI	15 D			15 D		30 C	30 D	30 A2	60 A2	60 A2		90 A2

Building structures fire safety achievement's characteristics determination and verification

- accredited by investigation in notified body (f.i. independent test laboratory),
- based on calculations using the relating Eurocode standards,
- happens on the basis of other defined legal documents (f.i. the fire safety performances of the existing structures can be found in the Fire Protection Technical Guideline: Fire Protection Properties for Building Constructions, Annex D, which are not under the Eurocode standards).

Literature

[A6] National Fire Safety Code issued by Ministerial Decree 54/2014 (XII. 05.) BM as amended by Ministerial Decree 30/2019 (VII 26) BM;

[A7] Fire Safety Technical Guideline: Fire Protection Properties For Building Constructions (11.2:2020.01.22.)

[A8] Eurocode 3: Design of steel structures - Part 1-2: General rules - Structural fire design

[A9] Fire Safety Technical Guideline: Risk Classification (14.1:2020.01.22.)

Poland

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Among many documents regarding fire safety of buildings in Polish regulations, the most important are: CPR 305/2011, polish building law [A10] and regulations [A11]. Buildings are divided into 3 categories based on the usage type, with buildings intended for:

- people (ZL, 5 categories),
- industrial and storage (PM),
- and livestock buildings (IN).

The requirements for ZL buildings are further based on the height of the building, and grouped as:

- N – with height up to 12 meters above ground level or residential buildings up to 4 storeys above the ground.
- SW – with height between 12 and 25 meters above ground level or residential buildings with more than 4 to 9 storeys above the ground.
- W – with height between 25 and 55 meters above ground level or residential buildings with more than 9 to 18 storeys above the ground.
- WW - with height above 55 meters above ground level.

A building is assigned a fire resistance class of a building (denoted as a letter "A" to "E"), which determines the requirements for building members, Table A–3.

Table A–3 Fire resistance classes of buildings with respective fire resistance classes of members

Fire resistance class of a building	Required fire resistance class of a building member					
	Main loadbearing structure	Roof supporting structure	Floor	External wall	Internal wall	Roof
„A"	R 240	R 30	R E I 120	EI 120 (o↔i)	E I 60	R E 30
„B"	R 120	R 30	R E I 60	E I 60 (o↔i)	E I 30	R E 30
„C"	R 60	R 15	R E I 60	E I 30 (o↔i)	E I 15	R E 15
„D"	R 30	(–)	R E I 30	E I 30 (o↔i)	(–)	(–)
„E"	(–)	(–)	(–)	(–)	(–)	(–)

The required fire resistance classes for ZL buildings are presented in table A–3, as a function of usage type and height category. For example, a ZL II building with 5 storeys will fall into "S" height group, which in turn will result in fire resistance class of the building "B" (Tab. A–3). This means main supporting structure shall withstand fire exposure for at least 120 minutes (Tab. A–4).

The requirements of industrial and storage buildings (IN) are based on height of the building and the maximum fire load density Q (with lowest requirements for buildings with Q ≤ 500 MJ/m2 and highest for Q > 4000 MJ/m^2. The required fire resistance classes may be changed based on, for example, presence of fire extinguishing or smoke venting systems.

Table A–4 Fire resistance classes of buildings for ZL buldings

Build-ing	ZL I	ZL II	ZL III	ZL IV	ZL V
	with rooms for more than 50 people	for people with disabilities, such as hospitals or kindergartens	public use build-ings, not in ZL I or ZL II	residen-tial build-ings	residential,such as hotels, not in ZL I or ZL II
N	„B”	„B”	„C”	„D”	„C”
SW	„B”	„B”	„B”	„C”	„B”
W	„B”	„B”	„B”	„B”	„B”
WW	„A”	„A”	„A”	„B”	„A”

Walls or floors separating fire compartments, shall be made of non-combustible materials. Additionally, members in most of the buildings shall be classified as NRO (non fire-spreading). The EN 13501-1 equivalents are A1 or A2 class for non-combustibility criterion and at least B class for NRO. Additional requirements for smoke production and droplets apply. Those requirements limit the development of timber-based structures in Poland.

Both prescriptive rules (with thermal actions based on nominal fire) and performance-based methods (with physically based thermal actions) are allowed. In case of advanced fire models, Polish National Annex to EN 1991-1-2 recommends the use of Computational Fluid Dynamics (Table A–5).

Table A–5 Polish National Annex comments to EN 1991-1-2.

Provision in EN 1991-1-2	Recommended	Not recommended	No comment
3.2 Nominal temperature-time curves	X		
3.3 Natural fire models			
3.3.1 Simplified fire models			
3.3.1.1 General		X	
3.3.1.2 Compartment fires (Annexes A, B: parametric, external)		X	
3.3.1.3 Localised fires (Annex C: Heskestad, Hasemi)		X	
3.3.2 Advanced fire models			
3.3.2 (1) Use of Annex E (fire load densities, RHR)	X		
3.3.2 (2) One-zone			X
3.3.2 (2) Two-zone			X
3.3.2 (2) Computational Fluid Dynamics	X		

Literature

[A9] Ustawa Prawo Budowlane. https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU19940890414

[A10] Rozporządzenie Ministra Infrastruktury w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie. https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20020750690

Slovak republic

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Combination of legal documents (acts and regulations) and technical standards sets out the rules for building fire safety design.

Acts and regulations as legal documents are mandatory and they refer to technical standards for specific requirements and calculations [A11-A13]. However, some parts of the technical standards are identical to (copied from) the technical standards. This is to mandate certain important elements of the design approach and in many cases also acceptance criteria or important input values.

The technical standards, primarily the STN 92 xxxx series [A14], themselves provide detailed requirements on the specific part of the fire safety design method they deal with, such as: fire risk, compartment size, structural requirements, evacuation, separation distances, water supply, etc. Although not mandatory there is no official way to prove satisfactory performance other than through the STN 92 xxxx suite.

The fire safety design system is prescriptive, although engineering calculations are utilized significantly in certain design steps. Acceptance criteria / limits for calculations are always set prescriptively with little "maneuvering" space.

Some requirements are set prescriptively, e.g. protected escape routes shall be constructed from non-combustible materials.

A combination of building categories and specific purpose groups (where applicable) is used. This combination defines the design approach, calculation methods to be employed and applicable prescriptive requirements. For individual rooms multiple parameters (fuel load, occupants load etc.) have to be established through space use types.

Fire resistance requirements

Fire resistance requirements are based on a fire safety level, which is determined from a combination of the following:

- construction system type based on the combustibility and combination of load-bearing and fire-separating construction elements, see Figure A–5;
- fire risk – expressed by calculated fire load or equivalent fire duration (calculated fire load is in principle the same value as equivalent fire duration – standard furnace exposure);
- building height – from the floor level of the ground level storey to the floor level of the uppermost storey.

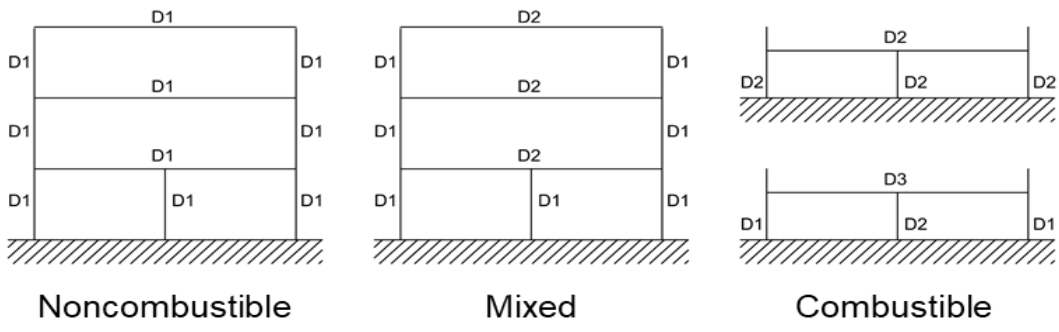

Figure A–5 Classification of construction system types

Classification of construction element types is based upon the reaction to fire class of their individual components as shown in Figure A–6. The construction element types, construction system types and fire resistance levels are all defined in STN 92 0201-2 [A15].

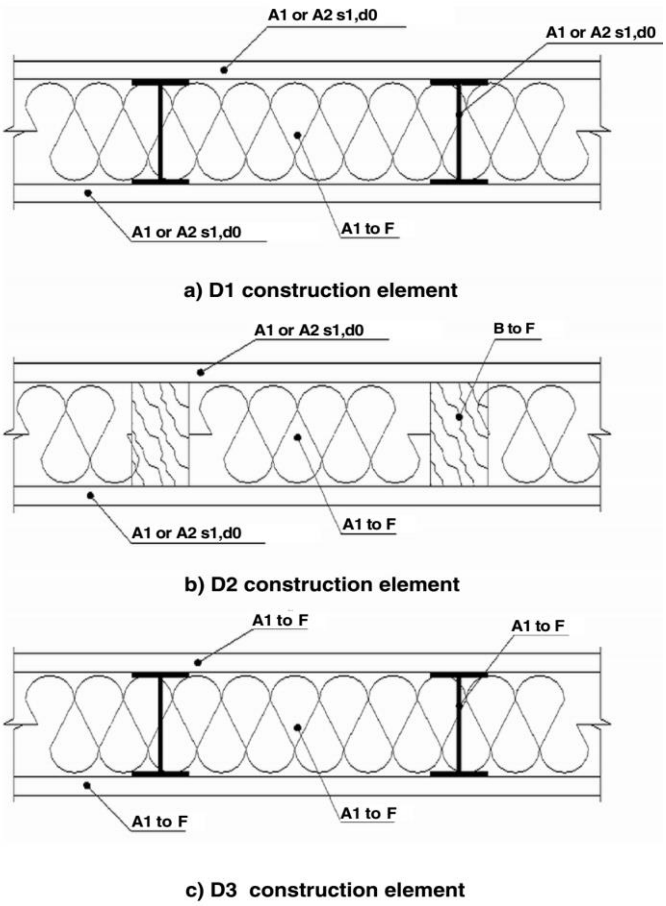

Figure A–6 Classification of construction element types

The fire risk value is calculated for each compartment and counts in variable and fixed fire load, fuel type (fire growth rate) and ventilation conditions. There are a series of calculations, which are different for non-industrial and industrial buildings, the details are in STN 92 0201-1 [A16].

Once the three parameters listed above are calculated then the fire resistance grade is established from a series of tabulated values, an example for non-industrial building is reproduced in Table A-6.

Table A–6 Determination of fire resistance grade

Building construction system type	Fire risk - calculated fire load in fire compartment kg.m^{-2}	Lowest allowed fire safety level of fire compartment				
		I.	II.	III.	IV.	V.
		Building height *h* lower than (m)				
Noncombustible	≤ 15	22.5	No restriction			
	>15 ≤ 30	12	30	No restriction		
	>30 ≤ 45	6	22.5	45	No restriction	
	>45 ≤ 60	6	12	30	45	No rest.
	>60 ≤ 90	0	6	12	30	No rest.
	>90 ≤ 120	0a	0	6	22.5	45
	>120*	N1	0a	0	12	30

Mixed	≤ 10	12	12	18 (12)	22.5 (12)	N2
	>10 ≤ 25	6	12	18 (12)	22.5 (12)	N2
	>25 ≤ 35	6	12	18 (12)	22.5 (12)	N2
	>35 ≤ 50	0	6	18 (12)	22.5 (12)	N2
	>50 ≤ 75	0	6	12	22.5 (12)	N2
	>75 ≤ 100	0a	0	6	12	N2
	>100*	N1	0a	0	6	N2
Combustible	≤ 10	9	9	12	12	N2
	>10 ≤ 20	4	9	9	9	N2
	>20 ≤ 30	4	9	9	9	N2
	>30 ≤ 40	0	4	9	9	N2
	>40 ≤ 60	0	4	4	9	N2
	>60 ≤ 80	0a	0	4	4	N2
	>80*	N1	0a	0	4	N2

Subsequently for each relevant type of construction element the duration of fire resistance rating is established from a series of tabulated values; an example for non-industrial building is reproduced in Table A-7. The fire resistance criteria, e.g. integrity, insulation, etc. are also defined by the STN 92 0201-2 standard [A15] and depend on the function of the particular construction element.

Table A–7 Fire resistance requirements.

Building height	Ref.	Purpose of construction element	Minimum required FR and type of construction element based on fire safety level					Importance coefficient
			I.	II.	III.	IV.	V.	k9
Multi-storey buildings	1	**Fire-separating constructions (walls, partitions and ceilings):**						
		a) underground storeys	45/D1	60/D1	90/D1	120/D1	180/D1	1.3
		b) storeys above ground	30	45	60	90	120	1.0
		c) uppermost storey	15	30	45	60	90	0.5
		d) partywalls	45/D1	60/D1	90/D1	120/D1	180/D1	1.3
	2	**Exterior walls:**						
		a) loadbearing						
		1. underground storeys	45/D1	60/D1	90/D1	120/D1	180/D1	1.3
		2. storeys above ground	30	45	60	90	120	1.0
		3. uppermost storey	15	30	45	60	90	0.5
		b) non-loadbearing	15*	30*	45*	60*	90*	0.5
	3	**Roof:**	15*	30*	45*	60*	90*	0.5
	4	**Fire doors and shutters:**						
		a) underground storeys	30/D1	45/D1	45/D1	60/D1	90/D1	-
		b) storeys above ground	30	45	60	90	120	-
		c) uppermost storey	15	30	45	60	90	-

	5	**Stairs inside fire compartments which are not protected escape routes:**	-	15	30/D2	30/D1	45/D1	-
	6	**Shafts and channels:**						
		a) fire-separating construction						
		1. evacuation and fire-fighter lift shafts	as per Item 1					
		2. other lift shafts	30/D1	30/D1	45/D1	60/D1	90/D1	-
		3. service shafts and channels	30/D1	45/D1	60/D1	90/D1	90/D1	-
		b) fire doors and shuters in:						
		1. evacuation and fire-fighter lift shafts	as per Item 4					
		2. other lift shafts	30/D1	30/D1	30/D1	30/D1	45/D1	-
		3. service shafts and channels	30	45	60/D1	90/D1	90/D1	-
	7	**Roof supporting structure without fire-separating function (eg. trusses)**	15	30	45	60	90	0.5
	8	**Loadbearing construction inside building (superstructure)**						
		a) underground storeys	45/D1	60/D1	90/D1	120/D1	180/D1	1.3
		b) storeys above ground	30	45	60	90	120	1.0
		c) uppermost storey	15	30	45	60	90	0.5
	9	**Loadbearing construction inside building (substructure)**	15	30/D2	45/D2	60/D1	60/D1	0.4
	10	**Exterior loadbearing construction (superstructure)**	15	30	45	60/D1	90/D1	0.5
	11	**Construction supporting equipment, collapse of which contributes to fire spread**	15	30	45	45/D1	60/D1	0.4
Single-storey structurally-independent buildings	12	**Fire walls**	30/D1	45/D1	60/D1	90/D1	120/D1	-
	13	**Fire doors and shutters**	15/D1	30/D1	45/D1	45/D1	60/D1	-
	14	**Vertical fire barriers in exterior walls, exterior walls without unprotected openings**	15/D1	30/D1	45/D1	45/D1	60/D1	-

Literature

[A11] Act no. 50/1976 on urban planning and building order (building act)

[A12] Act no. 314/2014 on protection against fire

[A13] Ministry of Interior's regulation no. 94/2004 on technical requirements on fire safety of building construction and use

[A14] STN 92 0201 Structural fire protection. Common regulations

[A15] STN 92 0201 Part 2: Building constructions

[A16] STN 92 0201 Part 1: Fire risk, fire compartment area

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Fire resistance requirements

A fire zone is a part of the facility that, in terms of structuring and its functions, makes a single construction unit that is, in terms of fire, detached from the remaining parts of the facility by means of fire-resistant structures.

A fire zone is a room or a group of rooms within a facility that can be treated independently in terms of certain technical and organizational fire security measures (fire and fire-specific load, fire alarm zone, automated fire extinguishing zone, etc.), and it is detached from the other parts of the facility by means of fire-resistant structure.

Any residential, business, or public facility must have an access point constructed in line with the requirements regulating this field.

In accordance with the maximum number of persons occupying a facility and the maximum area of a fire zone A, the facilities are classified marked by P in accordance with the Table A–8.

Table A–8 Determination of facility classification.

Number of persons	**≤ 20**	**21 to 50**	**51 to 100**	**101 to 300**	**301 to 700**	**701 to 1500**	**>1500**
Fire zone area *A* [m²]	≤ 400	400 to 800*	800 to 1200*	1200 to 1600*	1600 to 2000*	2000 to 2500*	>2500
Class of facility *P*	P 1	P 2	P 3	P 4	P 5	P 6	P 7

The fire resistance degree of a facility is determined for the facility as a whole or for a fire zone only according to Table A–9, depending on its purpose, detachment, height, maximum fire zone area and maximum number of persons occupying the facility.

The fire resistance degree is the evaluation of the facility reaction to the fire and is expressed in ratings from I to V, i.e. as negligible (I), low (II), medium (III), higher (IV), and high (V);

Table A–9 Determination of fire resistance degree.

Facility classification	**IS1**	**NS1**	**IS2**	**NS2**	**IS3**	**NS3**	**IP1**	**NP1 IJ1**	**IP2 NJ1**	**NP2 IJ2**	**IP3 NJ2**	**NP3 IJ3**	**NJ3**
	Facility fire resistance degree												
P1	II	II	III	III	III	IV	II	II	II	III	III	IV	IV
P2	II	III	III	III	IV	IV	II	II	III	III	IV	IV	IV
P3	III	III	III	IV	IV	IV	II	II	IV	IV	IV	IV	IV
P4	III	III	IV	IV	IV	IV	III	III	IV	IV	IV	IV	V
P5	IV	IV	IV	IV	IV	IV	III	III	IV	IV	IV	V	V
P6	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	V	V	V
P7	IV	IV	IV	IV	IV	IV	IV	IV	IV	V	V	V	V

Requirements in terms of fire resistance of structural members depending on the the facility fire resistance degree are determined in Table 6.

If the facility or a fire segment within the facility as a whole are furnished with a stable fire extinguishing installation, the design fire resistance degree may be reduced from level V to IV, or from level IV to III.

Table A–9 Determination of required fire resistance

Structural members	Location	Fire resistance of a structure component according to adopted fire resistance degree [h]				
		I negligible	II low	III medium	IV higher	V high
Load-bearing wall	Inside fire zone	¼	½	1	1 ½	2
Column		¼	½	1	1 ½	2
Girder		—	¼	½	1	1 ½
Floor construction		—	¼	½	1	1 ½
Non-load bearing wall		—	¼	½	½	1
Roof construction	/	—	¼	½	1	1
Wall	Between fire zones	¼	1	1 ½	2	2
Floor construction		¼	½	1	1 ½	2
Door of up to 3,6 m^2 in area		¼	¼	½	1	1 ½
Door of over 3,6 m^2 in area		¼	½	1	1 ½	2
Emergency exit structures/emergency corridor structures	/	¼	½	½	1	1 ½
Façade wall	Exterior structures	—	½	½	1	1
Roof cladding		—	¼	½	¾	1

Literature

[A17] Rulebook on technical standards for fire protection of residential and business facilities and public facilities.

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V4 guidelines on advanced structural fire safety design with Eurocodes

These guidelines provide background and outline practical approach to structural fire safety design with Eurocodes. The process is divided into three main parts: thermal effects of fire, heat transfer from fire to structure and thermal and mechanical response of the structure. Following these primary steps of structural fire safety design information is provided on control steps to ensure appropriateness and correctness of selected approach. This includes verification, validation, sensitivity analysis and uncertainty treatment. The main part of the guide is concluded by a series of case studies from the contributing V4 and partner countries. An annex complements the main body of the guide with a summary on establishing fire resistance requirements in the V4 and partner countries.

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