Igor Džolev [1]

Đorđe Lađinović [2]

FIRE RESISTANCE OF STRUCTURES

Abstract: When exposed to fully developed fires, structures experience additional stresses, as a result of thermal expansion, levels of constraint and material degradation at elevated temperatures. These stresses and deformations might surpass the load bearing and deformation capacity of structural members, leading to a partial or even full collapse of the structure. In order to estimate and assure the adequate fire resistance of a structure, these actions need to be considered during the design stage. Fire resistance depends on the type of structural system and structural materials and the fire scenario most likely to occur in a given building, based on fire risk assessment. In order to quantify fire resistance by calculation, methods of various levels of complexity and accuracy are proposed and adopted in the engineering practice.

Key words: fire resistance, structural fire response, fire models

[1] Assistant Professor, PhD, University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, Novi Sad, Serbia, idzolev@uns.ac.rs

[2] Full Professor, PhD, University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, Novi Sad, Serbia, ladjin@uns.ac.rs

1. INTRODUCTION TO FIRE RESISTANCE OF STRUCTURES

1.1. Basic requirements

The general objectives of fire protection are to limit risks with respect to the individual and society, neighbouring property, and where required, environment or directly exposed property, in the case of fire [1]. According to the Construction Product Directive 89/106/EEC, the following basic requirements need to be fulfilled for the limitation of fire risks [2]:

- load bearing resistance needs to be provided for a specified period of time,
- generation and spread of fire and smoke need to be limited,
- spread of fire to neighbouring structures needs to be limited,
- safe evacuation of occupants need to be provided,
- safety of rescue teams needs to be taken into consideration.

These requirements impose additional considerations that need to be taken into account during the design phase, in form of passive and active fire protection measures, as to minimize the consequences in case the fire even takes place. Since, in general, such event cannot be predicted and eliminated as a threat (Figure 1), the engineering goal is to reduce the risks, by constantly upgrading the base of knowledge of the analysed phenomena and incorporating the solutions in engineering practice.

a) b) c)

Figure 1 – Novi Sad (Serbia) Open University high-rise building fire on April 6, 2000: a) fire spread to the entire story of origin, b) vertical fire spread and c) current state of the building

Methods of fire resistance assessment, either by tests or calculation, can be divided in following categories [3]:

- standard fire tests,
- tabulated data (largely prescriptive but also increasingly based on calculations),
- simplified calculations, neglecting complex effects, such as thermal stresses),
- advanced calculations (largely performance based),
- full scale fire tests.

According to Eurocode, structures can be evaluated at three levels of increasing complexity:

- member analysis,
- substructure analysis,
- global structural analysis.

In addition to prescriptive and testing methods, current technical development allows the assessment of thermal and structural response to fire also by calculation. Experimental studies provide the most comprehensive knowledge on the behaviour of structures in fire. However, the costs of conducting such studies is substantial (experimental setup, equipment, specialized furnaces and instrumentation). Given the limitations in size of furnaces, and the costs of providing the equipment, as well as the large amounts of energy for each conducted test, the need for more sustainable approach has resulted in the development of calculation procedures to ensure an acceptable cost-benefit solution to engineering practice.

When assessing the fire resistance, irrespective of the method used, the first step is to model the real fire to a realistic and conservative fire scenario. In general, fire severity depends on a number of factors, including [3]:

- availability of combustible materials,
- ventilation conditions, in terms of oxygen delivery,
- physical characteristics of the space in which fire is initiated.

1.2. Fire action and fire models

Each real fire is unique, yet the same phases can be noticed during the course of fire: ignition, growth, flashover, fully developed fire stage, decay stage and extinguishment. For the purpose of structural fire analysis, depending on the assumptions and the level of complexity, fire models are divided into three categories:

- nominal fire curves,
- parametric fire curves,
- multi-zone models.

As the precise prediction of the fire start location, as well as the conditions in which fire will develop, are practically impossible to establish with certainty, in order to define a reference fire model to be used in the fire classification of structural elements, standard (nominal) fire curves are introduced. Most commonly used are ISO 834 fire curve [4], ASTM E119 [5], hydrocarbon and external fire curve [2] (Figure 2). Standard fire curves are derived from the data base of maximum temperatures registered in real cellulosic fires and represent the temperature evolution after flashover occurs. Mathematically, the curves represent the hot gas temperature evolution in a fully developed fire situation, in respect to time. The basic assumptions are that the temperature inside the fire compartment is considered independent of the compartment size and materialization, amount of combustible fuel present and the ventilation properties of the surrounding envelope. The temperature during fire is also considered independent of the spatial coordinates inside the fire compartment. The temperature-time functions are monotonically increasing, disregarding the cooling phase that follows after the fully developed fire phase. When using standard fires, fire resistance is measured in minutes as the time until a predefined failure criterion is met. Depending on the member function and topology, fire resistance is defined based on the following criteria:

- R - load bearing function (ability of a structure or a member to sustain specified actions during the relevant fire, according to defined criteria),
- E - integrity function (ability of a separating element, when exposed to fire on one side, to prevent the passage through it of flames and hot gases and to prevent the occurrence of flames on the unexposed side),
- I - insulation function (ability of a separating element when exposed to fire on one side, to restrict the temperature rise of the unexposed face below specified levels).

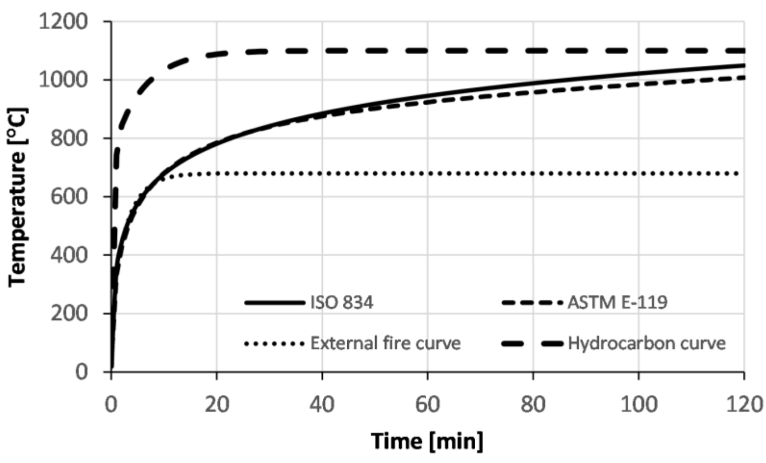

Figure 2 – Standard temperature-time fire curves

If a standard fire exposure is adopted, the load bearing function is required for a certain period of time, while, for parametric fire exposure, the structure should be able to withstand the fire action for the whole duration of the fire, including the cooling phase. Load bearing and integrity function can only be assessed through thermal stress analysis and/or experimental tests. The insulation function, on the other hand, can be determined only by means of the heat transfer. Usually, the insulation criteria is assumed to be satisfied if the average temperature rise over the whole of the non-exposed surface is limited to 140°C and the maximum temperature rise at and point of that surface does not exceed 180°C. The insulation criteria should prevent spontaneous ignition of the fuel load outside the fire compartment, preventing the fire spread to neighbouring structures and compartments.

The member is then classified using the markings denoting the resistance criterion and the minimum duration of the standard fire (in minutes) until failure criterion is met (e.g. "REI 60" provides load bearing, integrity and insulation function of a member for at least 60 minutes of standard fire exposure).

Although the use of nominal fire curves provides comparable solution for the fire resistance classification of members, a large deviation of the temperature-time evolution in comparison with real fires can be observed depending on the size of compartment, amount of fire load available, etc., often providing conservative solution, but also in certain cases, a solution which is not on the safe side. For a more detailed assessment of a fire that could develop in a specific fire compartment, parametric fire curves could be used, taking into account real geometric and material properties of the compartment, as well as ventilation conditions. Parametric fire curves, unlike standard fire curves, also include a cooling (decay) phase of the fire, providing temperature-time evolution during the whole course of fire. In the design procedure, when using parametric fire curves, it is necessary to prove that the structure possesses an adequate fire resistance during the entire duration of the fire, including the cooling phase, as well as the phase after the fire is completely extinguished. The latter, depending on the primary structural material, can be crucial, since for materials with large thermal inertia, peak temperatures in members, due to transient heat transfer effects, may occur when the fire is completely put out. This could be very important for the fire fighters, rescue service and first responders entering the building immediately after the event. This type of design approach is specific for performance-based design (PBD), which is increasingly in use nowadays, since unique contemporary architecture, use of modern materials and bold design solutions often cannot be comprehended using prescriptive design procedures.

An accurate fire model is fundamental part of fire-structure modelling. Although accurate models are still not available for post-flashover fires in non-combustible compartments, extensive research is being conducted in the last years.

In case a more accurate assessment of temperature development within the fire sector is needed, zone models, based on mass and energy conservation laws can be applied. Due to the complexity of the numerical calculation, iterative procedure is needed, conditioning the use of these models to specialized computer software.

An arbitrary fire compartment can therefore be analysed using different fire models, depending on the analysis objective and the level of uncertainty in case a fire occurs. An example of a residential dwelling under consideration is presented in Figure(s) 3 and 4. A three-room family apartment is considered as one fire compartment, where the geometry, layout, openings and the layers of enclosure are well defined (Table 1).

Table 1- Layers of the compartment enclosure

	Material	Thickness [cm]	Unit mass [kg/m^3]	Conductivity [W/mK]	Specific heat [J/kgK]
Floor	Ceramic tiles	1	2300	1.28	920
	Concrete screed	5	2200	1.40	1050
	Rock wool	15	60	0.037	1030
	Concrete	20	2300	1.60	1000
Ceiling	Mortar	1	1700	0.85	1050
	Concrete	20	2300	1.60	1000
	Rock wool	25	60	0.037	1030
	Concrete screed	5	2200	1.40	1050
Wall	Mortar	1	1700	0.85	1050
	Thermo-block	25	1400	0.61	920
	Rock wool	15	60	0.037	1030
	Mortar	1	1700	0.85	1050

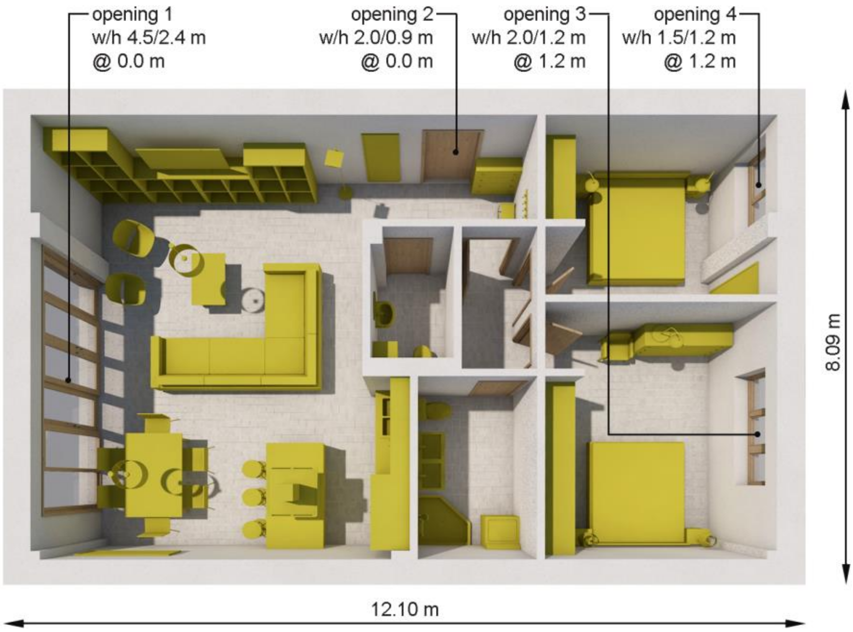

Figure 3 – Geometry and openings definition of the analysed compartment

Figure 4 – Boundary layers of the analysed compartment

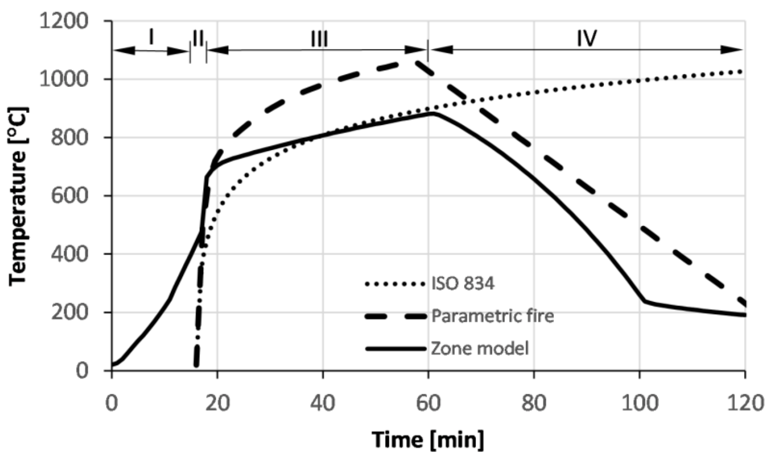

Figure 5 – Temperature-time curves corresponding to analysed compartment

Temperature-time curves developed for this particular compartment are presented in Figure 5. As previously described, for the subsequent structural fire analysis, different fire curves can be utilized, from simple (ISO 834), parametric (defined according to Annex A of EN 1991-1-2) to more complex, zone model, which incorporates compartment physical properties. It is important to outline that standard and parametric fire curves are post-flashover fires, which do not account for the duration of the growth phase following the ignition (stage "I"). If a simple comparison of the developed temperatures is needed, the origin of standard and parametric fire should be translated to the time of flashover (stage "II"), determined based on the zone model, developed in the computer software OZone [6, 7]. Standard fire curve, besides stage "I" and "II", also does not consider the decay phase of the fire (stage "IV").

Once a temperature evolution of the hot gas in the compartment is determined, it can be used as an input to determine heat penetration inside structural members in time. The thermal analysis outcome should provide temperature profiles in a space and time manner, needed e.g. for the determination of the insulation function of a separating member (bearing or non-load bearing), or for the assessment of strength and stiffness degradation of the bearing members, if the goal is to determine their load bearing function. Depending on the analysis goal, different fire resistance criteria can be assessed and the member/substructure/global structure fire resistance can be determined.

2. STRUCTURAL FIRE ANALYSIS METHODOLOGY

A structural fire design analysis should take into account the following steps as relevant [2]:

- selection of the relevant design fire scenarios,
- determination of the corresponding design fires,
- calculation of temperature evolution within the structural members,
- calculation of the mechanical behaviour of the structure exposed to fire.

A design fire scenario is a qualitative description of the fire development over time based on a fire risk assessment, which identifies key events that determine a fire and differentiates it from other possible fires. Typically, the process of ignition and fire growth, the state of a fully developed fire, cooling, as well as the environment within the building and systems that can affect the course of fire are defined.

Advanced calculation of temperature evolution within the structural members is based on the transient heat transfer analysis, by means of conduction, convection and radiation. The governing differential equation for conductive heat transfer is:

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right)=\rho c\frac{\partial T}{\partial t} \qquad (1)$$

Where:

$\lambda_{x,y,z}$ - is the thermal conductivity in all three directions (temperature dependent),

ρ - is the density of the material (temperature dependent),

c - is the specific heat (temperature dependent),

T - is the temperature,

t - is the time parameter.

The boundary conditions can be modelled in terms of both heat transfer mechanisms: convection and radiation.

The heat flux caused by convection is:

$$q_c = h_c (T_z - T_f) \tag{2}$$

Where:

h_c - is the coefficient of convection (for wall in room at ambient temperature the recommended value is $h_c = 4[\mathrm{Wm^{-2}K^{-1}}]$, while in case of room fire, its recommended value is $h_c \geq 25[\mathrm{Wm^{-2}K^{-1}}]$),

T_z - is the temperature at the boundary of the element,

T_f - is the temperature of the fluid around the element.

The heat flux caused by radiation is:

$$q_r = V\varepsilon\sigma_c (T_{z,a}^4 - T_{f,a}^4) = h_r (T_z - T_f) \tag{3}$$

$$h_r = V\varepsilon\sigma_c (T_{z,a}^2 + T_{f,a}^2)(T_{z,a} + T_{f,a}) \tag{4}$$

Where:

h_r - is the coefficient of radiation (temperature dependent),

V - is the radiation view factor (usually, $V = 1.0$),

ε - is the resultant coefficient of emission $\varepsilon = \varepsilon_f \varepsilon_z$, $\varepsilon_f = 1.0$ is the coefficient of emission for the surrounding fluid, ε_z is the coefficient of emission for the surface of the element, depending on the materialization (can be obtained from relevant Eurocode standards),

$\sigma_c = 5.67 \cdot 10^{-8} [\mathrm{Wm^{-2}K^{-4}}]$ - is the Stefan-Boltzmann constant,

$T_{z,a}$ - is the absolute temperature of the surface,

$T_{f,a}$ - is the absolute temperature of the fluid.

The solution to the differential equation is usually obtained using numerical procedures, e.g. finite element method (FEM).

Taking the radiation into account makes the problem nonlinear. This problem is solved by involving a new iterative procedure at every time step. The problem also becomes nonlinear when temperature dependent physical properties of the materials are assumed.

In that case, the conductivity and capacity matrix are defined at the beginning of each time step based on the temperature from the previous step.

Calculation of the mechanical behaviour of the structure can be determined if the temperature fields are obtained during fire. Usually, first a heat transfer is calculated and the mechanical response in time is determined by taking into account the temperature distribution in members, for a constant gravitational load. This means that temperatures are calculated on undeformed geometry, which, in case of structural systems, is sufficiently accurate. Although fully coupled thermal-structural analysis would model the actual physical phenomenon more realistically, the calculation procedure would result in finding a solution to the coupled sets of equations at each time step of the analysis. This introduces additional degrees of freedom and becomes computationally more demanding. Since response accuracy is practically unaffected, the structural analysis is conducted after the temperature fields are determined.

The structural model should be based on fundamental physical behaviour. It should be derived from continuum mechanics, starting from linear elasticity and expanding to include plasticity and damage evolution, beyond the linear elastic formulation. Nonlinearity is caused by the changes in material properties (both thermal and mechanical), as well as by the nonlinear temperature distribution in the element cross section. Also, for some types of structures, thermal expansion due to elevated temperatures can result in large deformations, which, for a realistic response assessment, requires taking into account geometric nonlinearity, as well. Given that analytical solutions are not developed, usually FEM is used.

Besides advanced calculation models, which can predict the overall response of structures in fire with sufficient accuracy, but are overly complicated and impractical for everyday engineering practice, Eurocode standards provide simplified methods for fire resistance assessment of individual elements. Depending on the structural material, a list of standards to be used for structural fire design is presented in Table 2.

Table 2- Layers of the compartment enclosure

EN	Part	Title
EN 1990	n/a	Basis of structural design
EN 1991	1-2	Actions on structures - General actions - Actions on structures exposed to fire
EN 1992	1-2	Design of concrete structures - General rules - Structural fire design
EN 1993	1-2	Design of steel structures - General rules - Structural fire design
EN 1994	1-2	Design of composite steel and concrete structures - General rules - Structural fire design
EN 1995	1-2	Design of timber structures - General rules - Structural fire design
EN 1996	1-2	Design of masonry structures - General rules - Structural fire design
EN 1999	1-2	Design of aluminium structures - Structural fire design

3. INFLUENCE OF FIRES ON STRUCTURES

Fire action is considered as accidental. Indeed, the temperatures that are developing in the structural members are affecting the mechanical resistance of entire structure, which, if not properly considered, could result in structural failure and collapse of entire building. High temperatures of the gases inside fire compartment, that are being developed when the fire load is ignited and burning cannot be suppressed, e.g. by the active fire protection measures (such as sprinklers), are heating the structural members by the heat transfer mechanism. Material properties that are affecting the temperature rise are thermal conductivity, specific heat and density. Thermal conductivity is a measure of the material ability to conduct heat. Heat transfer occurs at a lower rate in materials of low thermal conductivity than in materials of high thermal conductivity. For instance, metals typically have high thermal conductivity and are very efficient at conducting heat, resulting in faster penetration of heat and consequently, faster degradation of mechanical properties during fire. On the other hand, lower thermal conductivity, such as in concrete or timber structures, provide good insulating properties, which means that the temperature gradient is large and only the temperature of the outside layer is markedly increased, while the temperature on the internal parts of the element section remains comparatively low, retaining the load bearing capacity of a large portion of the section at close to ambient temperature level. Large temperature gradient induces high local stresses as a consequence of uneven thermal expansion of the part of the section. If those stresses exceed the strength of material, integrity of the section may be compromised. In reinforced concrete structures, high temperature gradient in the concrete cover (of the exposed member surfaces) could lead to chunks of concrete detaching from the member in a violent and explosive manner, phenomenon known as concrete spalling. One of the main parameters affecting concrete spalling in fire is the moisture content in members, since heating of the section would result in water vaporizing, increasing the pore pressure due to inability of free expansion, which induces additional pressures in the zones of interest. Other factors, such as the thickness of the concrete cover, size of the aggregate, rate of heating, porosity, permeability, as well as the applied stress level, could contribute to the evolution of spalling, which could be very hard to predict. If spalling occurs, reinforcement bars, otherwise protected by the concrete cover, will be directly exposed to burning flames. High thermal conductivity of steel would result in a faster heat transfer in the reinforcement, leading to a faster temperature rise and degradation of load bearing capacity, which could affect the overall resistance of the structure. It is essential, therefore, to assure that the probability of spalling occurring is minimized. For this purpose, the moisture content should be limited. Also, numerous efforts have been made in form of using additives in the concrete mix design, such as the polypropylene (PP) fibres in small amounts (ranging from 0 to 2% of the element volume), however, on the expense of concrete compressive strength degradation [9]. PP fibres, when uniformly distributed within concrete, play an active role in improving spalling resistance of concrete induced to elevated temperature. They have a relatively low melting point, after which they decompose (without producing noxious gases) and create space pockets, thus helping reduce the pressure in the pores during heating.

As opposed to concrete and wood, steel has relatively high thermal conductivity, resulting in fast heat transfer through the entire cross section and sudden turning point in terms of mechanical degradation of load bearing capacity. In order to postpone the temperature rise in steel during fire, assuring the desired fire resistance time, members are often protected by adding additional insulation materials (rock wool, plaster boards), or epoxy-based fire resistant coatings.

Specific heat of a material is the amount of heat to be supplied to a given mass of a material to produce a unit change of temperature. Materials with higher values of specific heat would therefore require larger amount of heat for the unit temperature change, resulting in material temperature change being delayed by a certain time phase compared to the external heat source temperature. In case of fire, this delay has beneficiary effect, postponing the temperature rise in structural elements and providing sufficient time for evacuation. However, at the later stages of fire, during the decay phase, when the gas temperature is getting lower, the temperature in elements might still continue to rise for some time, before starting to decline. This could be very dangerous for first responders and/or fire fighters entering the building after containing the fire.

Some materials, such as concrete and wood, exhibit density change at elevated temperatures, due to a loss of a free and chemically bounded water and/or chemical reactions that take place at higher temperatures. For steel, however, density remains constant in the entire range of expected temperatures in fire.

The essential requirement for structural fire safety may be observed by following various possibilities for fire safety strategies like conventional fire scenarios (nominal fires) or "natural" (parametric) fire scenarios, including passive and/or active fire protection measures.

Required functions and levels of performance can be specified either in terms of nominal (standard) fire resistance rating, generally given in national fire regulations or, where allowed by national fire regulations, by referring to fire safety engineering for assessing passive and active measures. Supplementary requirements concerning to the possible installation and maintenance of sprinkler systems; conditions on occupancy of building or fire compartment; the use of approved insulation and coating materials, including their maintenance are not given in this document, because they are subject to specification by the competent authority.

3.1. Concrete structures

Traditionally, concrete has been regarded as "fireproof" because of its incombustibility and relatively high thermal insulating properties. It is a versatile material and, if properly designed, can be inherently fire resistant. However, three main issues emerged from the concrete reaction to fire:

- deterioration of mechanical properties,
- damage caused by thermal deformations,
- spalling.

At the structural level, the development of fire engineering assessment methods came from the limitations inherent in the traditional prescriptive methods design. A set of conventions, rather than a rational approach with engineering tools, has its drawbacks, often being too conservative, but also not applicable for buildings of unique architectural and structural solution. In recent years, the whole package of conventions and requirements are re-examined in a holistic and scientific manner, advancing the field of structural fire engineering.

A full analytical procedure for structural fire design would take into account the behaviour of the structural system at elevated temperatures, the potential heat exposure and the beneficial effects of active and passive fire protection systems, together with the uncertainties associated with these three features and the importance of the structure (consequences of failure). At the present time it is possible to undertake a procedure for determining adequate performance which incorporates some, if not all, of these parameters and to demonstrate that the structure, or its components, will give adequate performance in a real building fire. However where the procedure is based on a nominal (standard) fire, the classification system, which calls for specific periods of fire resistance, takes into account (though not explicitly) the features and uncertainties described above. The prescriptive approach and the performance-based approach are identified. The prescriptive approach uses nominal fires to generate thermal actions, while the performance-based approach, using fire safety engineering, refers to thermal actions based on physical and chemical parameters.

3.2. Steel structures

The past two decades have seen great advances in understanding the behaviour of steel in fire, and it can now justifiably be claimed that more is known about steel than any other framing material in fire. Steel is isotropic homogeneous material. Unlike concrete, which is composed of aggregate and cement paste and has considerably different behaviour in tension and compression, affected by various parameters (water to cement ratio, aggregate size, etc.), or wood, having different mechanical behaviour in directions parallel and perpendicular to the grains, steel micro- and macroscale properties are the same.

Fire resistance of structural steel elements is a function of the size of the section, its degree of exposure to the fire and the load that it carries. The strength of hot rolled structural steel decreases with temperature. Following an extensive series of standard fire tests, the strength reduction has been quantified. Recent research has also shown that the limiting (failure) temperature of a structural steel member is not fixed but varies according to two factors, the temperature profile and the load.

For small, fully loaded hot rolled sections, exposed on all four sides, the inherent fire resistance without added protection can be as little as 12 minutes. For very large, hot rolled sections, lightly loaded and with some partial protection from concrete floor slabs on the upper flange, this can be as high as 50 minutes. Where the heated perimeter is further reduced by the method of the construction (e.g. shallow floor systems), up to 60 minutes inherent fire resistance can be achieved. This is considerably less compared to reinforced concrete structures. Desired fire resistance of steel is achieved not on the material level, but with the application of passive (protection materials and coatings) and active protection measures (“sprinkler” system). Nevertheless, these measures may or may not be sufficient to contain the fire from spreading and developing to its full potential. If the fire is not suppressed during the growth phase, eventually, flashover will occur (if sufficient oxygen is employed and enough fuel load is present), which will result in steel members mechanical resistance being reduced, affecting the stability and load bearing of the structure.

For everyday engineering practice, simplified methods for analysing structural fire resistance have been developed, taking into account strength and stiffness degradation at elevated temperatures [10].

3.3. Timber structures

Wood may be considered as the oldest structural material. In the last two centuries of the modern age, other structural materials, such as concrete and steel, have become dominant, due to their high performance and durability. Production of concrete and steel, however, results in a large CO_2 emissions in the atmosphere, which is becoming an increasingly significant issue regarding the impact CO_2 has on climate conditions. In recent years, construction industry is trying to reduce the level of emissions, by promoting the use of wood as structural material, resulting in a rise of timber building projects around the globe. This has raised a number of potential problems that could appear in timber structures if fire occurs, since, unlike concrete and steel, wood is combustible material and will contribute to the overall fuel load during fire.

Automatic fire sprinkler systems are the most effective way of improving the fire safety of all buildings. They are especially recommended for use in tall timber buildings. In some cases, the encapsulation of timber elements is necessary, either complete or limited. Complete encapsulation provides sufficient thickness of gypsum plasterboard or other similar material to prevent charring of wood in a complete burnout, providing the same level of fire resistance as a totally non-combustible material. Limited encapsulation is a more economical solution which will prevent any involvement of the structural timber in the fire until well into the burning phase, but may not guarantee complete burnout with no onset of charring. Also, layered encapsulation is possible, referring to structural elements made up of layers of wood and non-combustible materials, to improve the appearance and the fire resistance.

The main risk for external fire spread is from big flames coming out of windows in a fully developed compartment fire and spreading upwards along the façade. There is no consensus or procedures on how to determine the risk for the external flames reaching two stories above the compartment fire. For timber structures, the main interest is to verify that wooden façades can be used in a fire safe way, also as façade claddings on e.g. concrete buildings [11].

Once a fire scenario and design fire are determined, structural fire response can be calculated by using simplified or advanced calculation methods. Simplified method currently widely used in fire design, is the reduced cross-section method and reduced properties method, which is proposed in EN 1995-1-2 [12].

Once a fire is developed, members which are directly exposed begin to heat up, as a consequence of the heat flux acting on a surface of a member. Heat begins penetrating the cross-section of a member by means of heat transfer. The heat penetration is relatively slow, given the low values of thermal conductivity of timber. When the temperatures reach values between 250 and 350°C (usually a 300°C threshold value is adopted), charring of timber occurs. Charring is a chemical process of incomplete combustion of certain solids when subjected to high heat. Heat distillation removes water vapour and volatile organic compounds from the matrix. The residual black carbon material is char, as distinguished from the lighter coloured ash. Although the charring layer does not contribute to the load bearing capacity, it protects the remaining part of the cross-section, acting as an insulation, by slowing the process of heat penetration. If the integrity of the layer is preserved, the core of the cross-section remains relatively cold, preserving the mechanical properties at the ambient temperature level. Besides the char layer, an additional transition layer between the charring and unaffected layer is formed, with degraded mechanical properties.

In recent years, advancements are made in numerical modelling of structural response in fire, taking advantage of the computational resources that are constantly developing. Structural materials, such as concrete, steel and wood are being used simultaneously and are combined to comprehend for the strengths of each particular material. Contemporary structural systems, e.g. timber-concrete composite (TCC) slabs (Figure(s) 6 and 7), consist of a concrete slab (predominantly loaded in compression), supported by a timber beam (having higher strength in tension than concrete and being predominantly loaded in tension), with a connection between the two being in form of steel screws or plates (shear connection between the slab and the beam). Complex material behaviour and realistic modelling of the structural response is further complicated with the introduction of elevated temperatures, posing a challenge for engineers and researchers in the field. Further information on advanced numerical modelling of such systems can be found in [13].

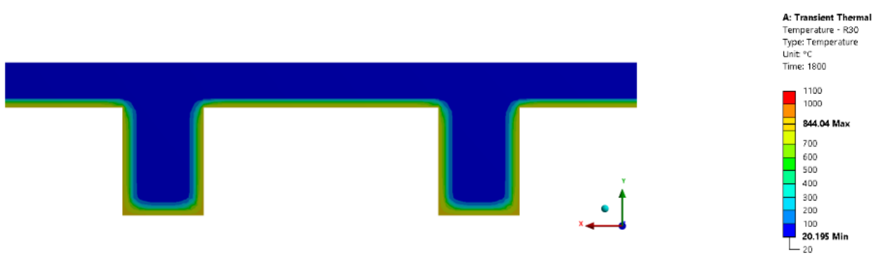

Figure 6 – Temperature profiles of TCC slab after 30 minutes of standard ISO 834 fire [14]

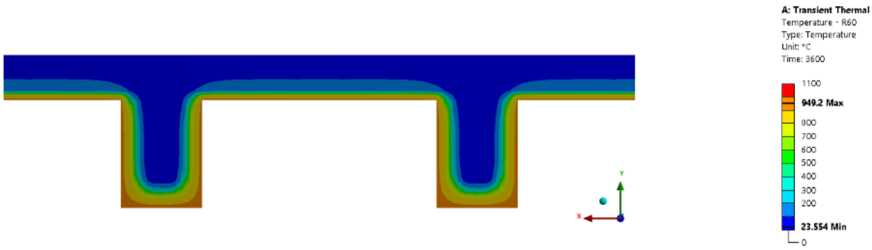

Figure 7 – Temperature profiles of TCC slab after 60 minutes of standard ISO 834 fire [14]

4. REFERENCES

[1] *EN 1992-1-2*, ”Design of Concrete Structures, General Rules, Structural Fire Design”, European Committee for Standardization, 2004.

[2] *EN 1991-1-2*, ”Actions on Structures, General Actions, Actions of Structures Exposed to Fire”, European Committee for Standardization, 2002.

[3] *CEB-FIP*, “Fire Design of Concrete Structures - Materials, Structures and Modelling”, Bulletin 38, International Federation for Structural Concrete (fib), 2007.

[4] *ISO 834*, “Fire Resistance Test - Elements of Building Construction”, International Standard 834, 1975.

[5] *ASTM E-119-08a*, “Standard Test Methods for Fire Tests of Building Construction and Materials”, American Society for Testing and Materials, 2008.

[6] J.-F. Cadorin, J.-M. Franssen, “A Tool to Design Steel Elements Submitted to Compartment Fires – Ozone V2. Part 1: Pre- and Post-Flashover Compartment Fire Model”, *Fire Safety Journal*, vol. 38, pp. 395-427, 2003.

[7] J.-F. Cadorin, D. Pintea, J.-C. Dotreppe, J.-M. Franssen, “A Tool to Design Steel Elements Submitted to Compartment Fires – Ozone V2. Part 2: Methodology and application”, *Fire Safety Journal*, vol. 38, pp. 429-451, 2003.

[8] A.H. Buchanan, “The Challenges of Predicting Structural Performance in Fires”, *Ninth International Symposium on Fire Safety Science*, Karlsruhe, Germany, pp. 77-90, 2008.

[9] S. Shihada, “Effect of Polypropylene Fibers on Concrete Fire Resistance”, *Journal of Civil Engineering and Management*, vol. 17, no. 2, pp 259-264, 2011.

[10] *EN 1993-1-2*, ”Design of Steel Structures, General Rules, Structural Fire Design”, European Committee for Standardization, 2002.

[11] A. Buchanan, B. Östman, A. Franghi, “Fire Resistance of Timber Structures”, A report for the National Institute of Standards and Technology, NIST, 2014.

[12] *EN 1995-1-2*, ”Design of Timber Structures, General Rules, Structural Fire Design”, European Committee for Standardization, 2003.

[13] Ch. Bedon, C. Chifliganec, I. Džolev, R. Pečenko, T. Hozjan, *Numerical Modelling of Timber Concrete Composite Structures in Fire - Guidance Document*, ETH Zürich, Switzerland, 2018.