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Analysis of Fire Resistance of Concrete Structures Based on Different Fire Models

Analýza požární odolnosti betonových konstrukcí s využitím různých modelů požáru

DOCTORAL THESIS

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Prague 2021

Declaration

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Thesis: Analysis of Fire Resistance of Concrete Structures Based on Different Fire Models

I hereby affirm that this doctoral thesis has been written by myself, under the supervision of prof. Jaroslav Procházka and Dr. Radek Štefan.

Some parts of this thesis have already been published in scientific papers co-authored by myself. All sources of information that have been used in the dissertation are acknowledged in the text and listed in the Bibliography, in accordance with the requirements given by the CTU Guideline[1].

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Martin Benýšek

Prague, 31 July 2021

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[1] *See Metodický pokyn č. 1/2009 O dodržování etických principů při přípravě vysokoškolských závěrečných prací (in Czech).*

Acknowledgements

I would like to thank my supervisor prof. Ing. Jaroslav Procházka, CSc. for guidance and encouragement.
Many thanks belong to my supervisor-specialist Ing. Radek Štefan, Ph.D. for his guidance, learnings, consultations, patience, willingness and ideas which led to the creation of several publications, software tools and to the creation of this thesis. Thank you Radek that you took me “under your wings”.

I am grateful to prof. Alena Kohoutková and doc. Lukáš Vráblík for employing me at the department of concrete and masonry structures.

I am grateful for the financial support provided by the following organizations:

- Grant Agency of the Czech Technical University in Prague
    - Grant No. SGS21/040/OHK1/1T/11 (research team member),
    - Grant No. SGS20/041/OHK1/1T/11 (research team member),
    - Grant No. SGS19/034/OHK1/1T/11 (principal investigator),
    - Grant No. SGS18/038/OHK1/1T/11 (principal investigator),
    - Grant No. SGS17/044/OHK1/1T/11 (principal investigator),
    - Grant No. SGS16/039/OHK1/1T/11 (principal investigator),
    - Grant No. SGS15/032/OHK1/1T/11 (principal investigator),
    - Grant No. SGS14/033/OHK1/1T/11 (research team member),
- Czech Science Foundation
    - Grant No. GA16-18448S, 2019-2018 (research team member),
- Ministry of the Interior of the Czech Republic
    - Grant No. VH20182020032, 2018-2020 (research team member),
    - Grant No. VG20132015114, 2013-2015 (research team member),
- Ministry of Education, Youth and Sports of the Czech Republic
    - Grant No. 1051412A000, 2014 (research team member).

I would also like to thank to company Bilfinger Tebodin Czech Republic, s.r.o., namely Ing. Josef Král, Ing. Pavel Chmelík, Ing. Jitka Pojkarová and Ing. Tomáše Perníček for support.

I am also grateful to Jakub Holan, Šárka Košťálová and Nicole Svobodová for many fruitful discussions.

Last but foremost, my gratitude goes to my girlfriend Martina.

Thank you all!

Abstract

The thesis is focused on the analysis of fire resistance of concrete structures based on different fire models. This thesis is divided into two main parts.

The first part of the thesis describes a brief overview of the problem; fire and its main phenomena, modelling of fire and models of fire are solved. The thesis is devoted to the deterministic and stochastic mathematical models of fire. At the end of the first part, methods for assessment of the fire resistance of structures are described.

The second part is focused on the author's results. The analysis of models of fire with the use of the deterministic fire models, simplified and advanced, and stochastic fire models was done. The stochastic approach was solved by the Monte Carlo and Latin Hypercube sampling method. For the analysis of the simplified models of fire, the in-house MATLAB or OCTAVE codes were used. For advanced models, the available software tools CFAST and FDS were used. The analysis subsequently led to the creation of the in-house supporting software tools FMC and DataPlot. The analysis of models of fire partly led to the focus on the heat release rate in detail. At the end of the second part, the analysis of the assessment of the structures is described. For simplified calculation assessment of the fire resistance concrete structures, the in-house code based on the one-dimensional strip method with the heat transfer was developed.

The main part of the thesis is the collection of the author's papers presenting achieved results. As the major benefit could be considered created software tools FMC and DataPlot which are freely available for download. And further the performed analysis of models of fire and assessment of structures that were published.

Keywords

Concrete Structures; Fire Resistance; Models of Fire; Fire Dynamics Simulator (FDS); Consolidated Fire and Smoke Transport (CFAST); Temperature-time Curves; Software Tools; MATLAB, Performance-based design

Abstrakt

Práce se zabývá analýzou požární odolnosti betonových konstrukcí s využitím různých modelů požáru. Práce je rozdělena na dvě základní části.

V první části práce je popsán úvod do problematiky, je řešen požár a jeho hlavní jednotlivé jevy, jak se požár modeluje a jaké jsou modely požáru. Práce se věnuje jak deterministickým, tak stochastickým matematickým modelům požáru. V závěru první části této práce jsou popsány metody posuzování požární odolnosti konstrukcí.

Druhá část je zaměřena na autorovy výsledky. Byla provedena analýza modelů požáru s využitím deterministických modelů požáru, zjednodušených i zpřesněných, a stochastických modelů požáru, které byly řešeny pomocí metody Monte Carlo a Latinských Nadkrychlí. Pro analýzu zjednodušených modelů požáru byly využity vlastní zdrojové kódy vytvořené převážně v prostředí MATLAB nebo OCTAVE. Pro zpřesněné modely byly využity programy CFAST a FDS. Analýza následně vedla k vytvoření vlastních podpůrných softwarových nástrojů FMC a DataPlot. Analýza modelů požáru částečně vedla i k detailnějšímu zaměření se na rychlost uvolňování tepla. Závěr druhé části je věnován analýze posuzování požární odolnosti konstrukcí. Pro zjednodušené výpočtové posuzování požární odolnosti betonových konstrukcí byl vytvořen vlastní zdrojový kód, který je založen na 1-D proužkové metodě s vlastním vedením tepla.

Součástí práce je také soubor vědeckých článků prezentující dosažené výsledky. Za hlavní přínos lze uvažovat vytvořené softwarové nástroje FMC a DataPlot, které jsou volně dostupné ke stažení. A dále provedené analýzy modelů požáru a posuzování konstrukcí, které byly následně publikovány.

Klíčová slova

Betonové konstrukce; Požární odolnost; Modely požáru; Fire Dynamics Simulator (FDS); Consolidated Fire and Smoke Transport (CFAST); Teplotní křivky; Softwarové nástroje; MATLAB, Požárně inženýrský přístup

Content

1. Introduction

In current engineering practice, the design of the fire engineering tasks (e.g. development of fire, assessment of the fire resistance of structures) is mostly solved by the simplest model of fire – the standard temperature-time curve (ISO 834), or other nominal temperature-time curves [1], [2]. These curves are only a function of time. Their applicability is very simple but, in most cases, too conservative. Structures are mostly assessed for fire resistance by the tabular values [3]. This approach is appropriate for lower required fire resistance but it is uneconomical for a higher requirement.

If the required fire resistance is higher or if the sophisticated task of the fire safety engineering is solved, it is more convenient to use advanced models of fire such as e.g. parametric temperature-time curves, zone or computational fluid dynamics models [2], [4]–[8].

The deterministic methods are mostly used in fire engineering practice because of their simplicity. However, it is necessary to consider that fire as a phenomenon is not in itself deterministic. It is a somewhat random phenomenon and it is not possible to solve it always only by the deterministic approach. In these cases, the probabilistic approaches are suitable.

Before setting the groundwork for the complete subject of fire safety engineering and its influence on the overall planning, design and construction of building structures, it is necessary to attempt to define what is meant by ‘fire safety engineering’. There is, as yet, no absolute definition, although the following may be found acceptable: *Fire safety engineering* can be defined as the application of scientific and engineering principles to the effects of fire in order to reduce the loss of life and damage to property by quantifying the risks and hazards involved and provide an optimal solution to the application of preventive or protective measures [9].

With the assessment of fire resistance, it is a similar issue as with the selection of a suitable fire model. For a simple application, unsophisticated structures and for low required fire resistance, simplified methods are convenient. In the case of buildings with specific purposes (or specific types of buildings) or if the required fire resistance is high, the advanced calculation methods, with a combination of the appropriate fire scenario, are more convenient.

For modelling of fire or assessment of fire resistance of structures, there are available many programs. Nevertheless, these programs are not perfect and do not offer everything that users need. This opens the way for the creation of own software tools which can subsequently effectively support and complement available programs.

The goals of the thesis:

First of all, it is necessary to mention that fire, fire engineering, structures, assessment of structures affected by the fire are very extensive topics and it was not in the author’s power in the thesis, nor the author’s goal, to solve everything that the academic community and engineering practice needs.

The main goal was to do “one small step forward”.

The objective was to perform an analysis of models of fire and an analysis of the method for assessing fire resistance of structures with the use of deterministic and probabilistic approaches. The goal was to compare deterministic and probabilistic approaches on a specific example with overlap to the assessment fire resistance of structures. And afterwards, create a set of software tools that could lead to simplification of the whole process of design of structures or buildings in fire safety engineering.

1.1 Motivation

Several motivations for this thesis were there. The author was aimed at similar work in bachelor and master theses during the previous study and there was an effort to continue in the same research. There was also a motivation to work and study under the excellent supervision of prof. Procházka and Dr. Štefan.

The main motivation was the fact that many times in technical literature and papers, modelling of fire or modelling of structures are solved separately, not as a combination of these two branches.

And, of course, the fire is a very interesting phenomenon.

1.2 Outline of the thesis

This thesis is organized as a collection of several papers supported and connected by the following chapters.

Chapter 1 provides the introduction, defined goals and the motivation for this thesis.

Chapter 2 is focused on the state of the art. The chapter is divided into four subchapters. In subchapter 2.1, the description of the fire, its basic phenomena, fire dynamics, the flashover and modelling of fire is described. In subchapter 2.2, models of fire, basic types and validation and verification, are listed. In more detail, the mathematical fire models are solved in subchapter 2.3 where nominal temperature-time curves and natural fire models are described. In subchapter 2.4, the fire resistance assessment options, namely tabular assessment and simplified and advanced calculation methods, are stated.

Chapter 3 is aimed at the author's results. The division of the chapter is the same as Chapter 2. The references are referred to the collection of the author's published papers.

Chapter 4 is focused on the discussion and conclusion of the thesis.

After the bibliography, the author's published papers are listed. The papers are chronologically arranged and create the main part of the thesis.

2. Brief overview of the problem

Next chapters (chap. 2.1, 2.2, 2.3, 2.4) introduce the state of the art. Chapters are divide into four basic areas: 1) Fire; 2) Fire models; 3) Mathematical models of fire; 4) Assessment of structures exposed to fire.

2.1 Fire

2.1.1 Description of fire

Fire development is mainly affected by an amount of flammable material and its distribution in a space. Another important factor is a supply and an approach of the oxygen. For a fire development, it is needed so-called the triangle of fire, where on its sides there are an ignition temperature, flammable material and oxygen availability. These three factors are in a mutual interaction. If a space, where a fire starts, is closed, its intensity will decrease which means the gas temperature in a space will be low. In some cases, a window can crack due to the temperatures. It depends on a layout, flammable material and type of window panes. Thus, a space will supply the oxygen which will subsequently support a combustion. The fire curve, see *Fig. 1*, represents a possible process of fire. It describes the average temperatures, which can occur during the fire.

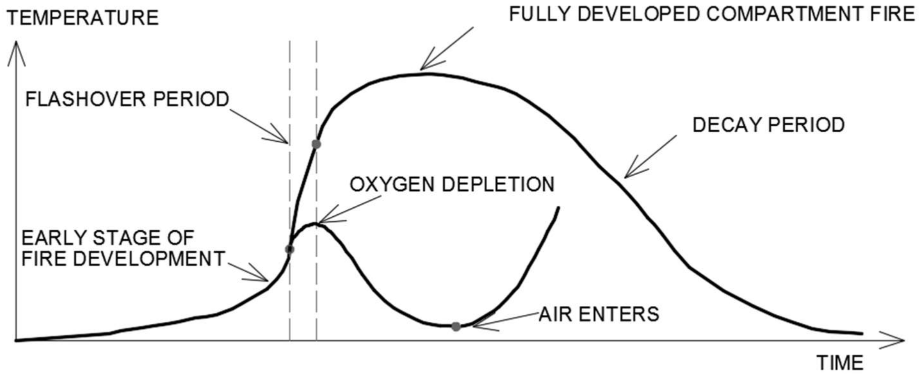


Fig. 1 – Phases of fire [10].

The first phase of the fire after ignition is called the early stage of fire development. After the flashover effect it occurs the phase of fully-developed compartment fire, which gradually passes, when burns 70 – 80 % of a fuel, to the decay phase A person cannot survive a flashover. From the point of view of savings lives, it is necessary to prevent a creation of the flashover (spatial ignition). The flashover effect may not develop in a fire. Its creation can prevent the active fire safety systems, such as the sprinkler systems or fire ventilation [7], [10]–[12].

Most fires release the flammable gasses. The term "fuel", required for a combustion, can be defined as a state of matter in a form of gases, liquids and solids, burning in air. If we consider burning of solids, for example a piece of furniture in a room – for almost every type of solids, chemical decomposition (pyrolysis) is responsible for yielding products, which are low molar weight, that can volatilize from a surface and enter to a flame as a fuel, see Fig. 2 [8].

The fire has its dynamics. This phenomenon is shortly described in the next chapter.

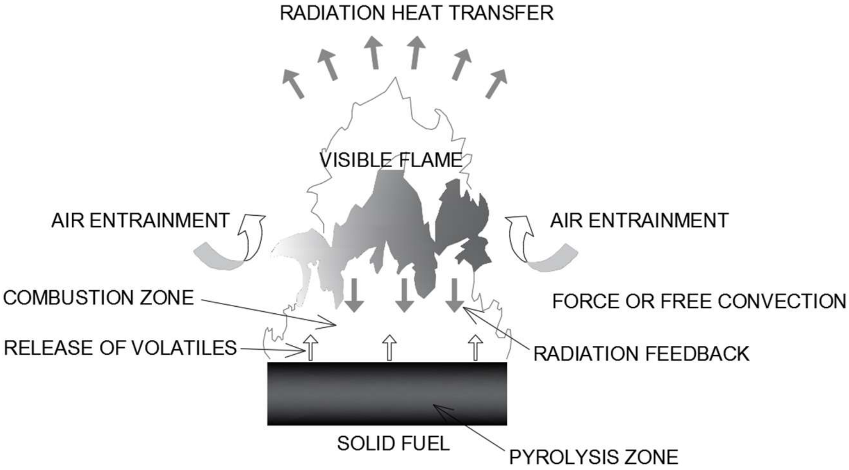


Fig. 2 – Scheme of burning solid [8].

2.1.2 Fire dynamics

Fire dynamics in a fire safety engineering serves to obtain the numerical expression of parameters for a fire safety design, thereby it idealizes a real fire development, which may occur in the building. The idealization of the fire process is denoted as a design fire and it is characterized by these variables:

- rate of heat release,
- rate of smoke,
- fire sizes,
- gas temperature in a space,
- time to critical events (for example flashover effect).

The fire dynamics is well described in literature, e.g. [6], [7], [10], [11].

2.1.3 Spatial ignition – flashover effect

The flashover effect is a very important and significant phenomenon. It is defined as a state when the whole surface of an enclosure space is full of a burning of the flammable materials. The flashover is assessed as a transition between two states then as a precisely defined event. Initial conditions for the flashover are sufficient fuel and sufficient ventilation so that the fire can develop to the required size. The ceiling must also be able to hold the flue gases and the geometry of the room must allow so that the radiant heat flux of a hot layer reach such an extent so that all flammable surfaces in the room could ignite in a few second. Flashover usually occurs if the temperature of the hot layer reaches the value 500 – 600 °C or if the density of heat flux on the floor is approximately 20 kW/m^2 [2], [6].

The flashover effect can be determined by the simple equations – Babrauskas model, eq. (9.9) [7], Thomas model, eq. (9.10) [7] and McCaffrey et al. model, eq. (9.19), (9.20a), (9.20b) [7] are available.

2.1.4 Modelling of fire

Fire can be described by a model. Types of models are described in the next chapter. Modelling of fire is an approach for predicting various aspects of fire phenomena mainly in compartments. It approximates the reality [6].

2.2 Fire models

2.2.1 Basic types of fire models

The basic types of fire models are:

- physical models,
- mathematical models,
    - probabilistic [13]–[22],
    - deterministic [9], [23]–[32].

Physical modelling has provided the basis for understanding of the fundamentals of fire dynamics. Many problems in other branches of engineering were resolved by the same approach. It is about applying procedures or phenomena which permit full-scale behaviour to be predicted from the results of small-scale laboratory experiments. For example, fire resistance testing in fire laboratories is the species of physical models. The full-scale or small-scale testing (or some kind of scaling) can be applied [7].

The mathematical model can be probabilistic ("simply say – same inputs, different results") or deterministic ("simply say – same inputs, same results"). For the probabilistic approach of fire models, the Monte Carlo method or Latin Hypercubes sampling are commonly applied, see e.g. [13]–[22].

Deterministic approach, which become predominant in the last decades, is as the probabilistic model a subgroup of a mathematical model. The results are determined by using the input data. If the input data are the same, the results will always be the same. The fire is solved by the mathematical equations which describe the physical and chemical processes. The range of deterministic fire models can be wide, from very simple models, which have a dependence on a few physical values to complex models that describe fire behaviour in one or more rooms. Solving of the fire scenarios can be very different in time. Among basic and well-known deterministic models belongs zone models and field models – called CFD models (Computational Fluid Dynamics), see Fig. 3 [33].

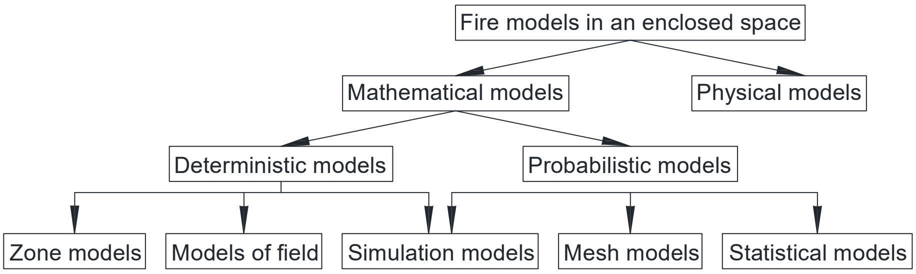


Fig. 3 – Types of fire models [33]

Modelling of fire does not serve only for the simulation of fire, but in case of using advanced fire models, it is possible to simulate e.g. smoke development, toxicity, heat transfer or some fire devices like fire alarms and detections, smoke ventilation, or sprinkler systems. Afterwards, it is possible to use some (or combine with fire simulations) additional applications e.g. for the evacuation of people, see Fig. 4.

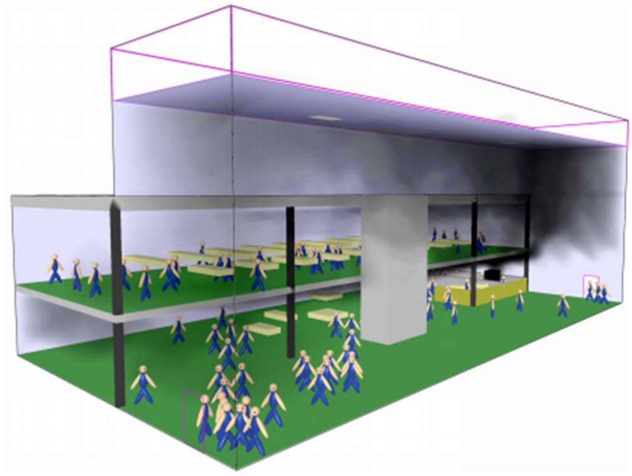


Fig. 4 – *Evacuation in FDS+EVAC* [34]

2.2.2 Validation of the fire model

The authentication of the fire models is performed by the validation and verification.

Validation is a process serving to determine how good the mathematical model predict actual physical phenomenon. It usually contains a comparison of a model with an experimental measuring, quantification of differences measurement uncertainty and inputs and it decides if the model is appropriate for given application. Verification is a process in which is controlled a modelling space, correctness of algorithm and code and accuracy of the mathematical calculation. It can be used a standard for this checking. Basic techniques for detecting model errors and shortcomings are mentioned in Tab. 1 [35].

Tab. 1 – Techniques for detecting model errors and shortcomings [35]

Techniques	**Incorrect algorithms**	**Incorrect constants**	**Missing processes**	**Inappropriate numerical techniques**	**Coding errors**
Theoretical review	X	X	X	X	
Analytical tests			X		X
Comparison with reference programs	X	X	X		
Experimental verification		X	X		X
Code checking					X

2.3 Mathematical models of fire

2.3.1 Nominal temperature-time curves

The temperature-time curves often describe the phase of a fully developed fire – after the flashover with a characteristic rapid increase of temperatures. The nominal temperature-time curves solve only fire developing in a fire compartment (or e. q. in tunnels) and they are usually used for an assessment of fire resistance of structures and they work very well for concrete structures for the fire resistance up to 60 minutes. If the fire resistance is higher, more sophisticated fire models are more convenient.

They are the simplest fire models, which are commonly used. The temperature-time curves are very conservative because of not considering the decrease phase, ventilation and materials of structures etc. They are only a function of time. Nominal temperature-time curves are well known and they are detailed described in many publications [1], [2], [6], [7], [36], [37].

Fire scenario recommendation is described for example in [37], see Tab. 2.

Tab. 2 – Fire scenario recommendation [37]

HRR [MW]			**Road, examples vehicles**	**At the fire boundary**
Risk to life		5	1-2 cars	ISO 834
		10	Small van, 2-3 cars	ISO 834
		20	Big van, public bus, multiple vehicles	ISO 834
		30	Bus, empty HGV	ISO 834
	Risk to construction	50	Combustibles load on truck	ISO 834
		70	HGV load with combustibles (approx. 4 tons)	Hydrocarbon
		100	HGV (average)	Hydrocarbon
		150	Loaded with easy comb. HGV (approx. 10 tons)	RWS
		200 or higher	Limited by oxygen, petrol tanker, multiple HGVs	RWS

Notes:
1) HGV – Heavy goods vehicle
2) ISO 834, Hydrocarbon, RWS are the nominal temperature-time curves, see chap. 2.3.1 or 3.3.1)

2.3.2 Natural fire models

Natural fire models are divided into two basic types – simplified and advanced fire models.

The simplified fire models are based on the specific physical parameters with limited areas of use. It is assumed a uniform distribution of temperatures as a function of time during the fire in fire compartments. Localised fires assume a non-uniform distribution of temperatures as a function of time. These models are as follows:

- parametric temperature-time curves, Annex A [2], or other parametric temperature-time curves [4], [5],
- thermal actions for external members – simplified calculation method, Annex B [2],
- localised fires, Annex C [2],
- fire load density, Annex E [2],
- rate of heat release, Annex E [2].

The advanced fire models should consider the gas properties, mass exchange and energy exchange. Among these advanced fire models belong:

- one-zone model, which assumes a uniform, time dependent heat distribution in a fire compartment,
- two-zone model, which expects an upper layer with a time dependent thickness and with a time dependent uniform temperature and a lower layer with a time dependent uniform and lower temperature,
- the computational fluid dynamic model, well known as a CFD model, which determines a development of temperatures in a compartment completely time and spatially dependent Annex D, [2].

Zone models express an ideal process of fire in an enclosed space and it is a traditional methodical process for determining of a simplified spread of combustion products. Zone models concept uses empiricism – it is based on physical phenomena operating in real fires. One-zone model assumes a creation of the flashover effect. Two-zone model assumes two separate zones, see Fig. 5. Two-zone model becomes one-zone model if the temperatures in an upper layer exceed 500 °C or if the smoke layer height covers 80 % of the fire compartment height.

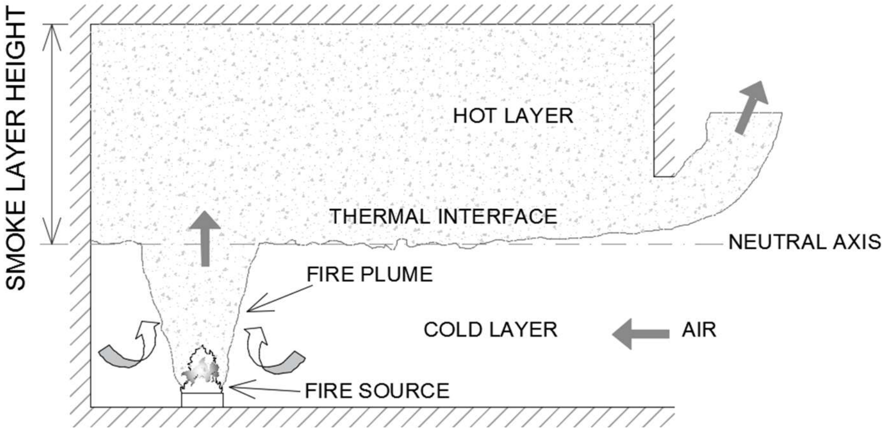


Fig. 5 – Schematic representation of two layers assumption taken in zone modelling [8]

The application of the zone fire models is dependent on the type of solved tasks. Initially, the model describes the process of fire in a room before the flashover effect – there are two zones – two-zone fire model. This model divides a room during the fire to two homogeneous zones, where each zone has the same density, temperature and concentration of gases. The lower layer is cooled by an intake air and the upper layer is warmed by an upward flow of combustion products of the fire – so-called the fire plume [2], [8], [38]–[41].

CFD techniques are used in numerical simulations of the mathematical fire models and it is the most sophisticated available method. The main principle is based on the division of the calculated area to an amount of three-dimensional cells, so-called “control volumes”. Zone models assume only two control volumes, CFD models have n-control volumes. Basic equations are based on the conservation of mass, energy, momentum and particle composition – so-called Navier-Stokes equations (N-S equations). These N-S equations are three-dimensional, time dependent, non-linear partial differential equations. This numerical approach encompasses the whole history of fire which includes a local development of variables. The advantage of CFD models is their general use, the disadvantage is an amount of inputs and high hardware requirements. The temperatures in a fire compartment are time and spatially dependent [2], [33], [38]–[40], [42], [43].

2.4 Assessment of structures exposed to fire

All structures must be assessed for the effects of fire. As was mentioned above, fire is an undesirable phenomenon which can highly affect structures. Fire resistance is an ability to withstand the fire for a specific period of time. For the structures, firstly, it is necessary to specify their function, if they are load-bearing and/or a fire separation. Secondly, if they are assessed as a separate item, part of the structure or as a whole structure.

Verification of fire resistance can be, in general, proved by the condition of reliability in terms of the time, strength or temperature.

In time assessment, the required and actual fire resistance are compared (e.g. in a case of a column $R_{actual}\ 30 > R_{required}\ 15$). In strength assessment, the applied load in a fire situation and the ultimate strength in a fire situation are compared (e.g. applied bending moment $M_{Ed,fi} = 15$ kNm < ultimate strength in fire situation $M_{Rd,fi} = 30$ kNm). In temperature assessment, the actual temperature and the critical temperature of a given material or structure are compared (e.g. actual temperature in fire situation $\theta_{actual} = 400$ °C < critical temperature in fire situation $\theta_{critical} = 500$ °C).

Three basic methods may be applied for the determination of the fire resistance of concrete structures:

- tabular assessment,
- simplified calculation methods,
- advanced calculation methods.

These methods are shortly described in the next chapters.

Although concrete is non-flammable material, during the high temperatures the concrete strength and reinforcement strength is decreased and the integrity and cohesion are compromised.

The appropriate method should be determined with respect to the type of the material (wood, concrete, steel etc.) in relation to the required fire resistance. If the calculation methods are used, the adequate fire scenario must be chosen, see chap. 2.2, 2.3 of this thesis, see also [2], [9], [23], [44].

2.4.1 Tabular assessment

Tables were assembled based on the empirical basis and they were confirmed by the experience and theoretical evaluation of the experiments. The values are derived from approximate conservative assumptions for more common load-bearing members. Table values correspond to the effect of the standard temperature-time curve (ISO 834). If the member fulfils the table values, it is not necessary to do any additional assessment relating to the shear, torsion etc. However, additional requirements must be applied in a case when the axis distance of reinforcing or prestressing steel from the nearest exposed surface is equal or higher than 70 mm – the surface reinforcement must be added.

For tabular assessment, several values are needed to be assessed. It is the simplest approach for assessment of the fire resistance. Table values are in many cases limited by the additional conditions.

The example of the table assessment is shown in Fig. 6. The fire resistance of the items is fulfilled if the minimum values of b_{min} (minimum width) and a_{min} (minimum axis distance of reinforcing or prestressing steel from the nearest exposed surface) in EN 1992-1-2 [2] are smaller than the real values of b and a [3], [44].

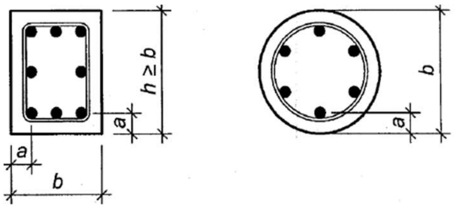


Fig. 6 –Schematic representation of the assessment by the table values [3]

2.4.2 Simplified calculation methods

Several simplified calculation methods are available:

- 500 °C isotherm method (Annex B.1 [3]),
- zone method (Annex B.2 [3]),
- buckling of columns under fire conditions (Annex C [3]),
- calculation methods for shear, torsion and anchorage (Annex D [3]),
- Simplified calculation method for beams and slabs (Annex E [3]).

All these methods are applicable with the standard temperature-time curve (ISO 834). Only the 500 °C isotherm method can be applied with the parametric fire [2], [3].

2.4.3 Advanced calculation methods

Advanced calculation methods for the assessment of concrete structures exposed to the fire are not described in detail in EN 1992-1-2 [3]. Only general principles are mentioned there which must be fulfilled. These methods must allow a realistic analysis of structures exposed to fire.

These methods should contain calculation models for determination:

- the development and distribution of the temperature within structural members (thermal response model);
- the mechanical behaviour of the structure or of any part of it (mechanical response model) [3].

Advanced methods may be applied with any temperature-time curve (model of fire) assuming that the material properties are known for the required temperature range and the heating rate. Only material properties for heating rate 2 - 50 K/min are given in EN 1992-1-2 [3].

For simplified and advanced methods, heat transfer in structures must be known. Heat transfer has three basic items – conduction, convection and radiation. Heat transfer is well described in [45]–[50].

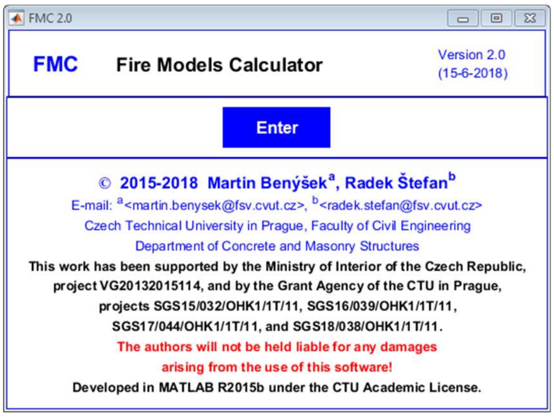
Advanced calculation methods for the assessment of concrete structures exposed to the fire were not be used in this thesis.

3. Author’s results

3.1 Fire

3.1.1 Spatial ignition – flashover effect

As was mentioned in the state of the art of this thesis, see chap. 2, flashover effect is a significant phenomenon. It can be determined by the simple calculations. These calculation models are occupied, e.g., in the Fire Models Calculator tool, see Fig. 7, Fig. 8, see [Paper 1, Paper 7] and they can determine the value of the heat release rate which is needed for the flashover effect. This calculation may help with the determination of the appropriate fire model. In a case that the fire reaches the flashover energy, the nominal temperature-time curves, parametric temperature-time curves or Computational Fluid Dynamics models are suitable for next analysis; if not, the localised fire or two-zone model may be considered. However, the selection of the appropriate fire model is more sophisticated. It also depends whether there is a tendency to reduce the requirements for the fire design, or if the performance-based design is needed.



FMC Fire Models Calculator

Version 2.0
(15-6-2018)

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This work has been supported by the Ministry of Interior of the Czech Republic, project VG20132015114, and by the Grant Agency of the CTU in Prague, projects SGS15/032/OHK1/1T/11, SGS16/039/OHK1/1T/11, SGS17/044/OHK1/1T/11, and SGS18/038/OHK1/1T/11.
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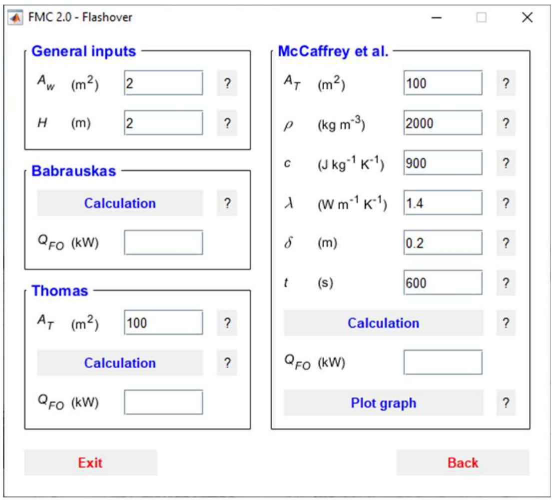
Fig. 7 – Initial window of the FMC software tool [51]



General inputs
A_w (m^2) 2
H (m) 2

Babrauskas
Q_{FO} (kW)

Thomas
A_T (m^2) 100
Q_{FO} (kW)

McCaffrey et al.
A_T (m^2) 100
ρ (kg m^{-3}) 2000
c (J kg^{-1} K^{-1}) 900
λ (W m^{-1} K^{-1}) 1.4
δ (m) 0.2
t (s) 600
Q_{FO} (kW)

Fig. 8 – FMC: Flashover [51]

3.1.2 Modelling of fire

Modelling of fire is very important, interesting, and significant in fire engineering. Advanced models of fire are the future in designing buildings. For modelling of fire, mainly the *FDS – Fire Dynamics Simulator* (based on computational fluid dynamics fire model) and *CFAST – Consolidated Fire and Smoke Transport* (based on zone fire model) were used. These software tools were chosen because they have big support from developers, they are user-friendly, and are applicable for commercial or non-commercial uses. Also, these software tools are very favourite for scientific purposes.

For author’s researches, programs FDS and CFAST were supplemented by the own tools (or scripts), mainly created in MATLAB or OCTAVE.

3.2 Fire models

As was mentioned in chap. 2.2, fire models can be physical or mathematical. Physical models of fire were not used for this thesis. The thesis was focused mainly on mathematical models of fire.

Probabilistic and prescriptive models were studied and explored. For probabilistic models (discussed e.g. in our previous work, see [Paper 4] or [52]), the Latin Hypercubes Sampling method and the Monte Carlo method were used. They were applied for the determination of the parametric temperature-time curve with subsequent evaluation of the fire resistance of a structure, see Fig. 9.

Based on results, Latin Hypercubes sampling is more advantageous because fewer curves are needed for sufficient results. Thanks to probabilistic approach, more possible results can be tested and, of course, the subsequent assessment of the fire resistance of structures captures more options of the possible results which leads to higher reliability of construction items, see [Paper 4]. It is generally known that a fire can behave differently than prescribed by a deterministic model.

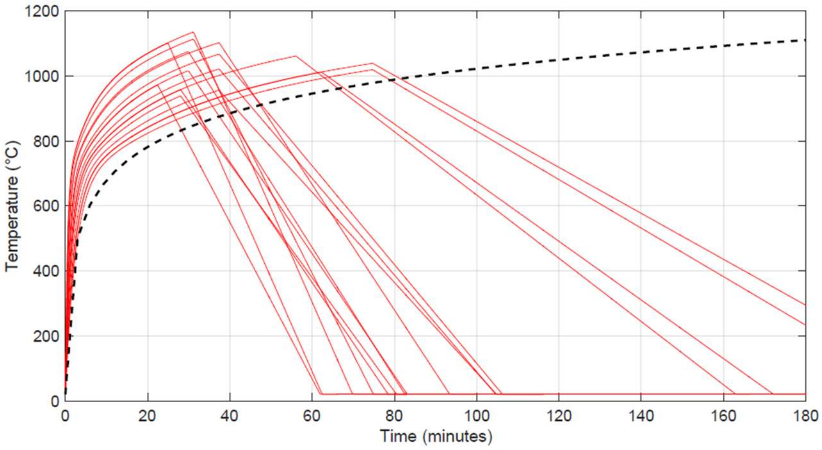


Fig. 9 – Example of the fire models: Probabilistic model represented by the parametric temperature-time curves according to EN 1991-1-2 (red curves) solved by the Latin Hypercubes sampling compared with the standard temperature-time curve according to EN 1991-1-2 solved as a deterministic fire model (black curve) [Paper 4]

For deterministic models (discussed e.g. in our previous work [Paper 1, Paper 2, Paper 3, Paper 5, Paper 6, Paper 10, Paper 11, Paper 12]), all frequently used fire models were applied and compared in different cases. Calculations were commonly supplemented by the own software tools [51], [53] and [Paper 1, Paper 2, Paper 3, Paper 6, Paper 7] or, in some cases, by the own calculation code created mostly in MATLAB (e. g. for thermal analysis of the concrete panel, or for fire resistance assessment, see [Paper 4, Paper 6]). The example of the results is shown in Fig. 10.

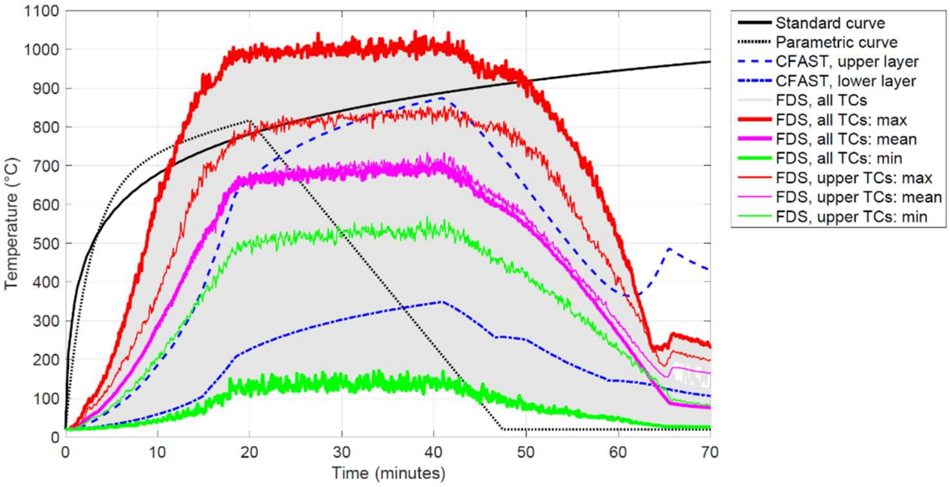


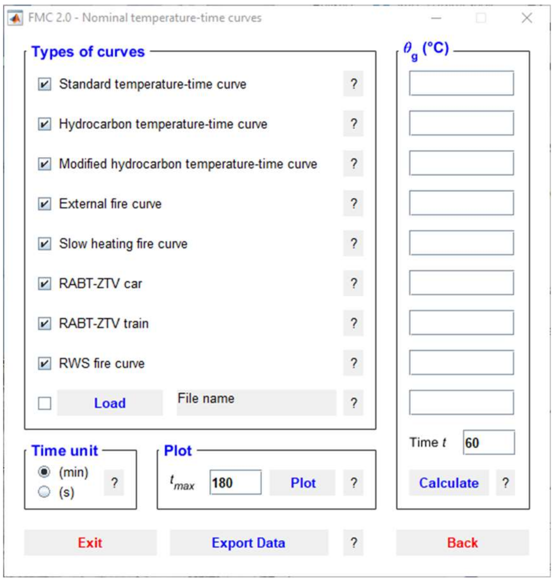
Fig. 10 – Example of the fire models: Deterministic model represented by the standard temperature-time curve, parametric temperature-time curve, zone model, CFD model according to EN 1991-1-2 [Paper 6]

Deterministic models are quite simple if the simplified methods are used. Compared to that, the advanced models are really sophisticated and sometimes it is challenging to use them. The biggest problem is that a lot of inputs is hard to find in literature or to determine. And, of course, CFD models are time-consuming. Zone models seem to be very useful because they give better results than simplified methods and they calculate the fire simulations in only a few minutes. But they cannot be applied for every fire-engineering problem as CFD. CFD is a more general tool.

3.3 Mathematical models of fire

3.3.1 Nominal temperature-time curves

In engineering practice or for academic-scientific purposes, nominal temperature-time curves are commonly used. It is the simplest fire model. Nominal temperature-time curves can by determined by the tool – Fire Models Calculator [51], see Fig. 11, Fig. 12. This tool is described in detail in [Paper 1, Paper 7].



FMC 2.0 - Nominal temperature-time curves

Types of curves

☑ Standard temperature-time curve ?

☑ Hydrocarbon temperature-time curve ?

☑ Modified hydrocarbon temperature-time curve ?

☑ External fire curve ?

☑ Slow heating fire curve ?

☑ RABT-ZTV car ?

☑ RABT-ZTV train ?

☑ RWS fire curve ?

☐ Load File name ?

θ_g (°C)

Time unit
● (min)
○ (s) ?

Plot
t_{max} 180 Plot ?

Time t 60
Calculate ?

Exit Export Data ? Back

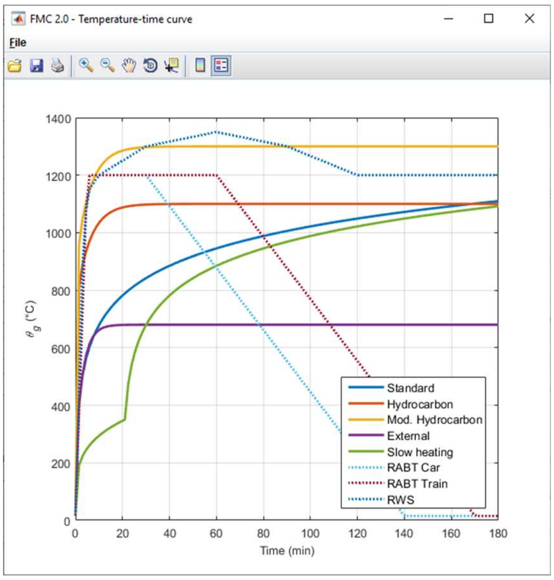


Fig. 11 – FMC: Nominal temperature-time curves [51]

Fig. 12 – FMC: Nominal temperature-time curves - output [51]

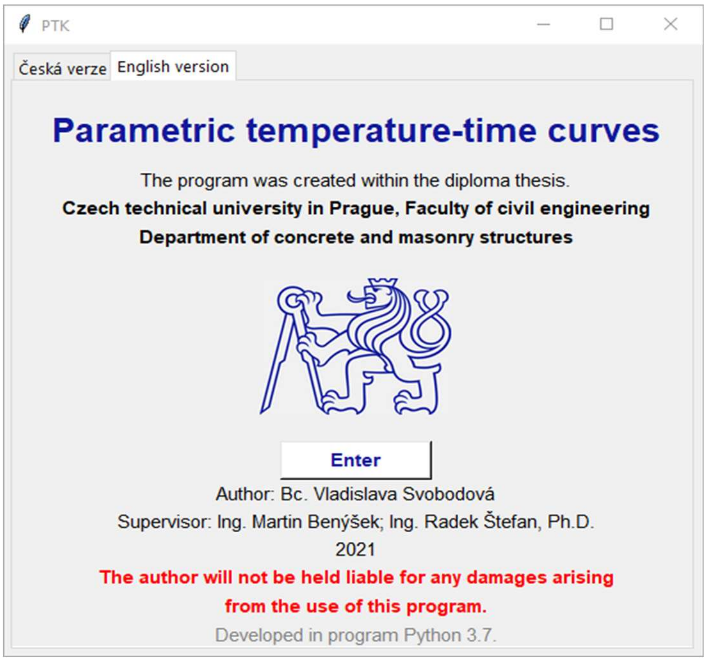
3.3.2 Natural fire models

Simplified fire models contain two significant and often used models which were studied by the author of this thesis – the parametric temperature-time curve and the heat release rate.

The parametric temperature-time curves are very useful for small compartments. They can be easily used with the prescriptive [Paper 1, Paper 6], [54] or the probabilistic approach [Paper 4] or [52]. The parametric temperature-time curves are contained, for example, in FMC [51] tool (only the curve from Annex A, EN 1991-1-2 [2]), or in PTK [55] tool (contain curve from [4], [5]), see Fig. 13, Fig. 14.

The heat release rate (HRR) is a very important phenomenon. It can be used for simplified calculations [Paper 11] or as an input for advanced [Paper 1, Paper 3, Paper 5, Paper 6, Paper 10, Paper 11, Paper 12]. For simplified calculation, the models HRR with activation of sprinkler nozzle, HRR of flammable liquid etc. can be used. For advanced models, the T-squared fire is mostly applied. All mentioned HRR models were also implemented into the FMC software tool [51].

T-squared fire is a fire model based on the HRR curve and it is described in Annex E.4, EN 1991-1-2 [2], see also [Paper 1, Paper 7]. HRR has two models – fuel controlled and ventilation-controlled model, and they can be even combined with the flashover effect if it can occur. The possible combinations are not described in the literature. It can be hard for understanding – that is the reason why the simple flowchart was developed, see Fig. 15. Based on this algorithm, the HRR (T-squared fire) was made in FMC tool [51].



Parametric temperature-time curves

The program was created within the diploma thesis.

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2021

The author will not be held liable for any damages arising from the use of this program.

Developed in program Python 3.7.

Fig. 13 – Initial window of the PTK software tool (it contains parametric temperature-time curves) [54], [55]

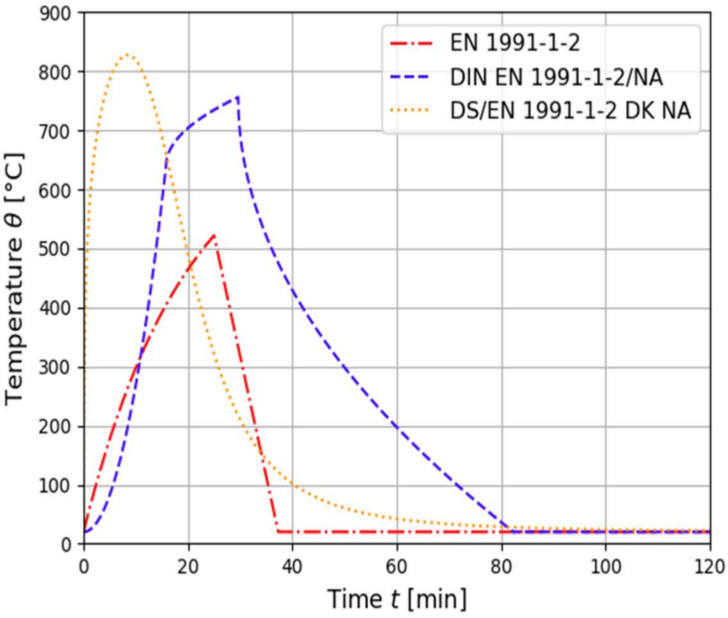


Fig. 14 – Parametric temperature-time curves created in the PTK software tool [55]

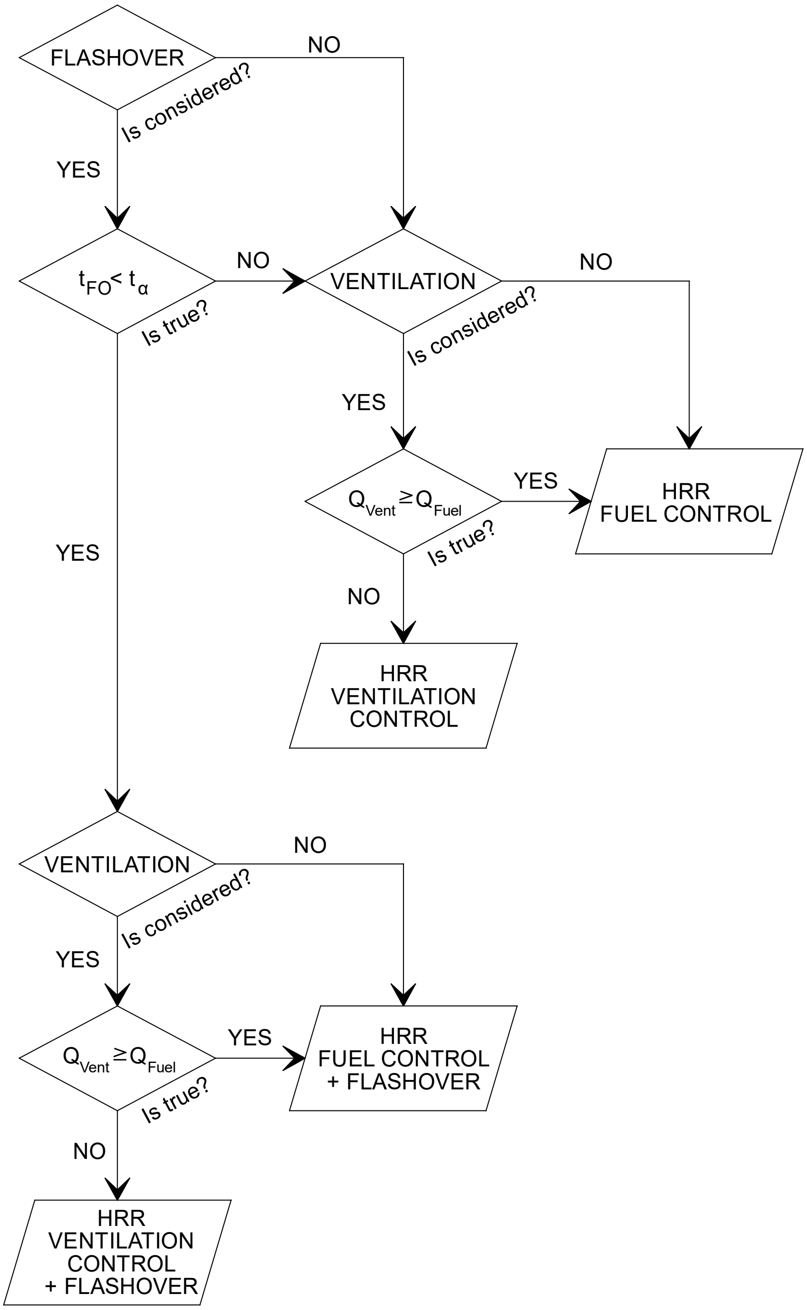
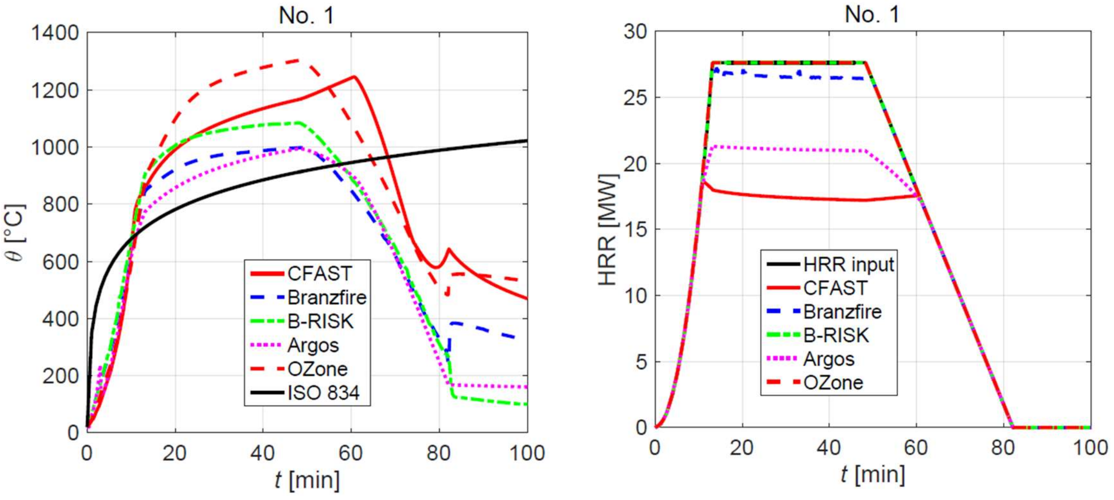


Fig. 15 – Algorithm for the determination of the HRR model type implemented in the FMC tool [51]. Notation: t_{FO} is the time when the fashover is assumed to happen; t_{α} is the fire growth rate coefficient; Q_{vent} is the maximum HRR value for a ventilation controlled fire; Q_{fuel} is the maximum HRR value for a fuel controlled regime; VENTILATION – if the ventilation is considered [Paper 1]

During the research, the HRR was applied for several illustrative examples. One of them was focused on the difference between the fuel-controlled fire and the ventilation-controlled fire. Based on achieved results, it seems that the HRR model for the ventilation-controlled fire, described in [2], does not give good results, see [Paper 1]. It is necessary to carry out a deeper study.

Advanced fire models are the most sophisticated models. They are very useful but the user must have some knowledge.

Zone models are simpler than the CFD models. For zone modelling, a lot of software can be applied but, as was proved, they do not have the same mathematical background which can lead to different results even if the inputs are the same, see Fig. 16 and [Paper 3]. Based on the author's results, it is recommended to study, before applying the zone model, the limits of each software in detail and maybe use more than one zone software in time.



(a) *(b)*

Fig. 16 – Comparison of the results obtained from several zone programs: a) temperatures; b) heat release rates [Paper 3]

CFD models are normally used for specific analysis or purposes [Paper 1, Paper 5, Paper 6]. They can also be used for the analysis after the fire [Paper 2], see Fig. 17, or, for example, for the analysis of the temperature field of the furnace for fire resistance testing, see Fig. 18, [56]–[60], or see [Paper 5].

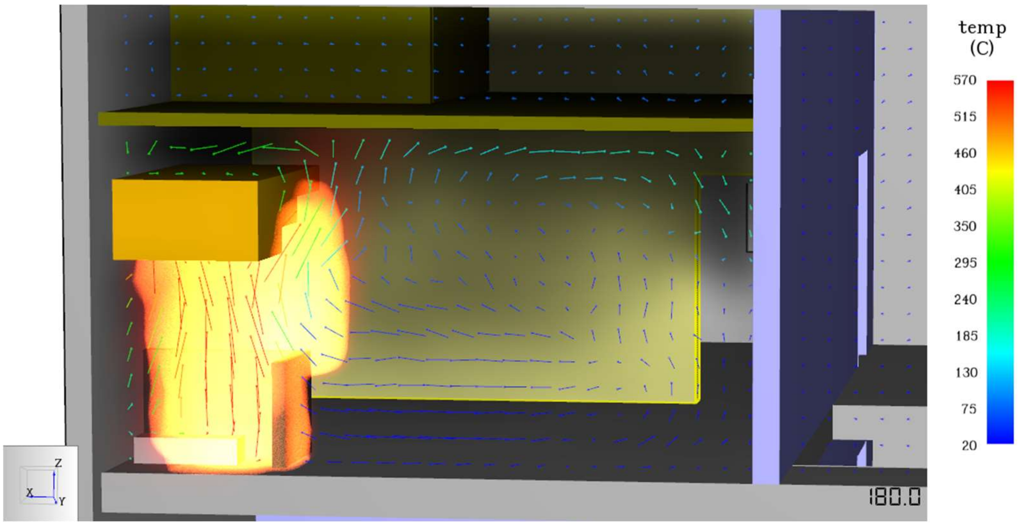


Fig. 17 – Analysis of structures after the fire with help of the FDS software [Paper 2]

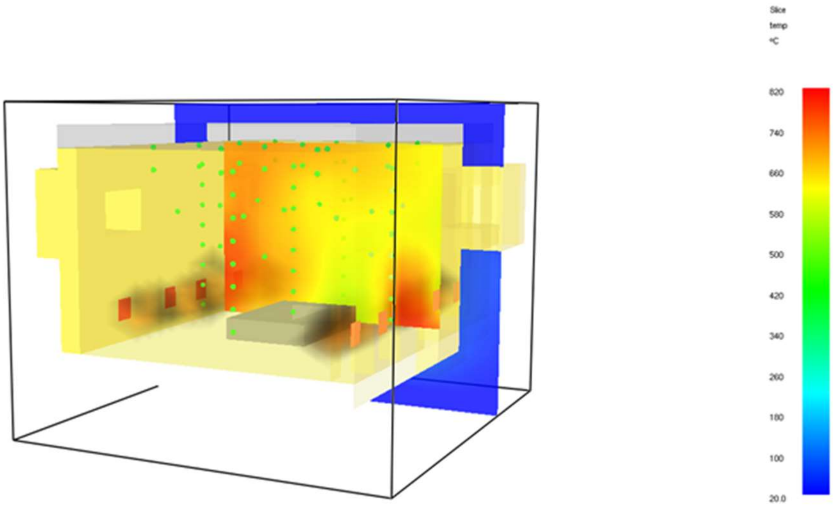
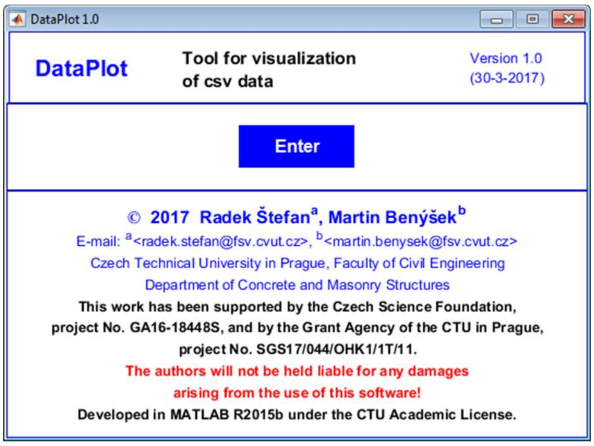


Fig. 18 – Analysis of the temperature field of the furnace for fire resistance testing with help of the FDS software, see [56]–[59] *or* [Paper 5]

3.3.3 Results from fire modelling as an input for next purposes

Fire models (respectively the results or outputs) are not useful only for the determination of the temperatures in a space. The outputs could be subsequently used for the thermal analysis of the structural items, analysis of the fire safety devices and their effectiveness or for the assessment of the evacuation etc.

As was mentioned in previous chapters, FDS and CFAST software were chosen for simulations of fire. Both software tools have as an output (all measured values e.g. from thermocouples or other devices) *.csv* files (coma-separated-values). These *.csv* files are a little bit “user unfriendly”. For rendering the data, it is necessary to reformat the data from *.csv* to *.xls* format and afterwards plot the required graph. From this reason, it was created the software called DataPlot – tool for visualization of *csv* data [53], see Fig. 19, see also [Paper 1, Paper 7]. This program was also developed in MATLAB.



DataPlot

Tool for visualization of csv data

Version 1.0
(30-3-2017)

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This work has been supported by the Czech Science Foundation, project No. GA16-18448S, and by the Grant Agency of the CTU in Prague, project No. SGS17/044/OHK1/1T/11.
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Fig. 19 – Initial window of the DataPlot – tool for visualization of csv data [53]

The usability and significance of the FMC [51] and DataPlot [53] tools in fire modelling is presented below, see Fig. 20, see also [Paper 1].

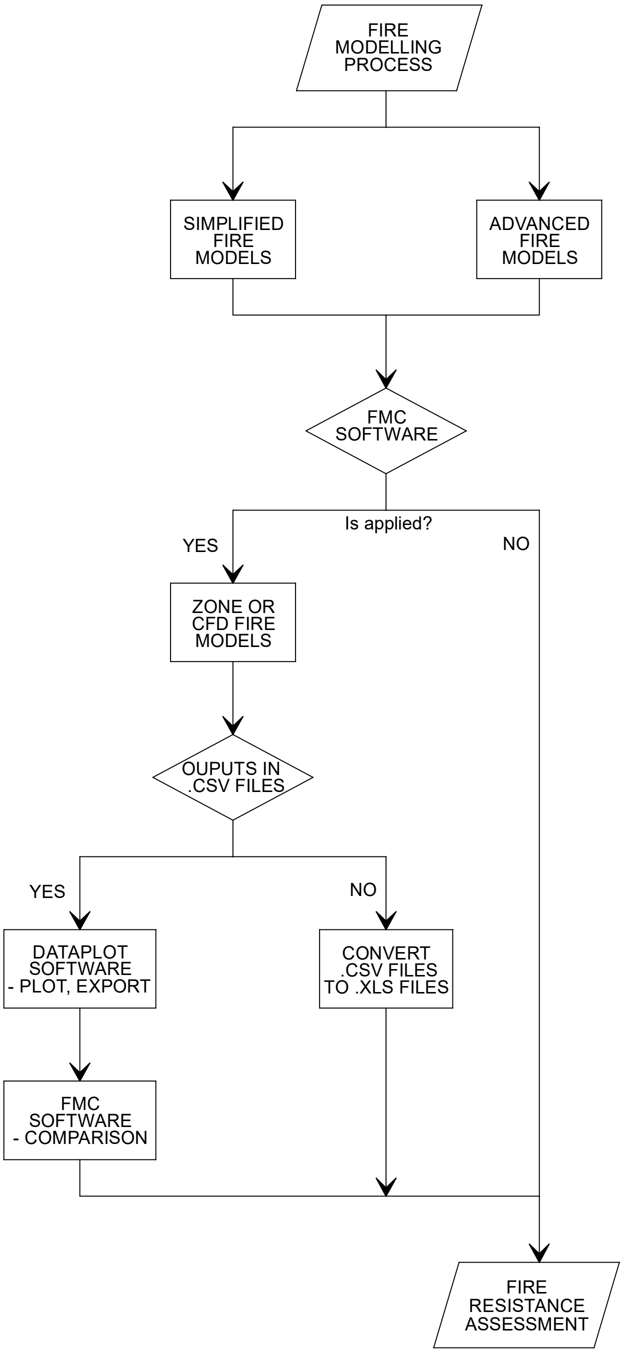
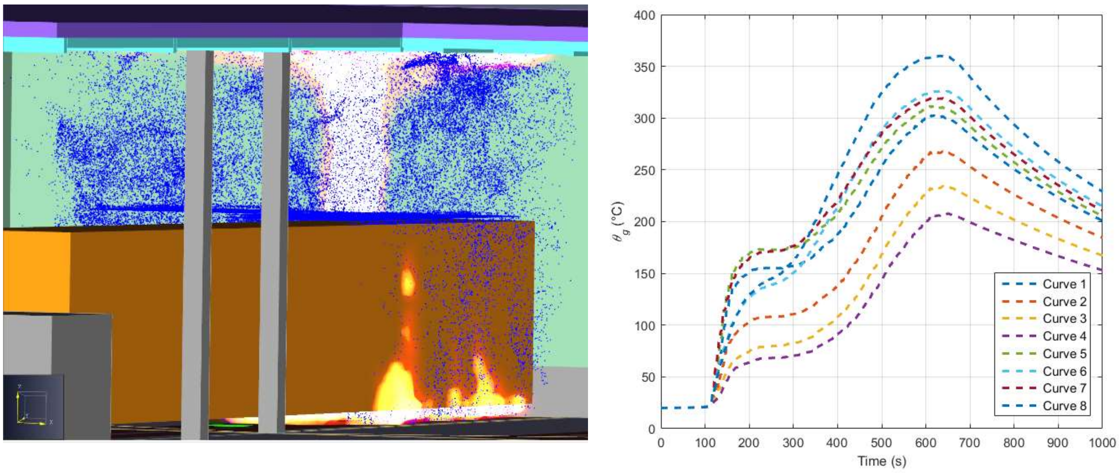


Fig. 20 – The usability of the FMC [51] and DataPlot [53] tools in the fire modelling process [Paper 1]

3.4 Assessment of structures exposed to fire

As was mentioned in the state of the art, see chap. 2.4, verification of fire resistance can be, in general, proved by the condition of reliability in terms of the time (see chap. 3.4.1), strength (see chap. 3.4.2) or temperature (see below).

In case of proof by temperature, no additional assessment of fire resistance is necessary. This type of assessment was applied in the author's expert assessment report [61]. The main goal of the report was to prove fire resistance of roof structures based on an active protection device (the sprinkler system) in a canopy where the plastic pallets were stored. The roof structure had no passive fire resistance. Simulation was created in FDS software [62] based on inputs. It was proved that in this case, roof structures did not exceed the limit critical temperature which was set up to 450 °C [63], see Fig. 21.



(a) (b)

Fig. 21 – Proof of the fire resistance by the limit temperature: (a) FDS – extinguishing the fire by sprinkler nozzle; (b) temperatures of the structural items [61]

3.4.1 Tabular assessment

Tabular assessment is the most popular and simplest method for assessment of fire resistance, mainly in engineering practise. For tabular assessment, several values are needed to be assessed. Table values are in many cases limited by the additional conditions – for simplification of the process the software tools for columns were created. These tools are only in Czech language and were not published yet – the tools were only described in [Paper 8].

3.4.2 Simplified calculation methods

All simplified calculation methods are applicable only with the standard fire (standard temperature-time curve). Only 500 °C isotherm method can be used with the standard temperature-time curve and parametric fires. That is the reason why the strip method for assessment of fire resistance of concrete structures was developed and subsequently applied for the author's calculations. The strip method was described in [Paper 6] and was applied in [Paper 6] and [Paper 7]. Results are shown and briefly described below.

The first application of the strip method was for the analysis of fire resistance of concrete structural members based on different fire models. The standard temperature-time curve, parametric temperature-time curve, zone model created in CFAST and CFD model created in FDS were applied, see Fig. 10. Temperature evolutions in the reinforcement, see Fig. 23, and comparison of the applied moment and the ultimate moments for the selected fire models, see Fig. 23, are shown below; for detailed description, see [Paper 6].

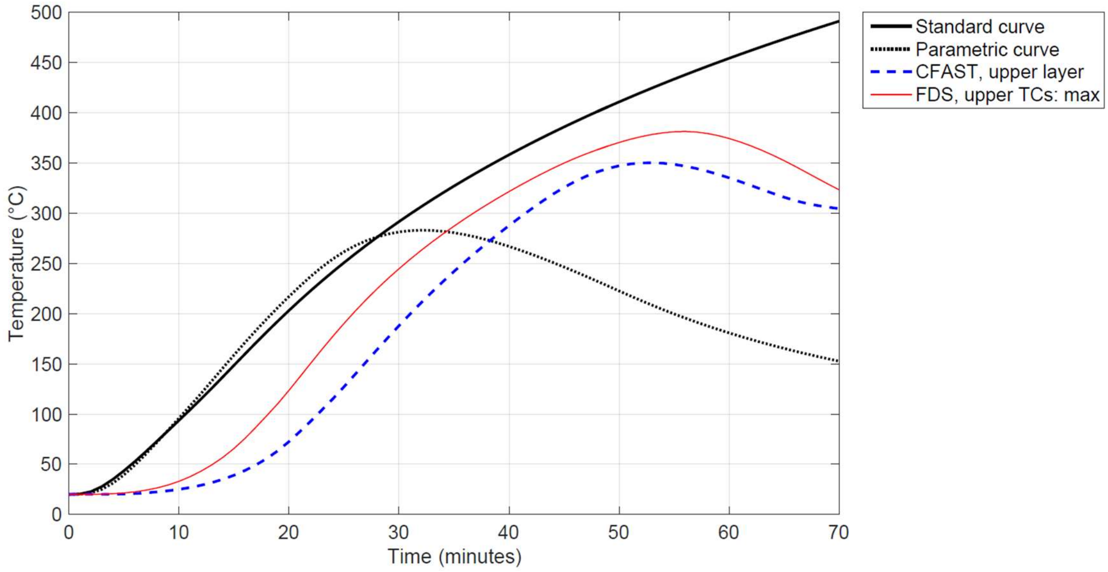


Fig. 22 – Temperature evolutions in the reinforcement (x = 25 mm) for the selected fire models [Paper 6]

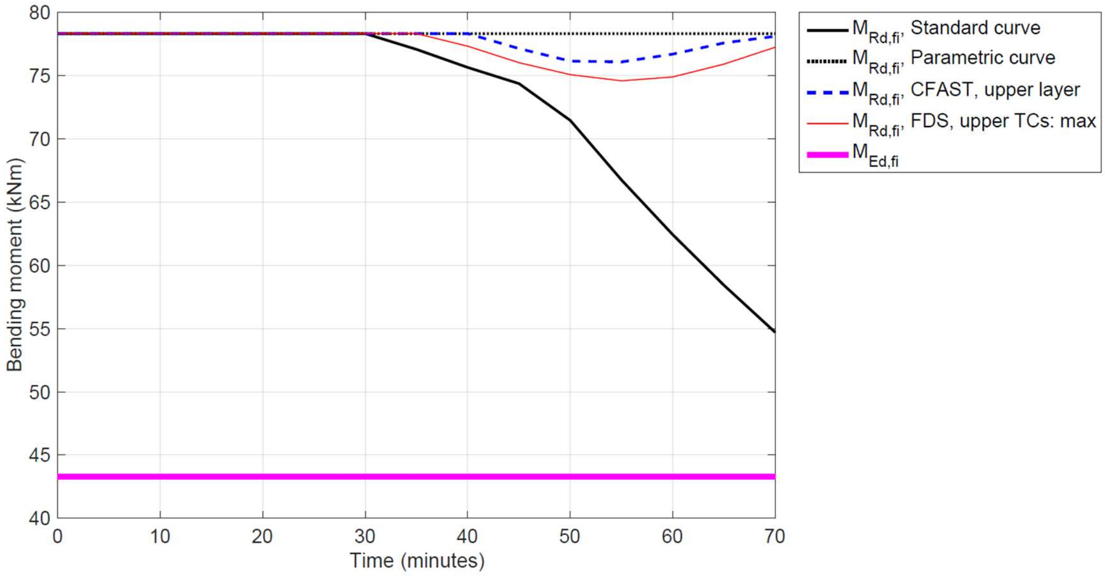


Fig. 23 – Applied moment $M_{Ed;fi}$ and the ultimate moments $M_{Rd;fi}$ for the selected fire models [Paper 6]

The second application of the strip method was for the effect of fire model parameter variability on determination of fire resistance of concrete structural members. The stochastic approach of the parametric temperature-time curve based on Monte Carlo and Latin Hypercubes Sampling methods were applied, see Fig. 9. Temperature evolutions in the reinforcement, see Fig. 24, and comparison of the applied moment and the ultimate moments for the selected fire models, see Fig. 25, are shown below; for detailed description, see [Paper 7].

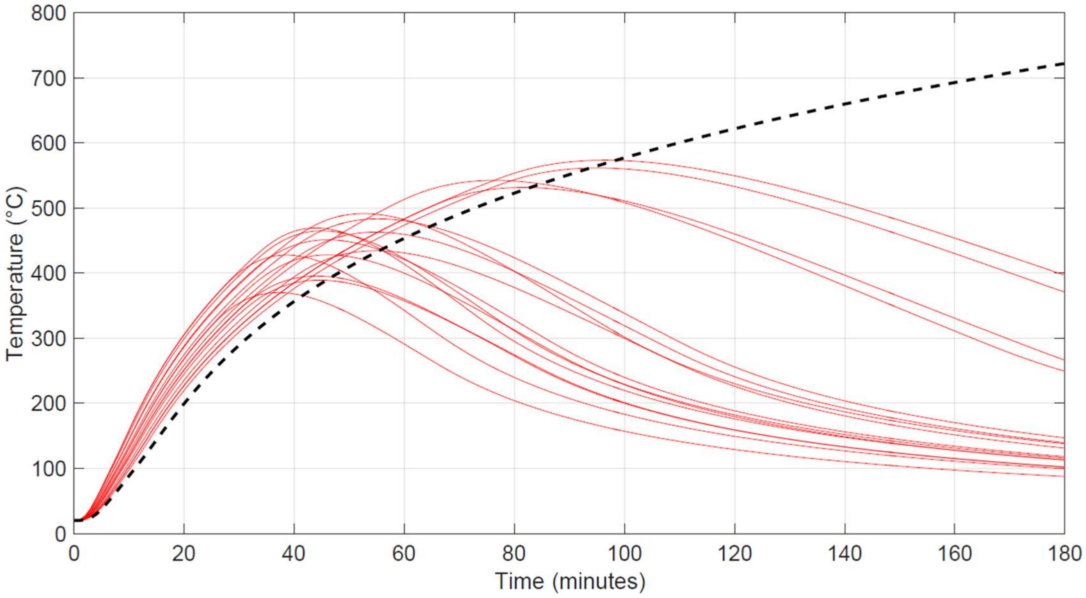


Fig. 24 – Temperature evolutions in the reinforcement (x = 25 mm) for the parametric fire curves assuming the parameter combinations obtained using the Latin Hypercubes method (solid lines); comparison with the reinforcement temperature for the standard curve (dashed line) [Paper 7]

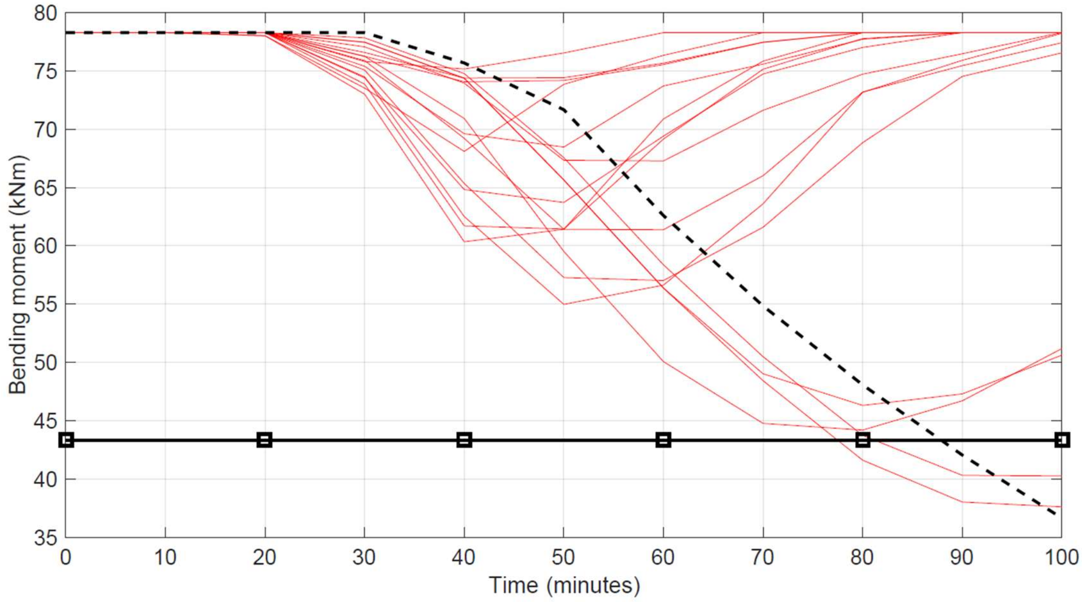


Fig. 25 – Applied moment $M_{Ed;fi}$ (dotted line), the ultimate moments $M_{Rd;fi}$ for the parametric fire curves assuming the parameter combinations obtained using the Latin Hypercubes method (solid lines) and for the standard temperature-time curve (dashed line) [Paper 7]

4. Discussion

4.1 General conclusions

The thesis is focused on the analysis of fire resistance of concrete structures based on different fire models.

The first part of the thesis is focused on the state of the art. In the introductory chapters (chap. 2.1, 2.2, 2.3, 2.4), a brief overview of the problem; fire and its main phenomena, and modelling of fire are solved. Then models of fire are described – basic types and their validation. Mathematical models are described in detail. Subsequently, the assessment of fire resistance of structures is listed. In the second part of the thesis, the author's results are presented.

The main goal was to perform the analysis of models of fire and the analysis for assessment of fire resistance of structures with the use of deterministic and probabilistic approaches. The simplified and advanced methods were applied. For the analysis of simplified models of fire, the in-house codes created in MATLAB or OCTAVE were developed and subsequently used for the mentioned analysis. Based on the analysis, it was found out that the supporting software tools are appropriate for the process of fire modelling because available programs for fire modelling do not provide everything that users need. The FMC [51] and DataPlot [53] software tools were developed – these tools are freely available for download.

The FMC tool [51] contains commonly used simplified models of fire that the FMC can determine, plot the graph, calculate maximum values and export data for next purposes. It is also available to load *.xls* files and compare the results from advanced fire simulations with, for example, nominal temperature-time curves.

The DataPlot [53] is a tool convenient for visualization and exporting the data from fire simulation programs CFAST and FDS. This tool originated based on the fact that mentioned simulation programs, in this point of view, are a little bit user-unfriendly. The output file with results is generated in *.csv* format and for data control, it is necessary to format the output file.

For a simplified calculation assessment of fire resistance of concrete structures, the in-house code was created in MATLAB. This code is based on a one-dimensional strip method with its own heat transfer, see [Paper 4, Paper 6].

Performed analyses were described in detail, see [Paper 1 – Paper 12] – it is a collection of the author's papers presenting achieve results. By the analysis, it was found out, that the HRR model for a ventilation-controlled fire determined according to EN 1991-1-2 [2] and the HRR model for a ventilation-controlled fire determined in FDS software has a significant difference in shape. It seems that this model is very inaccurate. It is recommended to modify this HRR model, determined according to EN 1991-1-2 [2], manually, see [Paper 1] where the results are detailed described.

Monte Carlo and Latin Hypercubes Sampling methods were applied for the probabilistic approach. Based on achieve results, see [Paper 4], the Latin Hypercubes Sampling method is the appropriate method for the stochastic approach. In a comparison with the Monte Carlo method, it is not necessary to carry out many permutations to achieve comparable agreement of results. And, of course, the stochastic approach performs more than only one possible calculation.

Simulation program FDS is appropriate for the analysis of structures after the fire, see the obtained results in [Paper 2], or for the analysis of the temperature field of the furnace for fire resistance testing, see [Paper 5].

Simulation programs, such as FDS software, are a very good tool for many applications. It is the future of fire design as a BIM (Building Information Modelling) approach. In a process of modelling fire, it is, unfortunately, still a problem to obtain the input data for simulations. This is the reason why the advanced fire simulations are often simplified and, in this case, sometimes, advanced simulations are not advanced. The next unforgettable limit is still the performance of computers to calculate simulations that are still not sufficient to dominate fire design in common practice.

4.2 Recommendations for the further research

Modelling of fire, especially advanced approach, is the future of the design and it is necessary to continue in the research of this significant branch. It is needed to focus on simplification of the whole process so that the advanced calculation methods can be used in engineering practice and more economical solutions can be applied that, however, often leads to a more environmentally friendly approach. It could be recommended to support the organization of the seminars, training or conferences focused on this topic.

As was mentioned above, the input parameters for advanced fire simulations are still not available to the extent that is needed. It is recommended to perform a collection of the input data and convert it to the online database.

It is recommended to create a program that will combine simplified and advanced fire models with simplified and advanced calculation methods for assessment of the fire resistance of structures, and ideally on the online version.

According to the author's opinion, it could be also recommended to describe more in detail the advanced calculation methods for assessment of the fire resistance of concrete structures – this is missing in the standard EN 1992-1-2 [3].

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6. Author's publications

6.1 Publications included in the thesis

Benýšek, M.; Štefan, R.; Holan, J.
Software Tools for Pre- and Post-Processing of Fire Modelling Data
In: Fire Technology, 2021. Under review, **60 %**, see Paper 1.

Müller, P.; Benýšek, M.; Štefan, R.
Post-Fire Structural Assessment of a Firefighting Training Facility: A Case Study
In: Journal of Fire Sciences, 2021. Submitted, **40 %**, see Paper 2.

Svobodová, N.; Benýšek, M.; Štefan, R.
Analysis of zone fire models and their application in structural design
In: 27th Concrete Days. Curich: Trans Tech Publications, 2021. p. 127-135. Solid State Phenomena. vol. 322. ISSN 1662-9779, **25 %**, see Paper 3.

Benýšek, M.; Štefan, R.; Procházka, J.
Effect of Fire Model Parameter Variability on Determination of Fire Resistance of Concrete Structural Members
In: 26th Concrete Days. Curich: Trans Tech Publications, 2020. p. 208-215. Solid State Phenomena. vol. 309. ISSN 1662-9779. ISBN 978-3-0357-3668-7, **60 %**, see Paper 4.

Cábová, K.; Zeman, F.; Blesák, L.; Benýšek, M.; Wald, F.
Timber Beam in Virtual Furnace
Journal of Structural Fire Engineering. 2020, 11(4), 437-446. ISSN 2040-2317, **15 %**, see Paper 5.

Benýšek, M.; Štefan, R.; Procházka, J.
Analysis of Fire Resistance of Concrete Structural Members Based on Different Fire Models: An Illustrative Example of the Slab Panel Assessment
In: 25th Concrete Days 2018. Curich: Trans Tech Publications, 2019. p. 173-182. Solid State Phenomena. vol. 292. ISSN 1662-9779. ISBN 978-3-0357-1459-3, **60 %**, see Paper 6.

Benýšek, M.
Software Tools for Fire Engineering
In: Proceedings of PhD Workshop, Department of Concrete and Masonry Structures 2020. Prague: CTU FCE. Department of Concrete and Masonry Structures, 2020. ISBN 978-80-01-06774-1, **100 %**, see Paper 7.

Benýšek, M.
Fire Resistance Assessment of Reinforced Concrete Columns (*in Czech*)
In: PhD Workshop 2018 – Full Texts. Prague: Czech Technical University in Prague, Faculty of Civil Engineering, 2018. pp. 33. ISBN 978-80-01-06417-7, **100 %**, see Paper 8.

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In: PhD Workshop - Full Texts. Prague: Czech Technical University in Prague, Faculty of Civil Engineering, 2017. ISBN 978-80-01-06132-9, **100 %**, see Paper 9.

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Comparison of Zone and CFD Fire Model (*in Czech*)
In: PhD Workshop - Full Text. Prague: Czech Technical University in Prague, Faculty of Civil Engineering, 2016. pp. 10-11. ISBN 978-80-01-05924-1, **100 %**, see Paper 10.

Benýšek, M.
Physical and Mathematical Models of Fire (*in Czech*)
In: PhD Workshop 2015 - Full Versions. Prague: Czech Technical University in Prague, Faculty of Civil Engineering, 2015. ISBN 978-80-01-05722-3, **100 %**, see Paper 11.

Benýšek, M.
Fire Resistance Analysis of Concrete Members with the use of Simplified and Advanced Models of Fire (*in Czech*)
In: PhD Workshop - Proceedings. Prague: Czech Technical University in Prague, Faculty of Civil Engineering, 2014. ISBN 978-80-01-05471-0, **100 %**, see Paper 12.

6.2 Created software tools included in the thesis

Benýšek, M.; Štefan, R.
FMC – Fire Models Calculator ver. 2.0
[Software] 2018, **50 %**.

Benýšek, M.; Štefan, R.
VOV – Výpočet odstupových vzdáleností (*in Czech*)
[Software] 2017, **50 %**.

Štefan, R.; Benýšek, M.
DataPlot – Tool for visualization of csv data
[Software] 2017, **50 %**.

6.3 Previous theses

Benýšek, M.
Fire Resistance Analysis of Concrete Members Assuming Simplified and Advanced Models of Fire
Supervisor: J. Procházka, opponent: P. Kučera; Praha: Defence date 2014-01-23. Master Thesis. Czech Technical University in Prague, Faculty of Civil Engineering, Department of Concrete and Masonry Structures.

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Design of computer tools to fire design of concrete structural members and their application on a real structure
Supervisor: R. Štefan, opponent: J. Procházka; Praha: Defence date 2012-06-20. Bachelor Thesis. Czech Technical University in Prague, Faculty of Civil Engineering, Department of Concrete and Masonry Structures.

6.4 Other publications

SVOBODOVÁ, V. Aplikace různých modelů požáru pro posouzení požární odolnosti konstrukcí. Praha: Defense date 2021-02-02. Master Thesis. CTU FCE. Department of Concrete and Masonry Structures.

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6.5 Paper 1

Reprint of the paper

- Software Tools for Pre- and Post-Processing of Fire Modelling Data (2021)

Contribution of the author of this thesis to the paper

- M. Benýšek is the author of the text of the paper (that was written under the supervision of R. Štefan).
- The author's contribution is 60 % [2].

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[2] The author's contribution to the publications expressed as percentages have been taken from the V3S database (CTU database publications, see https://v3s.cvut.cz/login).

Software tools for pre- and post-processing of fire modelling data

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Software tools for pre- and post-processing of fire modelling data

Abstract

Nowadays, a trend of applying more sophisticated and advanced models when modelling fire can be observed in fire safety engineering and structural fire design. For this modelling, sophisticate commercial programs are mainly used. However, these commercial programs often do not have suitable functions for pre-processing or post-processing. This paper presents new software tools FMC and DataPlot developed by the authors. The FMC tool contains frequently used fire models and can be used as a pre-processor and post-processor for commercial programs such as CFAST and FDS. The DataPlot tool can be used as a post-processor for programs which provide the output data in a `.CSV` (Comma-Separated Values) format, e.g. CFAST and FDS. This paper also present the application of these newly developed software tools on several examples aimed at the analysis of the heat release rate (HRR) and ventilation conditions. In these examples, the FDS software is used for the fire simulations, and the FMC and DataPlot software tools are used for both pre-processing and post-processing of data. Moreover, in these examples, the effect of the type of HRR is discussed with regards to the EN 1991-1-2 standard recommendations. The presented results suggest that the newly developed software tools are suitable for the use in fire safety engineering and structural fire design.

Keywords: Fire design, Fire Modelling, Fire Models, Software, Heat Release Rate

1. Introduction

One of the main tasks in fire safety engineering and structural fire design is the modelling of fire. When performing the modelling of fire, the appropriate fire scenario must be chosen carefully for the assessment of fire safety of buildings and fire resistance of structures. Simple fire models, such as the standard temperature-time curve (ISO 834 fire) or other nominal curves described in EN 1991-1-2 [1], are commonly used, see e.g. [2, 3]. Nowadays, more sophisticated and advanced models are often used as their use leads to more effective design. However, the increased sophistication also increases the time needed for the performance of the design. Commercial programs, which are frequently used for the modelling of fire, often do not have suitable functions for pre-processing or post-processing of data. For this reason, the authors of this paper have developed two novel software tools – FMC (Fire Models Calculator) [4], see section 3.1, and DataPlot (a tool for visualization of `.CSV` data) [5], see section 3.2 – which tackle this problem. The FMC tool [4] contains the frequently used fire models which can be used in the pre-processing as an input data for thermal analyses. The tool can also be used for the post-processing of data obtained from commercial programs, e.g. CFAST [6] and FDS [7]. The DataPlot tool [5] can be used as a post-processor for any program which provide the output data in a `.CSV` format.

This paper presents the application of these software tools on illustrative examples. The first example is aimed on the practical use and on the functions of the FMC [4] and DataPlot [5] software tools, see Section 4.1. The second example is aimed on the application of the heat release rate (HRR) model for fire modelling, see Section 4.2, with focus on the comparison of simplified (EN 1991-1-2 standard [1]) and advanced (CFD modelling) approach to the HRR modelling for two types of HRR models – i.e. ventilation-controlled fire and fuel-controlled fire.

The HRR model, which is examined in the second example is related to advanced fire modelling. When modelling fire using advanced models, the fire evolution can be controlled either using complex chemistry simulations of the burning process or using the HRR model which prescribes the heat release. The HRR is most commonly used due to its simplicity and sufficient accuracy. Thus, the heat release rate is one of the most significant parameter in the fire modelling, and hence, this parameter is analysed in detail in this paper, see Section 3.1.

2. Overview of fire models

Modelling of fire is a process, which determines and describes the theoretical evolution of fire which can occur in a given compartment [8].

The most frequently used fire models are the deterministic mathematical models. Deterministic models do not include possible variability of the input parameters. Thus, when the initial conditions are the same, the results will always be the same. The range of deterministic fire models is very wide, from very simple models (which depend only on a single parameter and describe fire evolution in one compartment) to complex models (which depend on many parameters and can describe fire evolution in complex spaces) [9–11].

The overview below is focused on the most commonly used deterministic mathematical fire models – i.e. nominal temperature-time curves and natural fire models.

2.1. Nominal temperature-time curves

The temperature-time curves are among the simplest fire models and they usually describe only the phase of a fully developed fire. The nominal temperature-time curves describe the fire development in a single fire compartment (e.g. single room, single tunnel etc.) and they are most commonly used for the assessment of the fire resistance of a structure. The temperature-time curves are very conservative because they do not consider the cooling phase of fire, the effect of ventilation nor the effect of structural materials. These models have only a single parameter – time. Nominal temperature-time curves are generally very well known and they are described in detail in many publications [1–3, 9, 10, 12–14].

2.2. Natural fire models

Natural fire models are often divided into two basic groups – simplified fire models and advanced fire models, see e.g. [1].

Simplified fire models are based on multiple physical parameters and have limited usability. When using these models, an uniform distribution of temperatures is often assumed in the compartment at any given time. Exception are the localised fires, which assume a non-uniform distribution of temperatures in the compartment. The simplified models include the

- parametric temperature-time curves [1, Annex A], [15–18],
- thermal actions for external members – simplified calculation method [1, Annex B],
- localised fires [1, Annex C],

- fire load density [1, Annex D],
- rate of heat release [1, Annex E].

Advanced fire models, which are also well-known and commonly used for fire simulations (see, e.g., [9–11, 19–25], see also our previous work [26–30]) are much more complex as they must consider physical laws of conservation [1].

According to EN 1991-1-2 standard [1, Annex D], among the advanced fire models belong

- the one-zone model, which assumes a uniform time-dependent temperature distribution in a fire compartment,
- the two-zone model, which assumes an upper layer with a time-dependent thickness and higher time-dependent uniform temperature and a lower layer with a lower time-dependent uniform temperature,
- the computational fluid dynamic (CFD) model, which determines the non-uniform time-dependent development of temperatures in a compartment.

2.3. Models used in this paper

In the examples presented in this paper, the CFD models implemented in the FDS software [7] are employed. The CFD models represent the most sophisticated approach to the fire design. As input parameter prescribing the fire evolution, the HRR models described in EN 1991-1-2 [1] are used.

3. Software Tools

In this section, novel software tools developed by the authors for the pre-processing and post-processing of fire-simulations are presented. The FMC (Fire Models Calculator) [4] and DataPlot (tool for the visualization of `.CSV` data) [5] tools were developed in the Matlab environment [31]. These software tools have also been briefly described in our previous work [32].

3.1. FMC – Fire Models Calculator

The FMC software [4] is an useful tool for fire modelling as it serves as a complement to sophisticated programs. Using this tool, temperature evolutions obtained from sophisticated programs can be clearly compared with frequently used simplified fire models.

The FMC tool [4] can be used to plot frequently used nominal temperature-time curves and can also determine the exact temperatures at any given time. An arbitrary number of the curves can be plotted. Moreover, `.XLS` data files containing results from other simulations (obtained e.g. using FDS [7] or CFAST [6] software) can be input into the FMC tool [4] and these results can be clearly compared with nominal temperature-time curves. Apart from the nominal temperature-time curves, the FMC tool [4] also contains the parametric temperature-time curve and others frequently used natural fire models. All the models included in the FMC tool [4] are listed below:

- flashover:
  - flashover according to Babrauskas, see e.g. [9, (9.9)] and references therein,

  - flashover according to Thomas, see e.g. [9, (9.10)] and references therein,
  - flashover according to McCaffrey et. al., see e.g. [9, (9.23)] and references therein;

- nominal temperature-time curves:
  - standard temperature-time curve [1, cl. 3.2.1], [12, cl. 4.2],
  - hydrocarbon temperature-time curve [1, cl. 3.2.3],
  - modified hydrocarbon temperature-time curve, see e.g. [10, Fig. 25.56] and references therein,
  - external fire curve [1, cl. 3.2.2], [12, cl. 4.5],
  - slow heating fire curve [12, cl. 4.3],
  - RABT-ZTV car, see e.g. [10, Fig. 25.56] and references therein,
  - RABT-ZTV train, see e.g. [10, Fig. 25.56] and references therein,
  - RWS fire curve, see e.g. [10, Fig. 25.56] and references therein,
  - user-defined temperature-time curve;

- natural fire models:
  - heat release rate taking into account flashover and ventilation [1, Annex E], [9, 10, 33],
  - heat release rate with activation of sprinkler nozzle [34, 35],
  - heat release rate of flammable liquids [9, 10, 33],
  - parametric temperature-time curve [1, Annex A],
  - localised fires [1, Annex C];

- equivalent time of fire exposure [1, Annex F].

All of the aforementioned models and the related parts of the FMC tool [4] are described in authors' previous work [32].

This paper is further focused on the HRR model as it is one of the most used models in fire modelling, e.g. [9, 10, 33], and is commonly used as an input parameter for advanced fire models. For the HRR model, the tool can calculate the maximum value and plot the graph of the heat release rate for the models listed above.

The outputs from the FMC tool [4] (e.g. HRR model) can be used as input data for advanced fire models (e.g. zone model or CFD model), and the tool also allows the export of the calculated and plotted data in a `.XLS` format, which can later be used by other programs.

A very important feature of the tool is that it can determine the type of the HRR model (i.e. fuel-controlled fire, ventilation-controlled fire, fuel-controlled fire with flashover, ventilation-controlled fire with flashover) based on the inputs. The authors have created an easily-understandable flowchart for the determination of the HRR model based on the input parameters, see Figure 1, and have implemented this algorithm in the FMC tool [4].

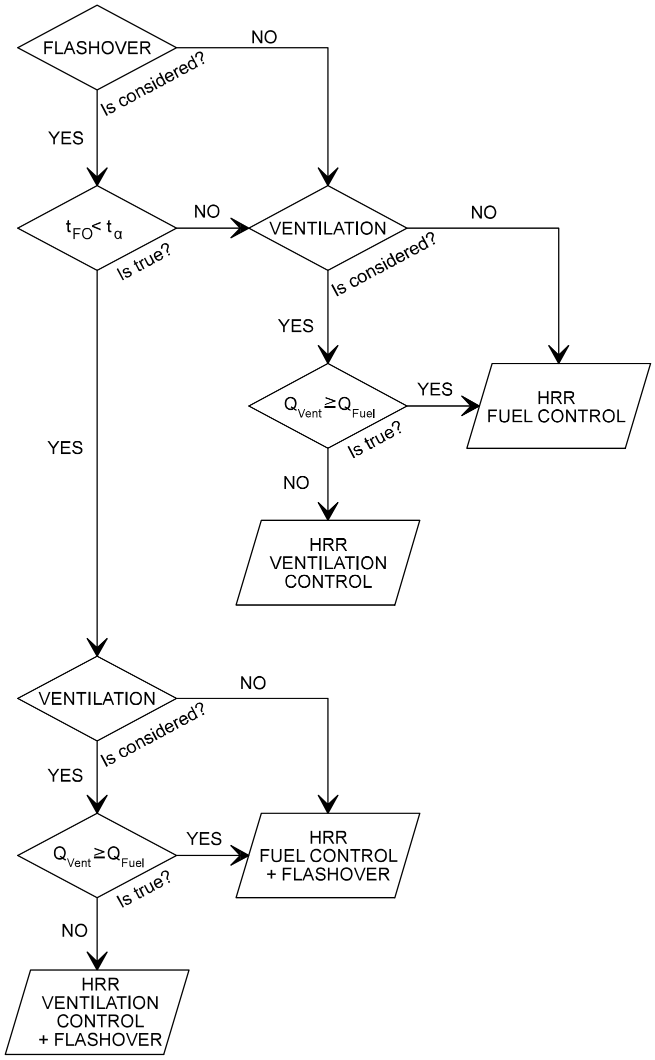


Figure 1: Algorithm for the determination of the HRR model type implemented in the FMC tool [4]. Notation: t_{FO} is the time when the flashover is assumed to happen, t_α is the fire growth rate coefficient, Q_{Vent} is the maximum rate of heat release for a ventilation-controlled fire, Q_{Fuel} is the maximum rate of heat release for a fuel-controlled fire.

3.2. DataPlot – Tool for visualization of csv data

Nowadays, for accurate investigations of the fire dynamics, advanced fire models are often used. These numerical models are used in sophisticated commercial programs. One of these programs is the FDS (Fire Dynamics Simulator) program [7]. This program is generally well-known and commonly used, see e.g. [21, 23, 24, 26, 30]. The program uses the CFD (Computational Fluid Dynamics) model, which simulates the fire in a given compartment based on given inputs. Another program, called Pyrosim [36], can be used as a pre-processor, but it is not a standard part of the FDS program. For the post-processing, i.e. visualization of simulation results, the SmokeView program [37] can be used. This program is a visualization program, which is used to display the results of the FDS simulations [7].

The `.CSV` output files from the FDS program [7] contain the data of evolution of the measured variable (e.g. temperature, pressure etc.) in all measured points. These `.CSV` files themselves are “user unfriendly” for subsequent post-processing. It is convenient to reformat the data from `.CSV` files to `.XLS` files for better usability and for data plotting. For a fast and easy reformat of the data and their visualization, the DataPlot tool [5] has been developed by the authors in the MATLAB environment [31].

The DataPlot tool can be used in the following way. First, a `.CSV` data file (output from commercial software such as FDS [7]) is loaded into the tool. Then, one column containing the x-axis values (time) and one or more columns containing the y-axis values (e.g. temperatures) are chosen. Using these selected values, a graph is subsequently plotted. Finally, the chosen and plotted values can be exported from the tool in the form of a `.XLS` data file. This exported `.XLS` file can subsequently be loaded into other software such as FMC tool [4] for further post-processing – e.g. to compare the values obtained from the FDS software (and reformated using the DataPlot tool) with nominal temperature-time curves. The usability of the FMC [4] and DataPlot [5] tools in fire modelling is presented below, see Figure 2.

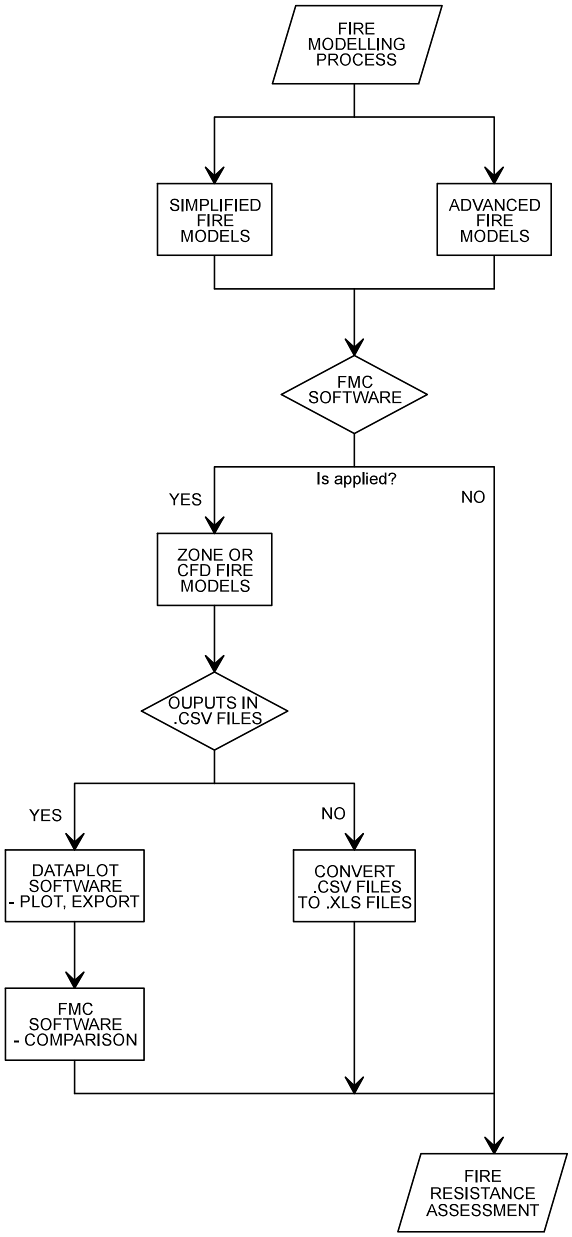


Figure 2: The usability of the FMC [4] and DataPlot [5] tools in fire modelling process.

4. Illustrative examples

This section contains two illustrative examples. The first example presents the usability of the two software tools developed by the authors – FMC [4] and DataPlot [5]. The second example is aimed on the application of the heat release rate (HRR) model for fire modelling with focus on the comparison of simplified (EN 1991-1-2 standard [1]) and advanced (CFD modelling) approach to the HRR modelling for two types of HRR models – i.e. ventilation-controlled fire and fuel-controlled fire.

4.1. Practical use of the FMC and DataPlot software

The application of the FMC [4] and DataPlot [5] tools as post-processors is presented using data previously obtained by the authors from the FDS software solver [7]. The data from the FDS software are of a mathematical model of a virtual furnace of fire resistance testing, see Figure 3, see also our previous work [26–29],

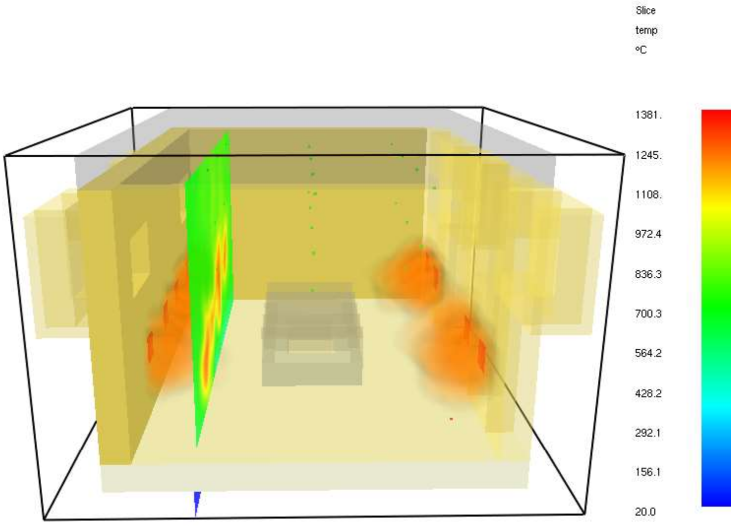


Figure 3: Virtual furnace – model from FDS software [7], see also [26–29].

As mentioned above, the data obtained from FDS simulation are stored in a `.CSV` file. This file can be loaded into the DataPlot tool [5]. This tool loads all data from the `.CSV` file and uses them as values for both the x-axis and y-axis, see Figure 4. The user of the DataPlot tool [5] can choose an arbitrary number of the y-axis data to be plotted, see Figure 5. The loaded and plotted data can then be exported to a `.XLS` file.

The `.XLS` file can be loaded in the FMC tool [4] (or other program supporting `.XLS` import), see Figure 6. In the FMC tool [4] the imported values can be plotted along with nominal temperature-time curves which is very convenient as it allows the user to clearly compare the calculated data from the FDS software [7] with the nominal temperature-time curves, see Figure 7.

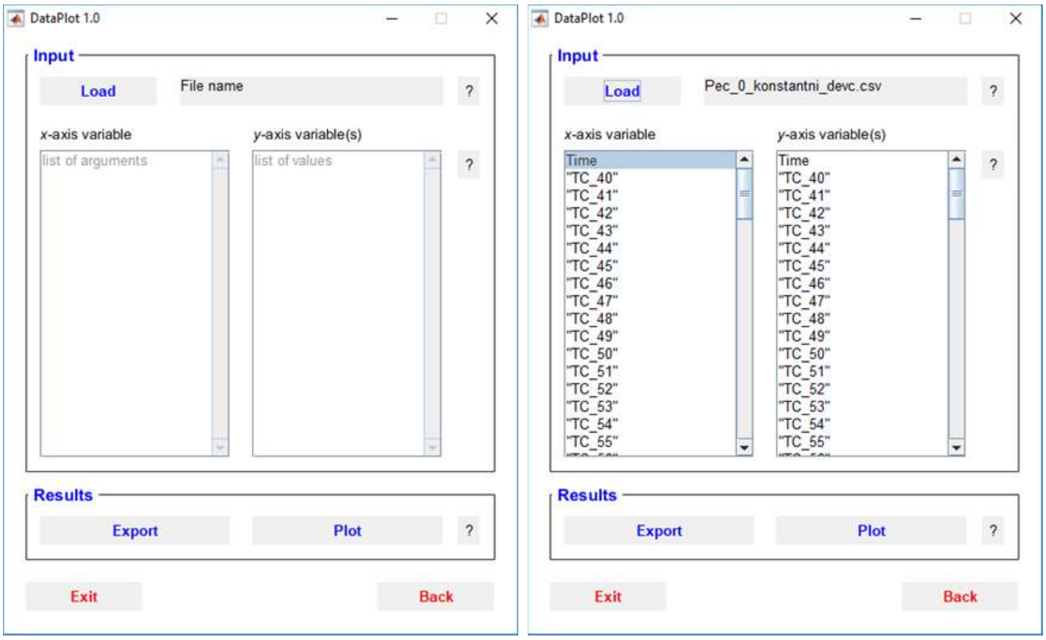


Figure 4: DataPlot [5] tool: Loading a `.CSV` file.

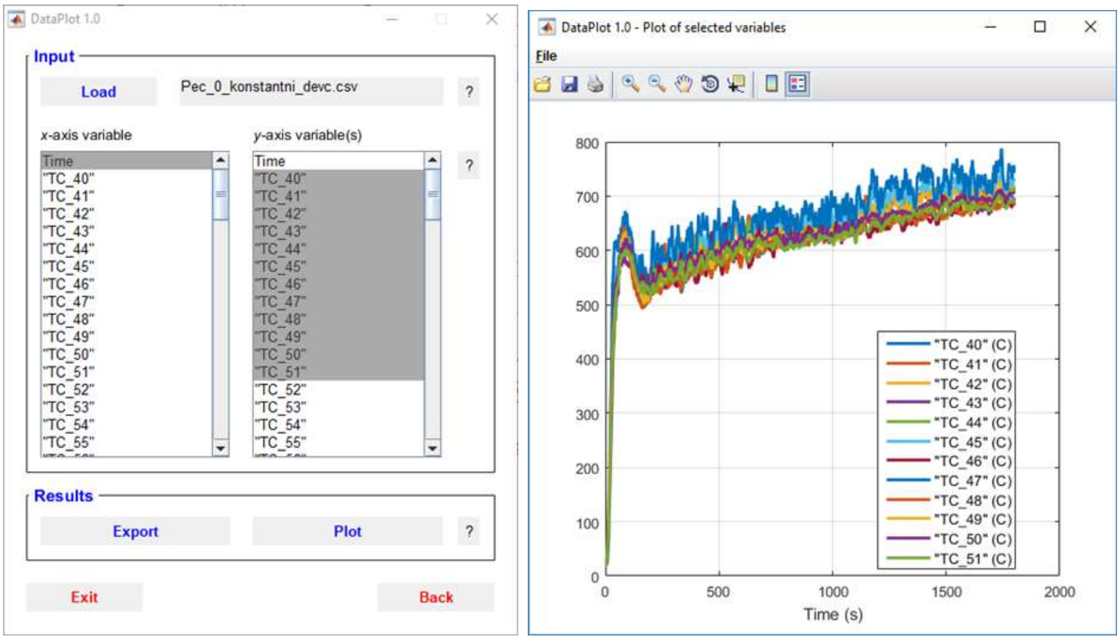
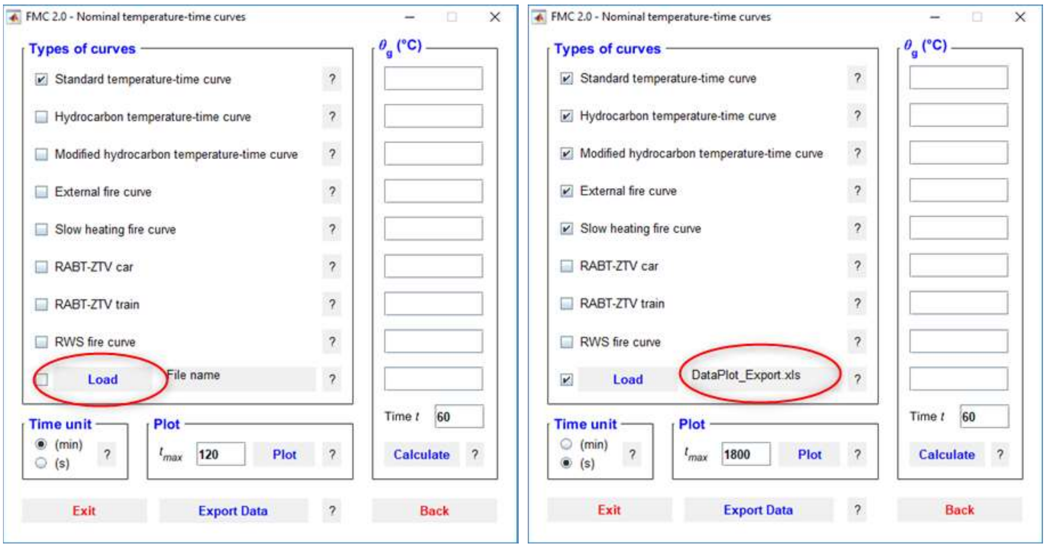


Figure 5: DataPlot tool [5]: Choosing values to be plotted (left) and the generated graph (right).


FMC 2.0 - Nominal temperature-time curves

Types of curves
☑ Standard temperature-time curve
☐ Hydrocarbon temperature-time curve
☐ Modified hydrocarbon temperature-time curve
☐ External fire curve
☐ Slow heating fire curve
☐ RABT-ZTV car
☐ RABT-ZTV train
☐ RWS fire curve
☐ Load File name
Time unit: ● (min) ○ (s)
Plot: t_{max} 120
Time t 60

FMC 2.0 - Nominal temperature-time curves

Types of curves
☑ Standard temperature-time curve
☑ Hydrocarbon temperature-time curve
☑ Modified hydrocarbon temperature-time curve
☑ External fire curve
☑ Slow heating fire curve
☐ RABT-ZTV car
☐ RABT-ZTV train
☐ RWS fire curve
☑ Load DataPlot_Export.xls
Time unit: ○ (min) ● (s)
Plot: t_{max} 1800
Time t 60

Figure 6: FMC tool [4]: Loading a `.XLS` file from DataPlot tool [5].

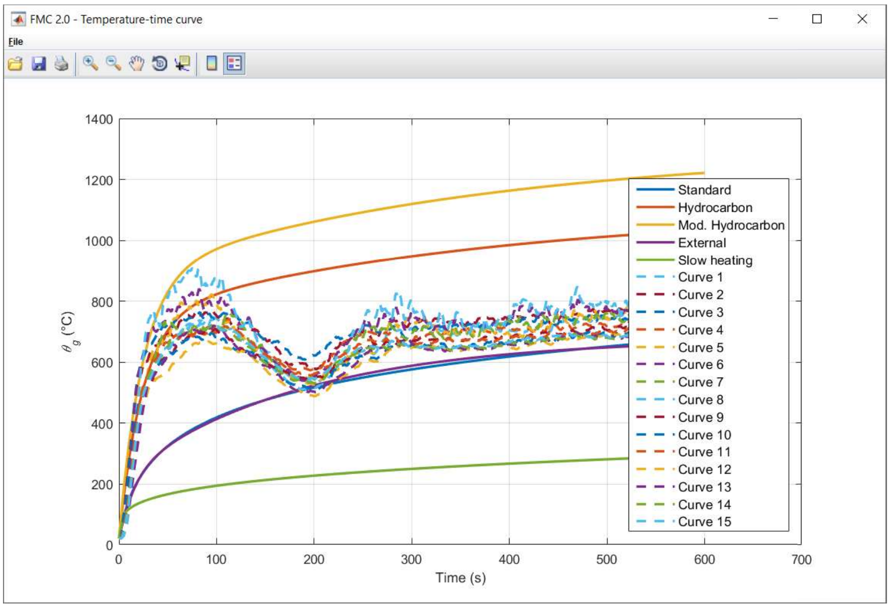


Figure 7: Comparison of the results obtained from the FDS solver [7] with nominal temperature-time curves using the FMC tool [4].

4.2. Application of the HRR for fire modelling

The illustrative example is focused on the comparison of the HRR model predicted by the EN 1991-1-2 standard [1] with an actual heat release rate obtained from a FDS software [7]. In this example, the FMC tool [4] is used as both pre-processor and post-processor for the data obtained from the FDS solver [7].

The main goal of this example is to determine whether the EN 1991-1-2 standard [1] predicts an appropriate type of HRR model in terms of the burning regime (i.e. ventilation-controlled or fuel-controlled fire) for given conditions, and whether the HRR model prediction provided by the standard corresponds with the actual heat release rate in a complex CFD calculations obtained by the FDS software [7].

A difference between the standard HRR model prediction and actual heat-release rate can arise due to the following fact. When defining the HRR models (i.e. the shapes of the HRR curves for the given conditions) using the EN 1991-1-2 standard [1], only few parameters of the given compartment are taken into account. However, the FDS solver [7] performing CFD calculations simulating the evolution of the fire takes into account many more parameters – such as the ventilation conditions (i.e. number and area of openings) and the chemical reaction producing the fire. Therefore, when a EN 1991-1-2 HRR model (a prediction of heat release rate) is used in the FDS solver [7] as an input prescribing the theoretical energy released by the fire, the actual evolution of the fire and the release of energy can be different than the theoretical heat release rate predicted by the EN 1991-1-2 standard [1].

For CFD modelling of fire development in FDS [7], a chemical reaction must be specified. No general recommendation for the selection of chemical reaction based on the compartment occupancies exists. Thus, based on previous analyses done by the authors, a methane reaction was chosen as the chemical reaction producing the fire. As mentioned above, the type of methane reaction can have considerable effect on the results, and more research in this area is appropriate and will be done by the authors in their future work.

In this example, the HRR models defined by the EN 1991-1-2 standard [1] were created using the FMC tool [4], see Section 3.1. These models were then imported into the FDS solver [7] as an input data prescribing the energy released by the fire. As stated above, the chemical reaction producing the fire and the heat release was chosen as a methane reaction in the FDS solver [7].

For the first variant, the ventilation conditions were chosen in a way that a fuel-controlled HRR model was obtained using the EN 1991-1-2 standard [1]. In this variant, five windows with dimensions 1500 mm × 2000 mm were considered (total openings area $A_w = 15\ \mathrm{m}^2$), see Figure 8.

The ventilation for the second variant were chosen in a way that a ventilation-controlled HRR model was obtained using the EN 1991-1-2 standard [1]. In this variant, two windows with dimensions 1500 mm × 2000 mm were considered (total openings area $A_w = 6\ \mathrm{m}^2$), see Figure 9.

In both cases, all windows were assumed as permanently opened, the door was not considered in the ventilation calculation. The fire compartment is identical with the compartment investigated in our previous work [30, 38]. The compartment walls are made of a lightweight concrete masonry, and the floor and ceiling are made of reinforced concrete. The input parameters used for the fire modelling are summarized below (see also [30]):

- characteristic fire load density $q_{f,k} = 511\ \mathrm{MJ/m}^2$ [1, Table E.4],
- design value of the fire load density $q_{f,d}$ was determined according to [1, Eq. (E.1)], active fire fighting measures were not considered,
- the heat release was determined determined according to EN 1991-1-2 [1, Annex E.4], assuming the medium fire growth rate, $t_\alpha = 300$ s, and $RHR_f = 250\ \mathrm{kW/m}^2$ [1, Table E.5],
- thermal and physical properties of the light weight concrete masonry (according to the masonry producer): $\lambda = 0.083\ \mathrm{W\,m^{-1}\,K^{-1}}$, $\rho = 300\ \mathrm{kg\,m^{-3}}$, and $c_p = 1000\ \mathrm{J\,kg^{-1}\,K^{-1}}$,
- thermal and physical properties of concrete (according to the FDS [7] database): $\lambda = 1.951\ \mathrm{W\,m^{-1}\,K^{-1}}$, $\rho = 2500\ \mathrm{kg\,m^{-3}}$, and $c_p = 900\ \mathrm{J\,kg^{-1}\,K^{-1}}$,

- geometry of the compartment is shown in Figures 8 and 9.

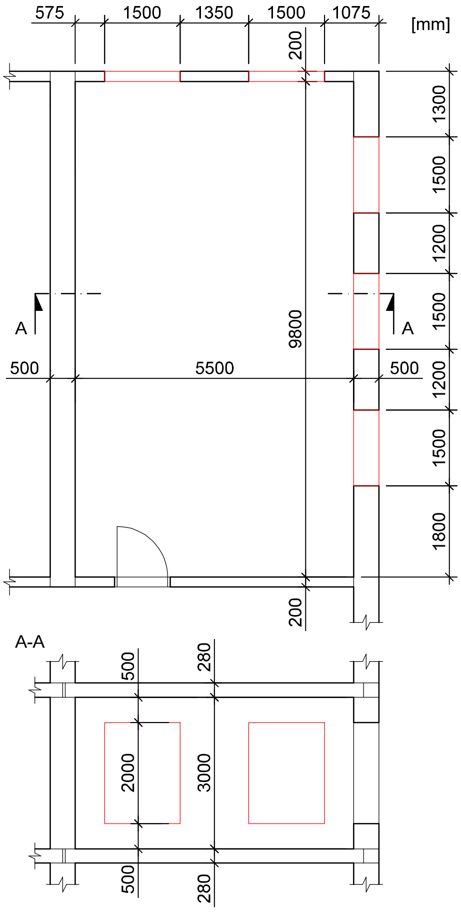


Figure 8: Scheme of the model fire compartment with five windows (see also [30]).

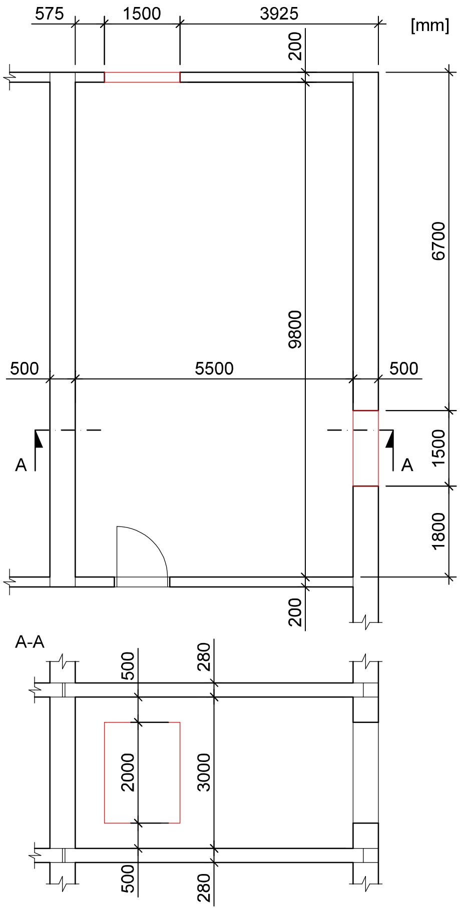


Figure 9: Scheme of the model fire compartment with two windows (see also [30]).

In this example, the HRR models defined by the EN 1991-1-2 standard [1] were created using the FMC tool [4], see Section 3.1. These models were then imported into the FDS solver [7] as an input data prescribing the energy released by the fire. The chemical reaction producing the fire and the heat release was chosen as a methane reaction in the FDS solver [7].

The FDS solver [7] then performed CFD calculations simulating the evolution of the fire in the given compartment – see the outputs from FDS software visualized using the Smokeview software [37] in Figure 10. From the obtained results, see subsections below, the actual heat release rate was compared with the theoretical heat release rate models prescribed by the the EN 1991-1-2 standard [1].

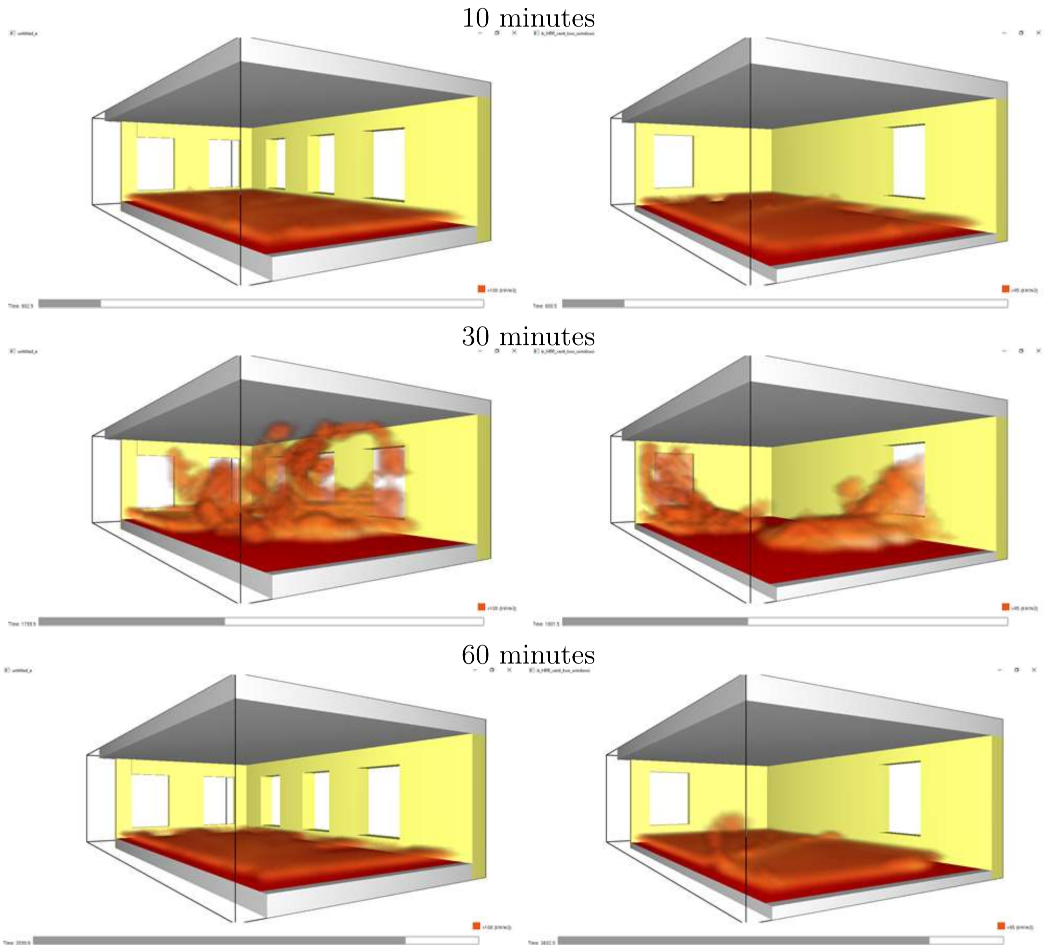


Figure 10: Visualization of the fire spreading obtained from the FDS solver [7] and Smokeview software [37] (see also [30]).

4.2.1. Fire controlled by fuel

In Figure 11, there are presented the graphs of the heat release rate predicted by the EN 1991-1-2 standard [1] for both the fuel-controlled (curve marked as *fuel-EC1*) and ventilation-controlled (curve marked as *vent-EC1*) fire in the fire compartment with five windows, see Figure 8. It is obvious that according to the EN 1991-1-2 standard [1], the fire in this fire compartment should be fuel-controlled as the predicted maximum value of the HHR curve for this burning regime is lower than the maximum value of HRR curve for the ventilation-controlled fire. In Figure 11, the graphs predicted by the EN 1991-1-2 standard [1] are also compared with the appropriate actual heat release rate obtained by the FDS solver [7]. It means that the *fuel-EC1* curve (used as an input for the FDS simulation) is compared with the actual heat release rate obtained by the FDS solver [7] – output curve marked as *fuel-FDS*; and the *vent-EC1* curve (used as an input for the FDS simulation) is compared with the actual heat release rate obtained by the FDS solver [7] – output curve marked as *vent-FDS*.

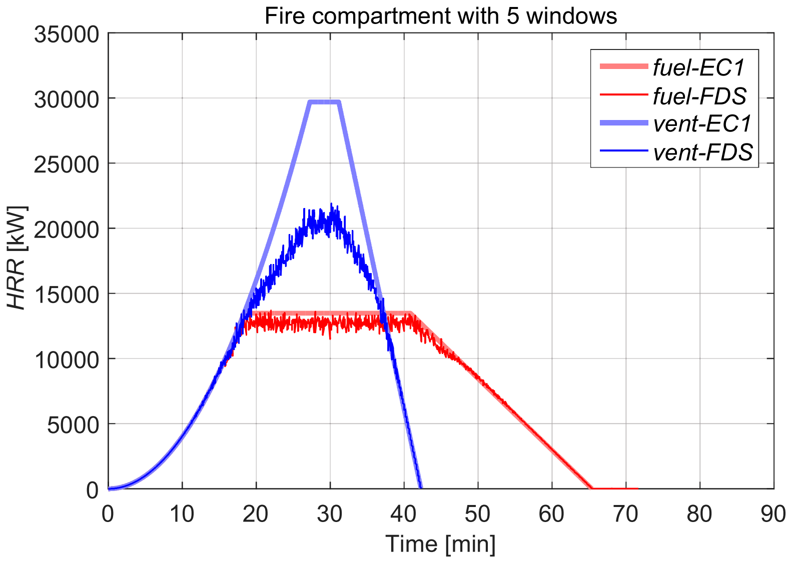


Figure 11: Comparison of the HRR prediction according to the EN 1991-1-2 standard [1] (*EC1*) and actual values obtained by the FDS solver [7] (*FDS*) for fuel-controlled (*fuel*) and ventilation-controlled (*vent*) fire in the fire compartment with five windows (see Figure 8).

For the fuel-controlled fire, the prediction of the heat release rate *fuel-EC1* shows a very good match with the actual heat release rate *fuel-FDS*, see Figure 11. This verifies that for the given compartment, the HRR type (i.e. fuel-controlled) predicted by the EN 1991-1-2 standard [1] was true.

Though the ventilation-controlled fire cannot be reached in the given compartment (i.e. there is not sufficient amount of fuel), the predicted (*vent-EC1*) and actual (*vent-FDS*) heat release rates are also compared, see Figure 11. In this case, a significant difference between the predicted and actual heat release rate can be observed both in terms of maximal values and shapes. The ventilation-controlled HRR model according to the EN 1991-1-2 [1] prediction assumed a significantly higher maximum value than the actual heat release rate calculated by the FDS solver. The maximum value according to the EN 1991-1-2 [1] is 29 600 kW, whereas the maximum value according to the FDS model is 20 900 kW which is a 30 % lower value.

4.2.2. Fire controlled by ventilation

In Figure 12, there are presented the graphs of the heat release rate predicted by the EN 1991-1-2 standard [1] for both the fuel-controlled (curve marked as *fuel-EC1*) and ventilation-controlled (curve marked as *vent-EC1*) fire in the fire compartment with two windows, see Figure 9. It is obvious from Figure 12 that according to the EN 1991-1-2 standard [1], the fire in this fire compartment should be ventilation-controlled as the predicted maximum value of the HHR curve for this burning regime is lower than the maximum value of HRR curve for the fuel-controlled fire (which means that there is not a sufficient amount of oxygen for the burning of the fuel). As in the previous case, the graphs predicted by the EN 1991-1-2 standard [1] are also compared with the appropriate actual heat release rates obtained by the FDS solver [7] in Figure 12.

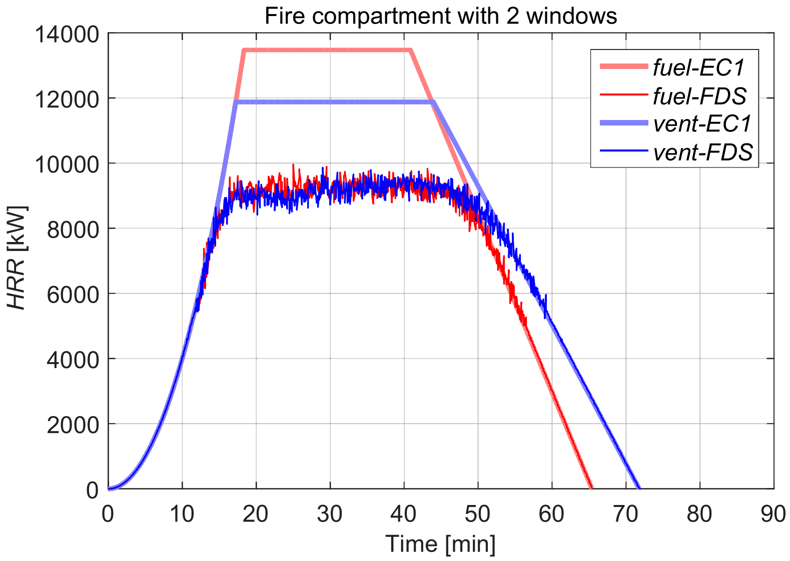


Figure 12: Comparison of the HRR prediction according to the EN 1991-1-2 standard [1] (*EC1*) and actual values obtained by the FDS solver [7] (*FDS*) for fuel-controlled (*fuel-*) and ventilation-controlled (*vent-*) fire in the fire compartment with two windows (see Figure 9).

The actual heat release rates obtained by the FDS solver [7] for both the fuel-controlled (curve marked as *fuel-FDS*) and ventilation-controlled (curve marked as *vent-FDS*) fire are significantly different from the appropriate HRR curves predicted by the EN 1991-1-2 standard [1], that were used as input data for the FDS simulations, see Figure 12. Since both curves of the actual heat release rates obtained by the FDS solver [7] provide almost the same maximum values of the HRR, they represent the maximal heat release rate which can be achieved for the given compartment conditions. This suggests that the given fire compartment does not allow the release of the energy in the amount predicted by the EN 1991-1-2 standard [1].

The difference between the predicted and actual HRR curves is lower for the ventilation-controlled fire than for the fuel-controlled fire. This could be expected since the ventilation-controlled burning regime was predicted by the EN 1991-1-2 standard [1]. However, also for the ventilation-controlled fire the difference is significant – the maximum value of the heat release rate predicted by the EN 1991-1-2 standard [1] is 11 900 kW and the maximum value determined by the FDS software [7] is about 9 400 kW which is 21 % less.

In this illustrative example, the compartment conditions did not allow for the release of energy in the amount predicted by the EN 1991-1-2 standard [1]. Therefore, for this compartment, the HRR model predicted by the EN 1991-1-2 standard [1] is relatively inaccurate and incorrect.

4.2.3. Modification of the EN 1991-1-2 prediction

From the assumption that a fire is an energy release, the HRR curve prediction can be modified to fit the actual heat release rate, see the EN 1991-1-2 recommendation [1, Cl. E.4(9)]. This modification must be carried out while satisfying the condition that the area under the actual HRR curve (i.e. the total released energy) must be equal to the area under the modified HRR curve.

As the FDS solver [7] is unable to perform this modification automatically, the HRR curve prediction according to EN 1991-1-2 standard [1] was manually modified. In this modification, the maximum value of the modified predicted HRR curve (marked as *vent-EC1-mod*) was set to be equal to the average maximum value according to the original numerical simulation from FDS solver [7] (marked as *vent-FDS*) given in Figure 12. The slope of the descending part of the modified predicted HRR curve was decreased according to the aforementioned EN 1991-1-2 recommendation [1, Cl. E.4(9)] in order to satisfy the total released energy condition, see Figure 13.

The modified HRR curve (*vent-EC1-mod*) was subsequently used as input data for a new numerical simulation in the FDS solver [7]. From this new numerical simulation, new actual HRR curve was obtained (marked as *vent-FDS-mod*), see Figure 13. The match between the modified HRR curve (*vent-EC1-mod*) and the corresponding actual HRR curve (*vent-FDS-mod*) is much better than in the previous calculation where the unmodified EN 1991-1-2 [1] curve was used. The slight difference between the two curves (*vent-EC1-mod* and *vent-FDS-mod*) is caused by the compartment structures (enclosure), see the next subsections.

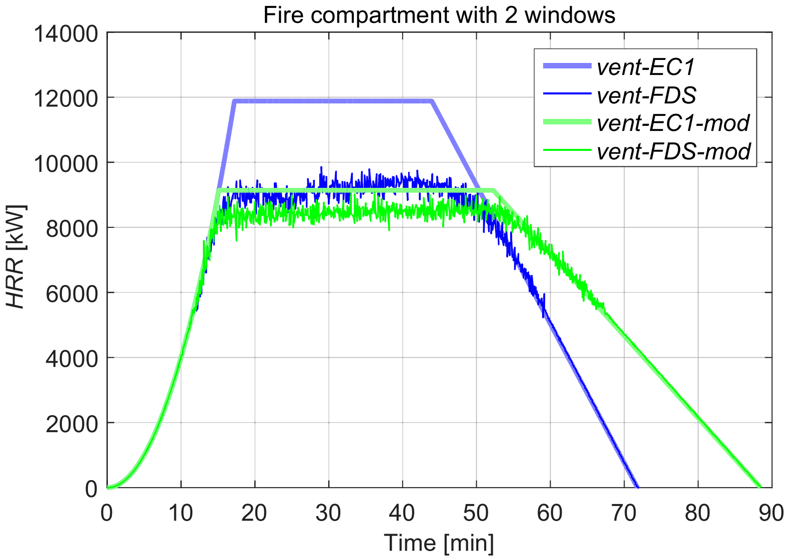


Figure 13: Comparison of the HRR curves for the fire compartment with two windows (see Figure 9) – application of the modified curve.

4.2.4. Shape of the actual heat release rate curves

In order to explain the fluctuating shape of the actual heat release rate curves obtained by the FDS solver [7], two additional CFD calculations were executed using the FDS solver [7] – one with adiabatic surfaces of the compartment structures (enclosure) and one with no enclosure.

When assuming adiabatic surfaces of the enclosure, the actual HRR curve is identical with the original actual HRR curve for boundary conditions specified in Section 4.2, see Figure 14. When assuming no enclosure, the actual HRR curve is almost identical with the predicted HRR curve, Figure 14. Based on the obtained results, it can be concluded that the fluctuating shape of the actual HRR curve and the difference between the predicted and actual HRR is caused mainly by the specific compartment structures.

However, the ventilation conditions and the type of the selected reaction (in this case the methane reaction was chosen) in FDS model have some effect on the results too.

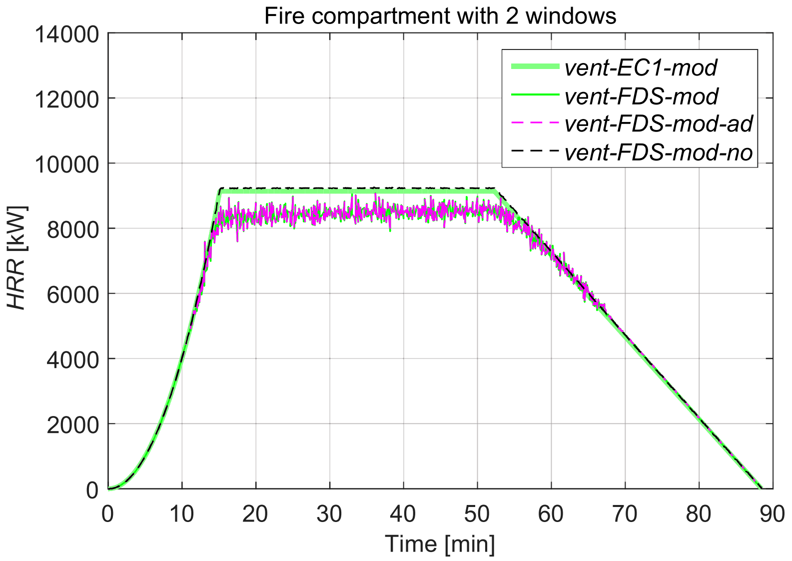


Figure 14: Comparison of the HRR curves for the fire compartment with two windows (see Figure 9) – the effect of compartment structures (enclosure) on the HRR curves. Notation: *vent-FDS-mod* – original enclosure, *vent-FDS-mod-ad* – adiabatic enclosure, and *vent-FDS-mod-no* – no enclosure.

4.2.5. Connection between the HRR and the parametric temperature-time curve

As mentioned in the previous sections, the HRR curve is dependent on both fuel and ventilation, and in this regard, the burning regime can be divided into fuel-controlled and ventilation-controlled.

According to the EN 1991-1-2 standard [1], the only other area of fire safety design where the type of burning regime (i.e. fuel-controlled vs. ventilation-controlled fire) is taken into consideration is the parametric temperature-time curve (PTC) described in [1, Annex A]. Thus, for comparison and to determine the connection between the HRR model and the parametric temperature-time curve, the burning regime predicted by the HRR model curve was compared with the burning regime determined by the parametric temperature-time curve. Moreover, temperatures obtained from FDS software for given HRR predictions were compared with the temperatures given by the parametric temperature-time curves.

The parametric temperature-time curves for both variants of fire compartment examined in this example (compartment with five or two windows) are presented in Figure 15.

The temperatures in the given compartments calculated by the FDS software were measured by 1520 thermocouples in each compartment. Both mean and maximal values of temperatures in the compartments were recorded and are also presented in Figure 15.

As can be readily seen in Figure 15, both parametric temperature-time curves assume the same burning regimes as in the case of HRR calculations – i.e. the fuel-controlled fire for the five-window compartment and the ventilation-controlled fire for the two-window compartment.

The main difference between the HRR models and the parametric temperature-time curves is the duration of the fire. For fuel-controlled fire (5 window compartment) the duration of the fire is 65 minutes for HRR model and 47 minutes for PTC model. For ventilation-controlled fire (2 window compartment) the duration of the fire is 72 minutes for HRR model and 142 minutes for PTC model. Thus, although the burning regimes are the same for HRR model and PTC model in each compartment, a significant difference can be observed in the two models. The difference can mainly be observed in regards to the durations of the fires. However, a difference can also be observed in regards to the temperatures in the compartments.

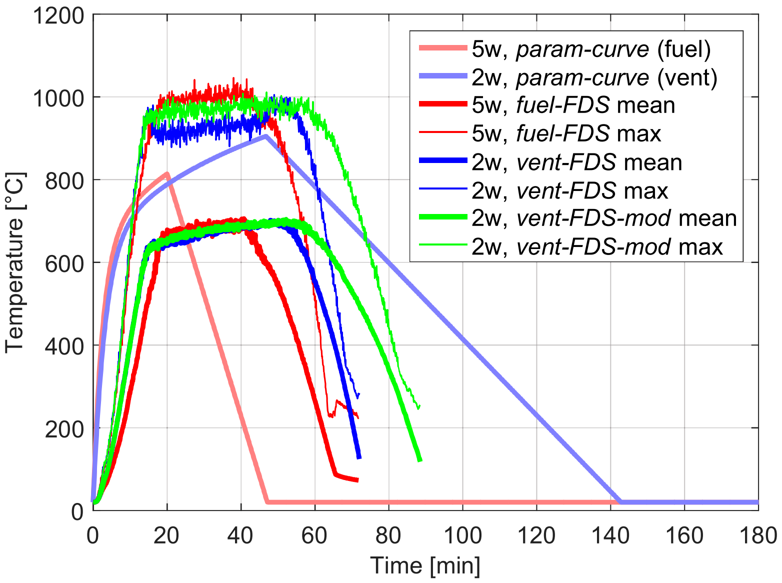


Figure 15: Comparison of the parametric temperature-time curves.

4.2.6. Discussion

From this illustrative example, the following conclusions can be drawn. The EN 1991-1-2 standard [1] accurately predicted the type of burning regime (fuel-controlled and ventilation-controlled) in both examined cases. In the case of fuel-controlled fire, the EN 1991-1-2 standard predicted the actual heat release rate almost exactly. In the case of ventilation-controlled fire, the difference between the EN 1991-1-2 standard prediction and the actual heat release rate was significant. However, when the EN 1991-1-2 standard HRR prediction was modified to fit the actual fire compartment, the difference between the prediction and the actual heat release rate was greatly reduced. A more detailed parametric study is needed in order to determine whether these results are applicable for other types of fire compartments.

5. Conclusions

In this paper, two novel software tools developed by the authors (FMC [4] and DataPlot [5]) were presented, and their applicability was illustrated on several examples. As presented in the paper, the newly developed tools are easily available for both pre-processing and post-processing of fire design related data obtained from other sophisticated programs.

Moreover, an analysis of heat release rate (HRR) of fire and ventilation conditions is presented. This analysis was focused on the comparison of simplified (EN 1991-1-2 standard [1]) and advanced (CFD modelling) approach to the HRR modelling. The main conclusion of this analysis is that the EN 1991-1-2 standard predicted the type of burning regime (fuel-controlled and ventilation-controlled) accurately. The obtained results also suggest that in the case of fuel-controlled fire, the EN 1991-1-2 standard predicts the actual heat release rate almost exactly, and in the case of ventilation-controlled fire, a significant difference between the EN 1991-1-2 standard prediction and the actual heat release rate can be observed. Thus, a modification of the EN 1991-1-2 standard prediction for ventilation-controlled fire was also introduced. When using this modified EN 1991-1-2 standard prediction the difference between the prediction and the actual heat release rate was greatly reduced. The authors of this paper recommend the use of this approach – i.e. modification of the standard prediction and recalculation of actual heat release rate based on the modified prediction – in scenarios where the standard prediction differs greatly from the actual heat release rate based on the standard prediction.

As the fire loading of structures is a significant and important topic, and the fire safety design is one of the most problematic parts of building design, further studies aimed at this topic will be carried out by the authors of this paper in the future.

Acknowledgement. This work has been supported by the Grant Agency of the Czech Technical University in Prague, project No. SGS21/040/OHK1/1T/11. The support is gratefully acknowledged.

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6.6 Paper 2

Reprint of the paper

- Post-Fire Structural Assessment of a Firefighting Training Facility: A Case Study (2021)

Contribution of the author of this thesis to the paper

- M. Benýšek is the co-author of the paper (that was written under the supervision of R. Štefan).
- M. Benýšek mainly carried out the numerical simulations of the fire stated in Section 3 of the paper (including results presentation).
- The author’s contribution is 40 %.

Post-fire structural assessment of a firefighting training facility: A case study

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Abstract

The paper focuses on a case study of a post-fire structural assessment of a training facility for firefighters. The study is conducted in order to assess the risk of damage of the load-bearing structures of the facility due to the repeated exposure to high temperatures. Flames during the fire trainings are made up by gas burners which are installed inside the building. Burners produce flames, smoke and high temperatures (up to 1000 °C). The duration of the fire trainings last 3 minutes in maximum. After the description of the analysed building, this study is divided into two main parts – a temperature analysis and a post-fire structural analysis. The Computational Fluid Dynamics (CFD) model of fire, implemented in the Fire Dynamics Simulator (FDS), shows as very powerful tool to simulate specific fire scenario. This tool, coupled with traditional structural diagnosis enables conducting the post-fire assessment and determining the level of structural damage.

Keywords: Post-fire Structural Assessment, Structural Diagnosis, Fire Fighting Training Facility, Models of Fire, CFD Model, FDS Software

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1. Introduction

The structures are normally assessed for fire resistance during the building design – before possible initialization of the fire. However, analysis of structures after the exposure of fire is also very important. So, it is necessary to determine the extent of structural damage. It depends on a specific thermal action, fire size, duration of the fire, ventilation conditions, etc. on one hand, and actual fire resistance of subjected structure on the other hand.

Some specific buildings are specially designed for repeating controlled fires. These buildings usually serve for firefighters as a training facility. It serves for the training of movement and orientation in a smoky space, exposure of firefighters to the high temperatures, eventually for the training of inhabitants evacuation. One of these objects is analysed in the present paper.

Fire can be idealized by models of fire. The basic mathematical models of fire are the nominal temperature-time curves, such as the standard temperature-time curve, external temperature-time curve, etc. These curves are only time-dependent and they are the most conservative models. The more sophisticated models of fire are the natural models which can be simplified (local fires, parametric temperature-time curves) or advanced (zone models or computational fluid dynamics models – CFD), see e.g. [1–11].

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Usually, when a structure has been exposed to fire, a post-fire assessment is needed in order to prove whether the structure is still safe and reliable. During the assessment, as much information about the fire event as possible have to be gathered – foremost duration of the fire and maximum reached temperatures. Moreover, material tests proving the actual mechanical properties are needed almost in every case. Also, the possibility of irreversible changes of a static scheme of the structural system has to be checked. Then, based on aforementioned information, the calculation of residual load-bearing capacity can be carried out. Results of such a calculation are then used for the decision about the future usability of the building. Generally, three possible decisions can be made: (i) the building is safe and reliable enough without refurbishment, (ii) the structure has to be strengthened (or acting loadings reduced), or (iii) the building has to be demolished for the reason that the strengthening and refurbishment is not possible nor cost-effective.

In order to obtain higher level of certainty of the post-fire assessment, the information gained experimentally on site or thanks to fire brigade reports should be accompanied by theoretical thermal analysis modelling a certain fire scenario. CFD models represent modern approach which can describe very specific fire scenarios assuming real conditions in the analysed space. Results of such calculations can be then used for post-fire structural diagnosis and assessment [13–16].

The present paper focuses on a case study of a post-fire structural assessment of a training facility for firefighters. It was decided to conduct the post-fire structural assessment in order to evaluate the extent of the possible negative effects the fire trainings should have on the structure in order to ensure the object's operation in the future. The assessment consists of two tasks – modelling of fire and post-fire structural analysis.

Modelling of fire focuses on restoring real fire scenario and evaluating the temperature evolution in the building. The Computational Fluid Dynamics (CFD) model of fire, implemented in the Fire Dynamics Simulator (FDS) [12], is employed for this analysis. The simulations help to determine the suitable positions of the core cut-outs of concrete specimens which are used for the post-fire structural analysis.

Second part of the assessment consists of post-fire structural analysis. At first, preliminary and detailed inspection of the building is conducted. Based on gained findings both concrete and steel specimens are extracted from structure and tested in laboratory in order to obtain actual material properties after the exposure to high temperature.

The results of the material tests are compared with theoretical material deterioration models with respect to the temperatures obtained using FDS simulations.

After that, residual structural performance is evaluated and appropriate refurbishment is designed.

The analysed building is described in Section 2. Input data for fire simulations and the models of fire created in FDS software are given in Section 3. Post-fire structural analysis consisting of visual assessment, structural diagnosis, evaluation of results, thermal analysis of selected elements and assessment of residual load-bearing capacity is stated in Section 4. In Section 5, summarizing conclusions are given.

2. Description of the building

The analysed building, see Fig. 1, is a part of firefighters headquarters and is being used as a training simulator for firefighter apprentices, who practice to fight real-scale fires. For such purposes, several gas burners producing flames, smoke and high temperatures (up to

1000 °C) are installed inside the building. Although very high temperatures are reached during the trainings (according to the thermal power of each burner), the trainings last only for several minutes, usually no more than 3 minutes.

Figure 1: The analysed building.

The analysed building is a two-floor structure with one underground floor. Overall dimensions of the building are approximately 13 m × 8 m and the height is 7.5 m. The structural system consists of reinforced-concrete (RC) walls and slab combined with steel floor beams. Roof structure consists of steel rafters and purlins and trapezoidal steel sheets. RC walls are 250 mm and 200 mm thick. RC slab above underground floor is 200 mm thick. Steel floor beams are I-shaped profiles (IPE180). In order to mitigate the structural damage caused by repeating high temperatures exposure, all rooms where the burners are installed are equipped with protective soffits and tiling made of steel sheets. The gap between the structure and protective layer is ventilated by fans during the training and also certain time after its ending. Thus, the structures are not exposed to the flames, high temperatures and extinguishing directly. Regardless of the positive effects of the protective measures, the structural assessment of the whole building was demanded by inner policy of the Czech Fire Rescue Service to specify the extent of structural damage caused by repeating fire trainings. For the reason that the building was originally not designed for this purpose, but it has been serving in this way for more than 10 years, the following questions are about to be answered:

- To what extent do fire trainings damage the structure?
- Is the structure reliable and safe enough to continue serving in the same manner in long-term views?
- Is it necessary to repair the structure or to strengthen it?

Based on the task, structural assessment was conducted in order to provide answers to the aforementioned questions. Within the assessment, the following steps were carried out:

- Detailed visual assessment of a structure.

- Structural diagnosis consisting of extracting samples of both concrete and steel, on-site non-destructive testing (NDT) of concrete and laboratory destructive testing of concrete and steel specimens, and evaluation of test results. Since the possibilities of diagnosis testing were limited, the material deterioration was also calculated using the theoretical material deterioration models proposed in [17–19], with respect to the temperatures obtained using FDS simulations (see Section 3). Results of both approaches were compared.
- Calculation of residual load-bearing capacity.
- Design of necessary refurbishment.

The floor plans of the analysed building, with the locations of the gas burners, are shown in Figs. 2 and 3.

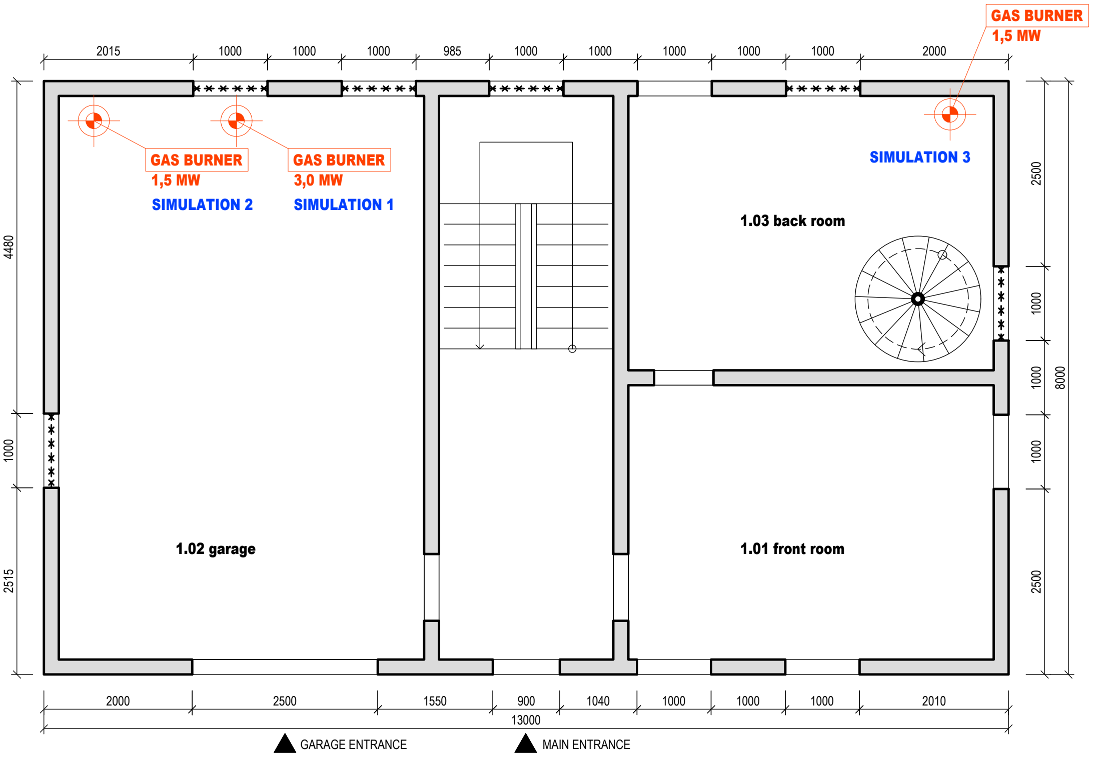

Figure 2: The first floor of the analysed building.

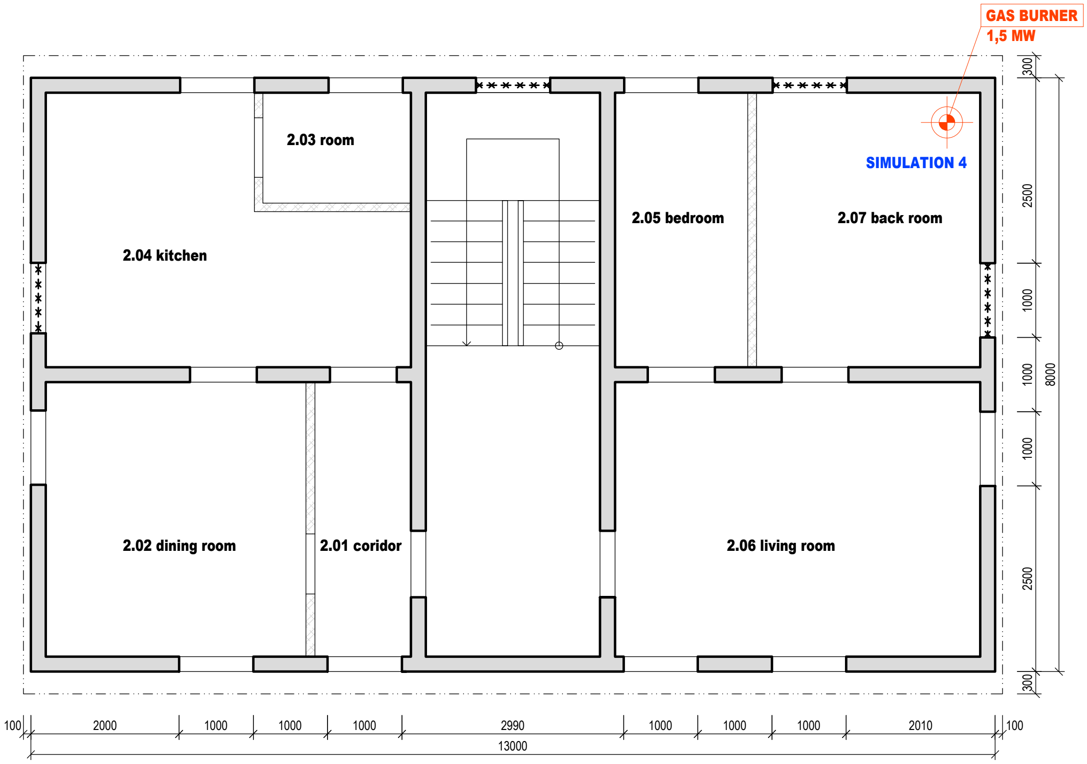

Figure 3: The second floor of the analysed building.

3. Modelling of fire

For the modelling of fire in the analysed building, it was needed to create the CFD simulations which were done in the FDS software [12]. The gas burners were used, positions and values of the heat release rate are depicted in Figs. 2 and 3. Based on the results, the appropriate positions (in areas with the highest temperatures) for the concrete core cut-outs were determined. These concrete core cut-outs were subsequently used for the structural analysis, see Section 4. LPG is used as the fuel of the burners. The trainings last only for several minutes while most often they last up to 3 minutes. As no burner was installed in the underground floor, this floor is not analysed in this study.

3.1. Input data for fire simulations

The conditions in the analysed building during the trainings and the appropriate input data employed for the FDS simulations are summarised below:

- only one burner is active at the same time,
- doors and gates are fully opened (both indoors and outdoors),
- some windows are without filling and for the simulation, these windows are assumed as permanently opened,
- some windows (highlighted by dashed lines with x markers in the plans) are covered by metal sheet, these windows are omitted in the simulations, see Figs. 2 and 3,

- space between the soffit and the load-bearing structure in the first and the second floor (except room No. 1.03) is intensively force-ventilated, ventilators are in progress during the training and couple minutes after its ending; the ventilation was neglected in FDS simulations,

- protective tiling of walls were also neglected in FDS simulations,

- space between the soffit and the load-bearing structure in the first floor in room No. 1.03 is not intensively force-ventilated,

- burners are equipped by the shielding plates which influence the flow of the hot gasses.

3.2. Fire simulations in FDS

The Fire Dynamics Simulator (FDS) [12] software was used for the simulations of fire in the analysed building to predict the temperature distribution in the space and to determine the most suitable positions for core cut-outs of the concrete for following analysis of the structure. As a pre-processor, the Pyrosim software [20] was used. For visualization of results, the Smokeview software [21] was applied. The overall model of the building is shown in Fig. 4.

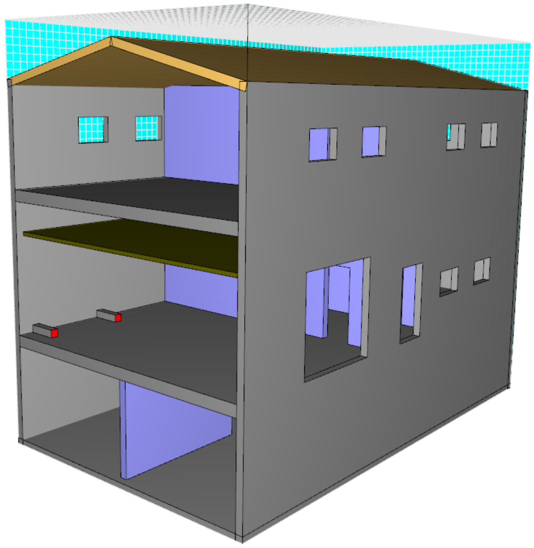

Figure 4: Overall visualization of the analysed building created in the Pyrosim software [20] (side wall is invisible).

During the simulations, the material properties are constant and they are considered according to EN 1992-1-2 [17]. The number of cells for the computational mesh is 143000, the cell size is 0.2 m × 0.2 m × 0.2 m, division method is uniform. Other parameters are as follows:

- fire simulation time 180 seconds according to the real training duration,

- ambient temperature 20 °C,

- ambient pressure 1013.25 hPa,

- relative humidity 40.0 %,

- simulation type – Very Large-Eddy Simulation (VLES) [12],
- temperatures were measured via thermocouples under the ceiling (mesh 0.5 m$\times$0.5 m), see Fig. 5.

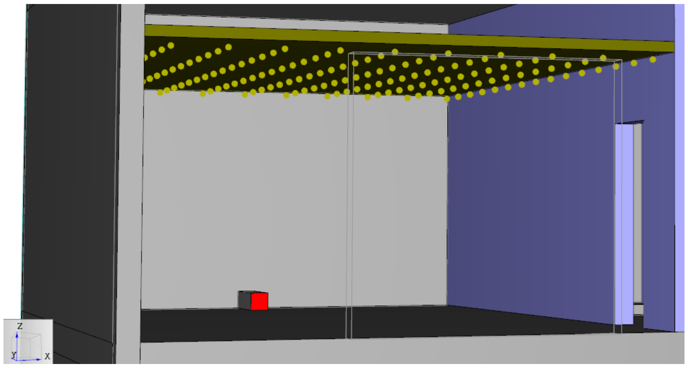

Figure 5: Visualization of the thermocouples in Pyrosim [20] (room 1.02; front wall is invisible).

The heat release rates of burners in simulations were set to 1.5 MW or 3.0 MW, according to the real power of the burner, see Figs. 2 and 3. The area of the burners was set as 0.2 m × 0.2 m. Each burner starts in $t = 0.1$ s with maximum released energy. With the respect of the burners location, four simulations in FDS were created:

- No. 1: burner in the middle of the room 1.02, HRR = 3.0 MW, see Fig. 6,
- No. 2: burner in the corner of the room 1.02, HRR = 1.5 MW, see Fig. 7,
- No. 3: burner in the corner of the room 1.03, HRR = 1.5 MW, see Fig. 9,
- No. 4: burner in the corner of the room 2.07, HRR = 1.5 MW, see Fig. 10.

3.3. Results

The results from the simulations No.1 and No.2 are shown in Figs. 6 and 7. The front wall is set as invisible. Temperatures are shown graphically.

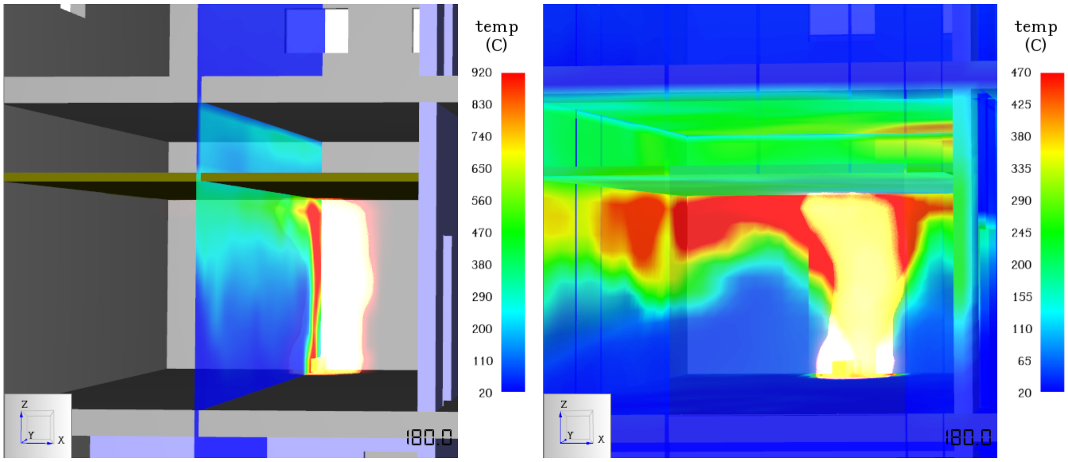

Figure 6: Simulation No. 1, $t = 180$ s, left – gas temperatures, right – wall temperatures (front wall is invisible); visualised by the Pyrosim software [20].

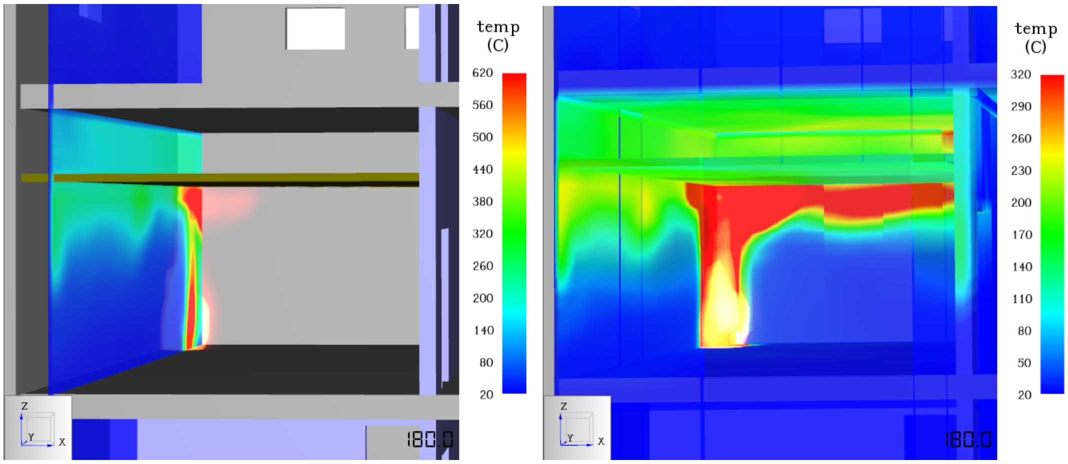

Figure 7: Simulation No. 2, t = 180 s, left – gas temperatures, right – wall temperatures (front wall is invisible); visualised by the Pyrosim software [20].

The graphs of temperatures from thermocouples and the heat release rate from simulation No. 1 are shown in Fig. 8 for the detailed description of the results. For the comparison, five thermocouples above the burner with the highest temperatures were chosen. The gas burner was set in this case to 3.0 MW, see Fig. 8. In simulation No. 1, the gas temperatures around the ceiling reach the maximum value approximately 920 °C, see see Fig. 8.

In simulation No. 2, the gas temperatures reach only approx. 620 °C which was assumed because the burner had a lower value of the HRR.

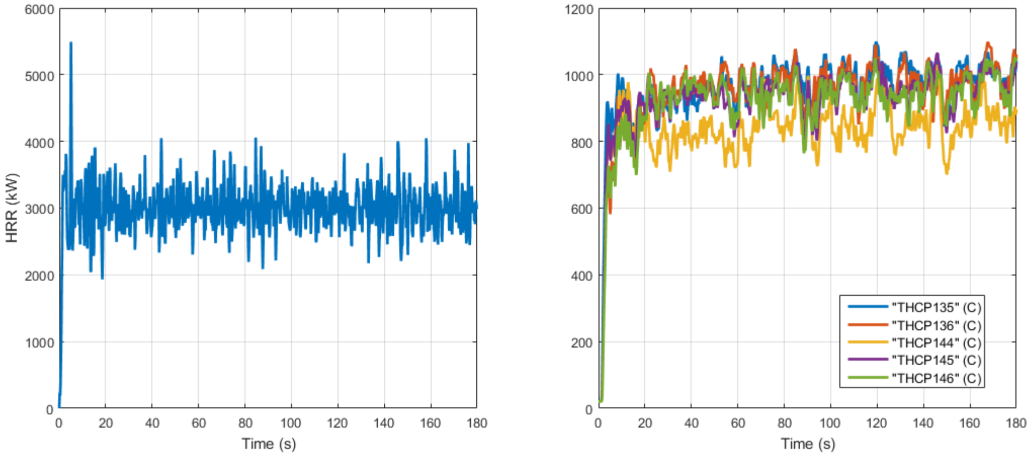

Figure 8: Simulation No. 1, left – heat release rate measured in FDS [12], right – five thermocouples above the burner with the highest gas temperatures; visualised by the Pyrosim software [20] and the FMC software [22].

The results of simulation No. 3, burner 1.5 MW, are shown in Fig. 9. It can be seen that the hot gases go through the spiral staircase into the room 2.07, where uncovered steel structures are exposed to high temperatures. The shielding plates which direct the flow of the hot gasses are placed around the burner. Hence, the hot gasses flow back to the side wall, see Fig. 9. Space above the ceiling of the room no. 1.03 is not force-ventilated, thus the high temperatures affect the ceiling structures.

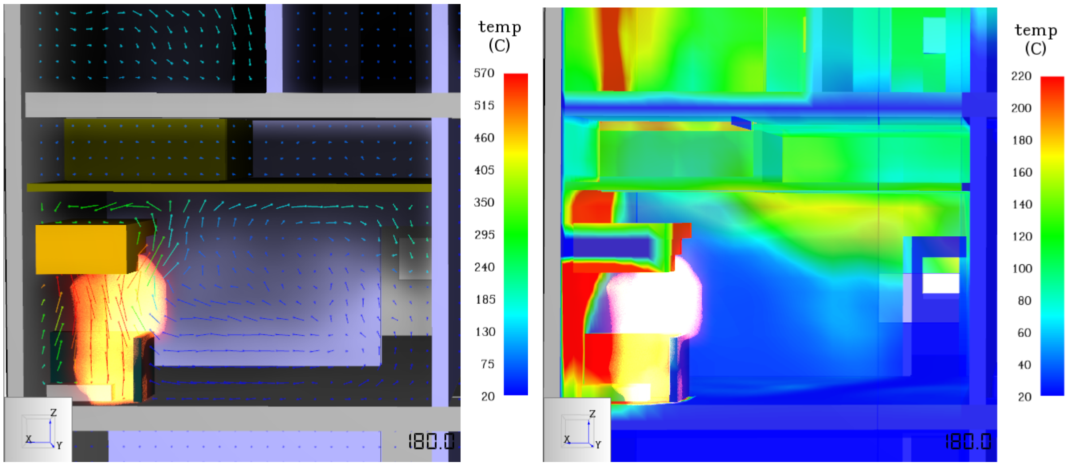

Figure 9: Simulation No. 3, $t = 180$ s, left – vectors of gas temperatures with smoke, right – wall temperatures (back wall is invisible); visualised by the Pyrosim software [20].

In simulation No. 3, the gas temperatures around the ceiling reach the maximum value approximately 570 °C, see Fig. 9.

The burner with HRR 1.5 MW for simulation No. 4 is placed in room 2.07, see Fig. 3. The results are shown below, see Fig. 10. In this case, gas temperatures reach approximately 770 °C and the shielding plates direct the flow of the hot gasses. The HRR for simulations No. 3 and No. 4 are shown in Fig. 11. The burners have in both cases 1.5 MW.

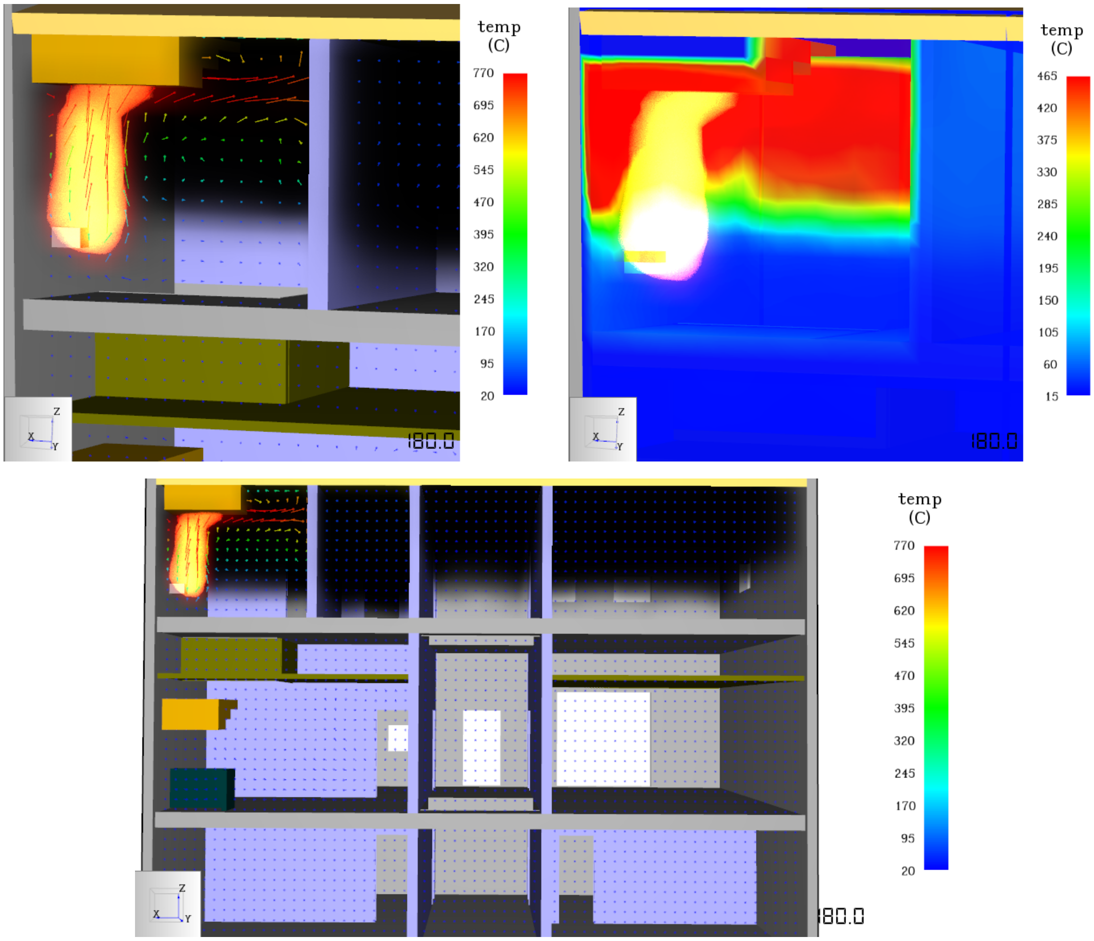

Figure 10: Simulation No. 4, $t = 180$ s, top left and bottom – vectors of gas temperatures with smoke, top right – wall temperatures (back wall is invisible); visualised by the Pyrosim software [20].

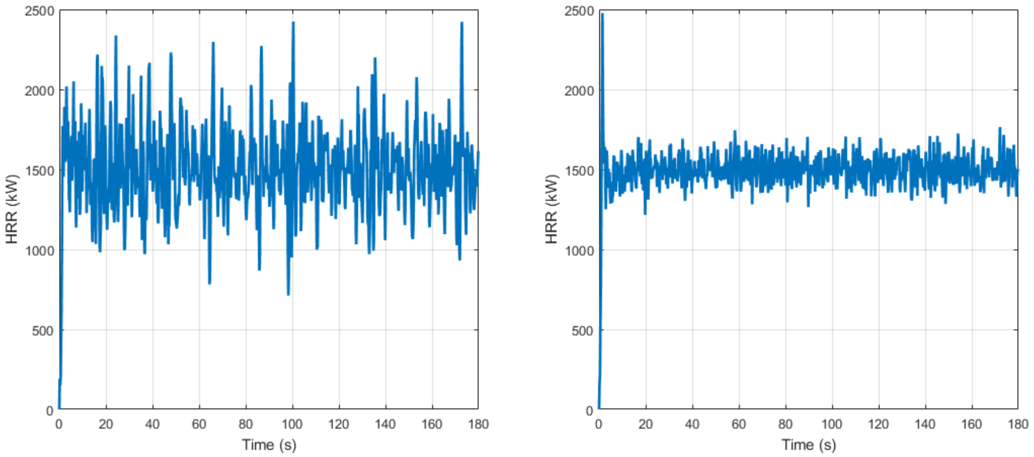

Figure 11: Heat release rate measured in FDS [12], left – simulation No. 3, right – simulation No. 4; visualised by the FMC software [22].

4. Post-fire structural analysis

4.1. Visual assessment

The post-fire structural assessment has begun with preliminary inspection of the whole building. The function of the burners was demonstrated by a short test, see Figs. 12 and 13.

Figure 12: Example of fire test in garage in the first floor.

Figure 13: Example of fire test near spiral staircase in the first floor.

Within the preliminary inspection the construction system together with protection substructures was studied. Potential critical spots were identified according to positions of gas burners and visible deterioration. Also, information needed for conducting the FDS simulations were obtained from the building's technicians, including specification of burners thermal power, their shape, position and type of the used gas. As a result of the preliminary inspection, extent of forthcoming structural diagnosis was determined.

As a following step of post-fire assessment, detailed inspection of the building was carried out. Areas and structures influenced by the fire trainings were identified and drawn into structural drawings of all floors, see Figs. 14 and 15. Such areas were marked as "ZONE 1"–"ZONE 3" with assumed maximal reached temperatures and duration. Individual structural elements were classified into "damage classes" according to their presumed damage level.

The classification was done in accordance with the methodology proposed in [23]. This classification of each affected element was also drawn into the mentioned drawings.

As a second part of the detailed inspection output the forthcoming structural diagnosis was planned. Spots for extracting cores out of RC walls and slab were defined as well as spots for extraction of steel specimens out of the floor beams. Then spots for conducting the rebound hammer tests were determined. All of mentioned information were drawn into the structural drawings. Table of used symbols can be found in Fig. 16.

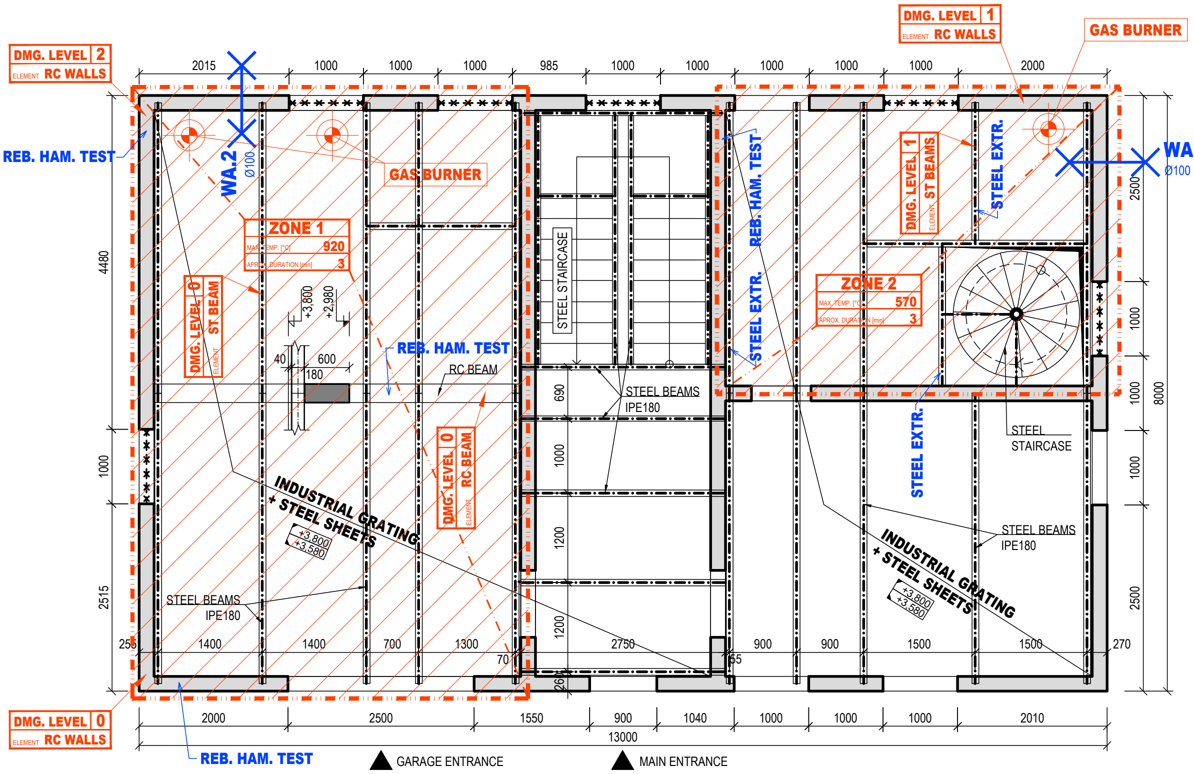

Figure 14: Shape of the first floor with drawn results of visual inspection.

Based on the performed visual assessment it can be stated that RC structures did not exhibit significant damage. The structural element surfaces were directly visible as the protective tilling and soffits were removed at the time of inspection. No extensive surface damage was found except of several places near the windows where hot gasses leave the building during the trainings. No spots with spalled cover layer were found. The reinforcement was thus nowhere exposed directly to air. Also, no buckled or ruptured rebars were found. The surface of concrete was either coloured to black by soot or had natural concrete colour. RC elements did not exhibit extensive deflections.

Steel floor elements in ceiling structures above the first and second floor are in very good condition since no evidence of corrosion, extensive deflections, buckling or distortion was found. This is probably thanks to the effective system of ventilated soffits. Based on this analysis, it can be concluded that the elements were affected by fire trainings only to negligible extent. However, there is one exception – the soffit in the room with spiral staircase in the first floor ("ZONE 2") was not ventilated. Therefore, hot air could accumulate in the space above soffit, even though its majority flew to the second floor through staircase opening due to the chimney effect. Nevertheless, steel beams in this location are much more corroded,

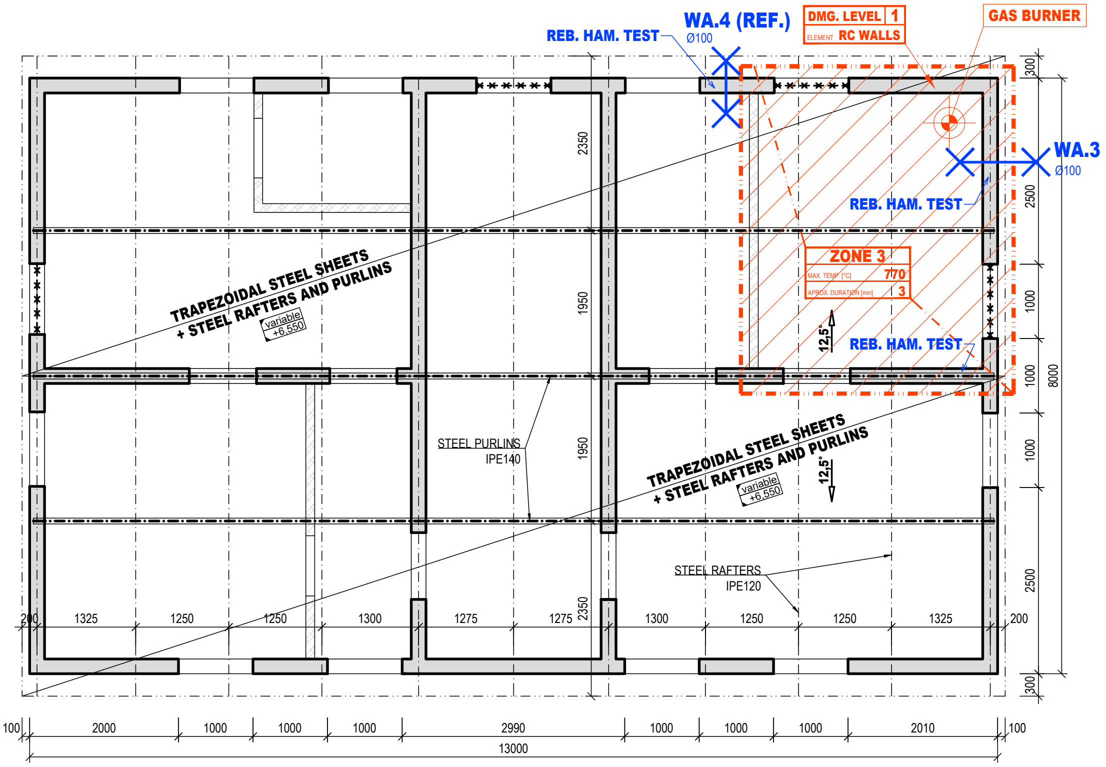

Figure 15: Shape of the second floor with drawn results of visual inspection.

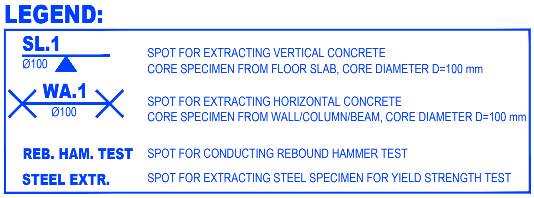

Figure 16: Legend of used symbols in the detailed inspection graphical output.

see Fig. 17. However, no excessive deflections nor buckling were found.

4.2. Structural diagnosis

After conducting the visual assessment, it was determined that the possibly damaged material will be inspected in detail in the terms of structural diagnosis. Number of spots were chosen for extracting concrete specimens by core drilling – 4 cores out of walls. Diameter of all cores was equal to 100 mm. The cores were then tested in laboratory hydraulic press to obtain concrete compressive strength (average value with respect to the damage depth caused by high temperatures exposure). Beside the destructive testing of concrete, it was also determined to inspect the concrete deterioration in the means of hardness decay of surface exposed to fire training by conducting rebound hammer test, which is testing method suitable for such purposes with some limitations [24]. Steel of elements in "ZONE 2" was about to be inspected by conducting yield strength tests of 8 specimens cut out of the structure (4 pieces from bottom flange of I-beams and 4 pieces of supplementary soffit structure). All information related to the structural diagnosis are plotted in blue in Figs. 14 and 15. The on-site diagnosis and laboratory tests are captured in Figs. 18 and 19.

Figure 17: Floor steel beams above the first floor near spiral staircase, “ZONE 3”.

Figure 18: Left: conducting rebound hammer test; right: steel specimen cut out of floor beam in “ZONE 2”.

4.3. Evaluation of results

Based on the results of both on-site and laboratory material tests, it can be stated that the compressive strength of concrete specimens obtained from destructive tests lies within range $f_{c,is} = 29.7$–42.6 MPa (the subscript “is” means “in structure”, see EN 13791 [25]). The range corresponds well with the mean compressive strength of concrete class C30/37 ($f_{cm} = 38$ MPa according to EN 1992-1-1 [26]). However, there is one exception – compressive strength of specimen “WA.2” from the peripheral wall in “ZONE 1” is equal to $f_{c,is} = 22.8$ MPa which corresponds rather to concrete strength class C16/20 ($f_{cm} = 24$ MPa according to EN 1992-1-1 [26]).

Rebound hammer tests were performed in spots in the RC slab, beam and walls (see Figs. 18 and 19). Ten “Q-value” measurements of characteristic area on an element were carried out. The lowest and the highest measured values were excluded and mean value and standard deviation were calculated. To convert the “Q-values” to the compressive strength standard conversion curve for modern concrete mixes proposed by hammer manufacturer was used. The results were then adjusted according to the approach given in [27] based on the comparison with destructive tests results. Based on the rebound hammer test results evaluation it can be stated that

- concrete compressive strength of corner wall near garage entrance is similar to reference measurements of unaffected elements (beam and upper part of walls above soffit) while compressive strength of walls near burners in the same zone are by 30 % lower than the referential strength;

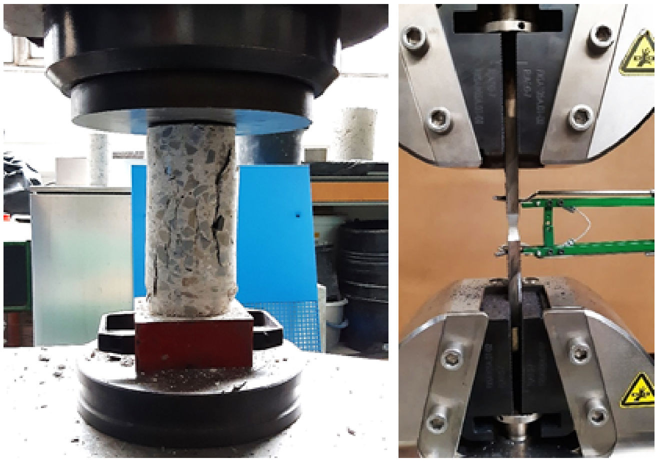

Figure 19: Left: concrete core destructive compressive strength test; right: steel yield strength test.

- measured strength of elements in “ZONE 2”–“ZONE 3” follows similar trend – strength of walls near burners are either equal to or slightly higher than required strengths and by 20 % lower than referential strengths in average.

By analysing the results of yield strength test, it can be stated the yield strength of steel specimens cut out of the structure lies within the range $f_{y,is} = 284.9$–383.8 MPa which corresponds very well with the steel strength class S235. Therefore no decay of load-bearing capacity is expected. Although the beams located in not-ventilated soffit visually seemed to be corroded, after closer inspection it was found out that the incoherent and blackened layers are the original damaged painting and pieces of soffit sheets which were fused to the beams by heat.

The case of the analysed building is specific in the way that the structural elements are being exposed to high temperatures repeatedly. However, according to the published knowledge [19], the most important aspects are the maximum reached temperature and the duration of the exposure. The potential repetition does not have significant effect on the residual load-bearing capacity. It could change the state of moisture content in concrete matrix and cause problems with explosive spalling, however this was not the case of the analysed building. Therefore, the structures and subsequent analysis were treated in the same way as in the case of single exposure to fire – which was satisfactorily confirmed by results of material tests.

4.4. Thermal analysis of selected elements

Because the possibilities and range of structural diagnosis were quite limited and the whole post-fire structural assessment had to be finished in a short time to ensure the continuity of the building service, it was not possible to conduct the diagnosis and its evaluation in more detail. Therefore, it was determined to support the diagnosis with the FDS simulation of temperatures evolution during the fire trainings. Attention was focused on critical spots where results of diagnosis were compared to the theoretical calculations which helped to derive more reliable conclusions.

According to maximal reached zone temperatures and results of material tests, the following structural elements were chosen to be inspected in detail:

- Peripheral wall near gas burners in “ZONE 1”, in the first floor;

- Steel floor beams in “ZONE 2”, above the first floor.

As a result of conducted FDS simulations, temperature-time curves in critical spots were derived and used in thermal analysis of a RC wall and one typical steel beam. Thermal analysis of RC elements was performed using in-house built software TempAnalysis [28], thermal analysis of steel beam was performed using incremental method in in-house tool developed in MS EXCEL environment. The resulting temperature profiles and evolutions are depicted in Figs. 20 and 21. Thermal properties describing concrete and steel behaviour at elevated temperatures were taken from EN 1992-1-2 [17] and EN 1993-1-2 [18] recommendations. Thermal conductivity of concrete was assumed by the lower limit and specific heat capacity was related to 2% moisture content. After correlation of surface temperatures the heat transfer coefficient was estimated as $\alpha_c = 10\ \mathrm{W\,m^{-2}\,K^{-1}}$.

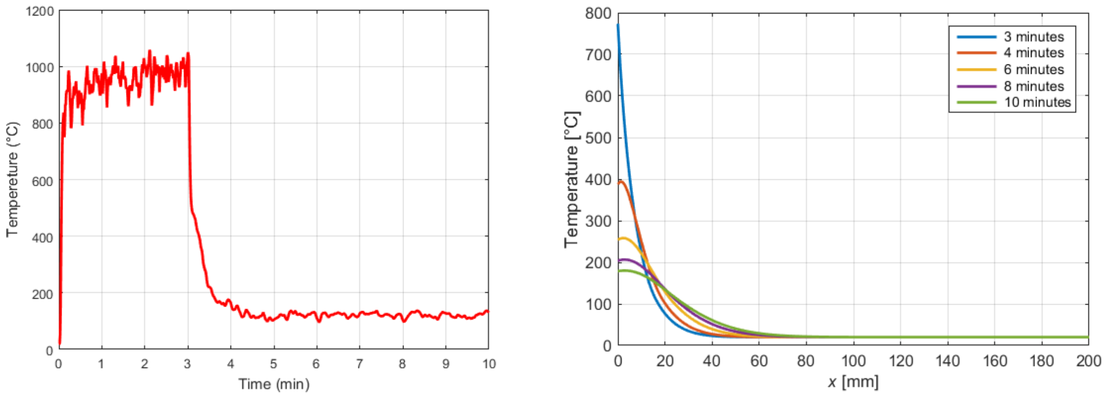

Figure 20: Left: temperature-time curve in “ZONE 1” – mean values of the gas temperatures presented in Fig. 8; right: temperature profiles of outer wall.

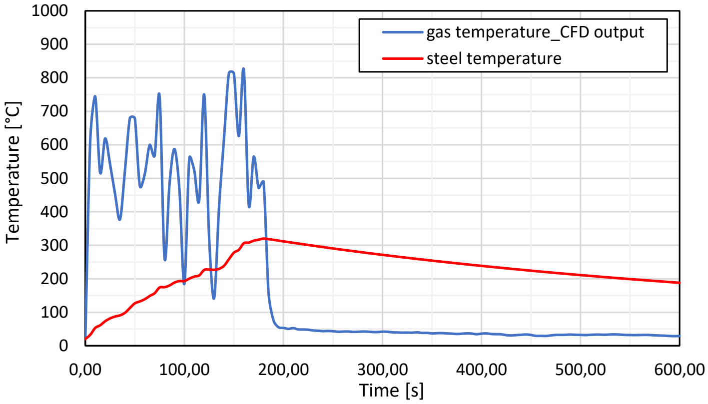

Figure 21: Gas and steel beams temperature in “ZONE 2”.

Based on the thermal analysis of selected structural elements, it can be stated that:

- The surface temperature of the outer reinforced-concrete wall in “ZONE 1” nearly reaches 800 °C in time $t = 3$ min. Thanks to the short exposure time most of the inner concrete remains unheated. Based on this findings, it is expected that the decay of mechanical properties takes place in the concrete cover only. According to the temperature profile it is expected that the surface layers heated to more than 300 °C are damaged (strength decay of approx. 20 % while the 300 °C isotherm is approximately 10 mm deep). The results rebound hammer test usually refer about state of approximately 20–30 mm thick surface layer [29]. Then it can be stated that the experimentally observed decay of hardness and subsequently compressive strength corresponds well with the theoretical strength decay assumed according to EN 1992-1-2 [17] – for average temperature of cover layer equal approximately to 250–300 °C the decay of compressive strength in range 15–20 % is expected.

- The temperature distribution along the concrete core seems to correspond well with the conducted indicative colorimetry analysis. According to that the colour of approximately 10 mm thick layer on the side exposed to high temperatures slightly changed to orange or pink shade. The photographs of chosen concrete core with notes can be seen in Fig. 22.
- According to CFD simulation and subsequential thermal analysis, the temperature of floor steel beams located in the not-ventilated soffit in "ZONE 2" reached approximately 350 °C which is temperature not lowering the yield strength, either at hot or residual state (e.g. [30]), thus the steel should preserve its initial yield strength. Results of destructive material tests confirmed that no significant decay of yield strength happened which corresponds well with the findings of thermal analysis.

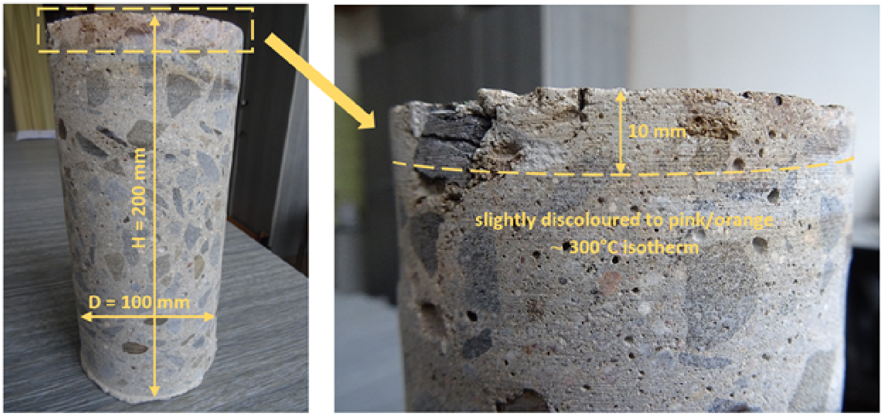

Figure 22: Concrete core "WA.2" – estimation of approximate damage depth using colorimetry method.

4.5. Assessment of residual load-bearing capacity

At this stage of structural assessment actual material properties and probable temperature distribution in the most exposed elements were known. Using this information residual load-bearing capacity could be checked. With the gained knowledge about the structure several elements were chosen to be calculated:

- corner part of outer wall in "ZONE 1" with reduced compressive strength of concrete,
- steel floor beam in the not-ventilated soffit placed along the opening in the ceiling for staircase.

In case of the outer wall the residual load-bearing capacity in Ultimate Limit State (ULS) could be calculated using several different approaches.

First option is to lower compressive strength of concrete for whole cross-section according to the strength of the surface layers. This approach is suitable for slightly damaged concrete elements with reinforcement unaffected by high temperatures.

Another approach is based on the principle of well-known "isotherm 500 °C" method for assessing fire resistance of concrete elements (see EN 1992-1-2 [17]). However, in case of assessing structures after fire the limiting temperature seems to be different to 500 °C due to the residual mechanical properties of concrete which are generally lower than those at "hot state" [31]. According to [23] the limiting temperature is said to be 300 °C – it means the part of cross section that reached during fire 300 °C or more is excluded from calculations.

Last possible approach is to conduct the calculation as detailed as possible and to divide the cross-section on strips according to temperature distribution during fire with its own reduction of residual compressive strength of concrete. In all cases the calculation itself is conducted in the same way as in normal temperatures but using different either material properties or cross-section dimensions, see e.g. our previous work [32–34] and references therein.

In case of the outer wall in "ZONE 1", the first option was chosen as a compromise between time and labour demands and needed accuracy. According to results of material tests concrete compressive strength was lowered by three concrete strength classes (from C30/37 to C16/20) and with such input the load-bearing capacity was estimated using N-M diagram (see Fig. 23). Since the post-fire situation is related to the ordinary ULS situation at normal temperature, all loadings and material safety factors are taken in the calculation with the values used for normal temperature calculations. It can be stated that the point representing loading lies deeply inside the diagram and that there is more than sufficient reserve in load-bearing capacity even though the element was negatively affected by exposure to high temperatures.

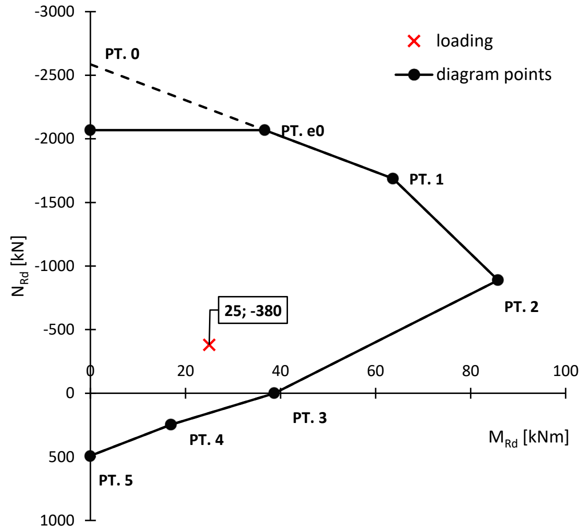

Figure 23: N-M diagram of outer RC wall in "ZONE 1" proving sufficient residual load-bearing capacity.

Tests of tensile strength of floor steel beams in "ZONE 2" together with conducted thermal analysis proved that the residual yield strength is not lower that the strength required in original documentation. Therefore, it was decided to check the load-bearing capacity with initial material characteristics. For this purposes diagram of bending moment along the beam was created with drawn load-bearing capacity (see Fig. 24). Since the assessment refers to the state after fire when structure has to fulfil the same requirements as undamaged structures, all loadings and material safety factors are taken in the calculation with the values used for normal temperature calculations.

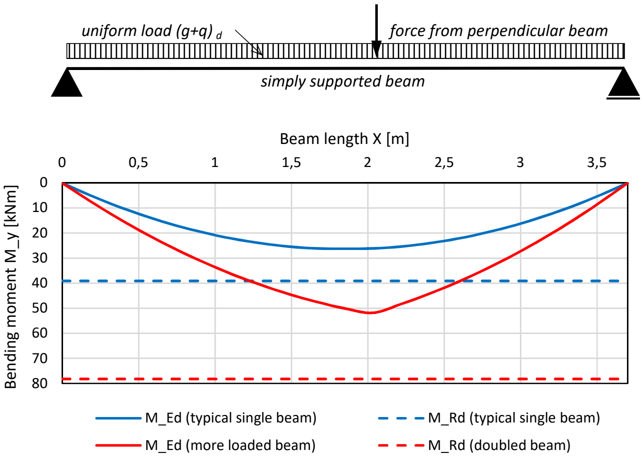

Figure 24: Diagram of bending moment along floor steel beam in "ZONE 2".

It is also worth to mention that the lateral torsional buckling of steel beams was not incorporated in the calculation due to ensured stability of compressed upper flange of beams by connected floor layers. Based on the diagram it can be stated that the load-bearing capacity of typical floor beam is sufficient.

Unrelated to the post-fire assessment another structural check was conducted. The longitudinal beam going along the opening for staircase is additionally loaded by transverse beam. The opening was made in the floor additionally and the structural consequences were not reflected. Thus, bending moment of mentioned beam exceeded the load-bearing capacity of single beam. Because it was not possible to lower the acting loads (mainly live loads) it was designed to double the beam with another IPE180 profile. Load-bearing capacity of such doubled-beam is then sufficient.

5. Conclusion

The paper was focused on the case study of post-fire structural assessment of a firefighting training facility. The purpose of this study was the fact, that the facility is repeatedly exposed to fires from the gas burners. The main aims were the determination of the temperatures during the tests and their impact on the structures.

For analysis of the temperatures, the CFD model of fire, implemented in the FDS software, was applied. Based on conditions in the analysed building, four numerical simulations of the fire were created. The simulations helped to determine the suitable positions of the core cut-outs of concrete specimens which were used for the post-fire structural analysis.

As it can be seen in the present paper, the FDS software is a very powerful tool for determination of the temperature evolution and provides a good match with the measured temperatures by the firefighters during the fire test in the analysed building.

From the structural point of view, concrete and steel load-bearing elements inside the analysed building are affected by repeating fire tests only locally and to limited extend. Most of the structures exhibit only negligible decay of structural performance or durability, which was proved by conducted structural diagnosis and material tests. Several elements were chosen to be inspected more deeply by thermal analysis and calculation of residual load-bearing capacity. Detailed investigation showed limited effect of repeating fire test which together with high reserve in load-bearing capacity prove satisfying state of structures for future use.

Nevertheless, during detailed inspection, two structural defects or faults not directly related to fire trainings were found. Hence, adequate measures were designed to ensure sufficient load-bearing capacity and structural durability.

As a result of described post-fire structural analysis it can be stated that using CFD models of fire as an approximation of real fire situation together with traditional post-fire structural diagnosis and material tests can be powerful tools making such assessment more accurate and more cost-effective.

Acknowledgement. This work has been supported by the Grant Agency of the Czech Technical University in Prague, project No. SGS21/040/OHK1/1T/11. The support is gratefully acknowledged.

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6.7 Paper 3

Reprint of the paper

- Analysis of Zone Fire Models and Their Application in Structural Design (2021)

Contribution of the author of this thesis to the paper

- M. Benýšek is the co-author of the text of the paper (that was written under the supervision of R. Štefan).
- The author’s contribution is 25 %.

Solid State Phenomena
ISSN: 1662-9779, Vol. 322, pp 127-135
© 2021 Trans Tech Publications Ltd, Switzerland

Submitted: 2020-11-16
Revised: 2021-01-15
Accepted: 2021-02-12
Online: 2021-08-09

Analysis of Zone Fire Models and Their Application in Structural Fire Design

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Keywords: Concrete, Zone Fire Model, Fire Modelling Software, Heat Release Rate, Enclosure Fire, Fire Resistance.

Abstract. This paper is focused on a comparison of zone fire modelling software tools and their application in structural fire design. The analysis of the zone models is performed for five selected computer programs, namely Argos, Branzfire, B-RISK, CFAST, and OZone. The limits and input parameters of the zone fire modelling software tools are described. In each software, two variants of the analysed compartment are created for simulating two types of fire scenario, including the fuel-controlled fire and the ventilation-controlled fire. The burning regimes are defined based on two heat release rate (HRR) curves, determined according to EN 1991-1-2. The HRR curves parameters are used as the main input data into the fire modelling software. The fire simulation method in each fire modelling software is selected based on the software capabilities. Although each program requires a different amount of input parameters, the aim was to create the same model in all programs and to compare the results. The fire modelling software outputs are exported into a spreadsheet. Subsequently, a comparison of the resulting graphs is performed, particularly the heat release rate graphs and the upper layer temperature evolution graphs. The fire resistance assessment of a simply-supported concrete slab panel is performed for all zone fire models and then the results are compared. The fire modelling software tools are finally quantitatively and qualitatively evaluated and compared to assess their differences.

Introduction

In structural fire engineering practice, the assessment of fire resistance of structural members is mostly based on simplified fire models represented, for example, by the nominal or parametric temperature-time curves, see, e.g., EN 1991-1-2 [6]. However, these simplified fire models are usually very conservative. In addition to simplified fire models, there are also more sophisticated (advanced) fire models which play an important role in the fire safety design of buildings. To determine the fire resistance of a structural member, it is necessary to know the temperature distribution in the analysed cross-section. This can be determined by solving the heat transfer problem for which it is necessary to determine the boundary conditions. The boundary conditions are usually bases on the temperature analysis of the fire compartment. With the expansion of the use of information technologies in the fire engineering field, several computer programs have been developed in recent decades, trying to simulate the burning process of fire in buildings by using more precise approaches. The more precise mathematical fire models include primarily the computational fluid dynamics (CFD) simulations and zone fire models [10, 12, 13, 25]. This paper deals with the zone fire modelling software tools. Namely, the following software tools are analysed: Argos [5], Branzfire [23], B-RISK [24], CFAST [18], OZone [4, 14]. The paper is based on the results obtained in [19].

Zone Fire Models

Zone fire models are classified as deterministic mathematical models and represent the idealized burning process of enclosure fires. Their principle is to divide the compartment into one or two homogeneous zones (layers), each layer having a direct-current density, temperature and gas concentration.

Zone models can be classified as either one-zone or two-zone. Two-zone models describe the burning process of enclose fires in the initial stage of fire before the spatial ignition (so-called flashover effect). One-zone models describe the enclosure fires after the flashover effect. The main advantage of zone models is the algorithm simplicity (in comparison with CFD models) and the calculation time. In general, zone models are not suitable for simulations of compartments with one predominant dimension (e.g., shafts, tunnels, corridors) [10, 11, 12, 13, 25].

The basic limits of the individual software tools are described in Table 1. The maximum dimensions of the simulated compartment are not usually explicitly defined, but in general, it is necessary to maintain the approximate square shape of the compartment. Nevertheless, some programs are also able to simulate fires in shafts and corridors, e.g., CFAST [18], B-RISK [24] and Branzfire [23].

Table 1: Limits of software tools Argos [5], Branzfire [23], B-RISK [24], CFAST [18], OZone [4].

Limitation factor	Argos	Branzfire	B-RISK	CFAST	OZone
Maximum number of compartments	10	10	12	100	1
Maximum number of horizontal flow (door/window) vent connections that can be included in a single test case	1000	1000	1000	2500	3
Maximum number of vertical flow (ceiling/floor) vent connections which can be included in a single test case	1000	1000	1000	1000	1000
Maximum number of fans that can be included in a single test case	1000	1000	1000	1250	3
Maximum number of fires which can be included in a single test case	1	1000	1000	2500	1
Maximum number of data points for a single fire definition	1000	1000	1000	199	121
Maximum number of thermocouples which can be included in a single test case	0	0	0	2500	0
Maximum number of detectors/sprinklers which can be included in a single test case	1000	1000	1000	2500	3

Illustrative Example

The illustrative example is focused on a single-room fire compartment of an office archive with dimensions depicted in Fig. 1. The room is ventilated naturally by window openings, the door is permanently closed. Two variants of the compartment are considered, differing only in the number of the window openings, see Fig. 1.

Modelling of Fire

The Heat Release Rate (HRR) curves were created for both variants of the model compartment. These HRR curves were defined according to EN 1991-1-2 [6] using the FMC tool [3]. The input values for the FMC tool were taken from EN 1991-1-2 [6, Appendix E, Tab. E.5], the parameters of the HRR curves differed only in the window openings area. These window openings are considered permanently open throughout the simulation. The parameters of both variants of the HRR output curves from the FMC program are given in Table 2. The burning regime is classified as the fuel-controlled fire in the case of variant No. 1 and the ventilation-controlled fire in the case of variant No. 2 [1, 6]. These HRR curves were used as input data for the individual zone fire modelling software tools.

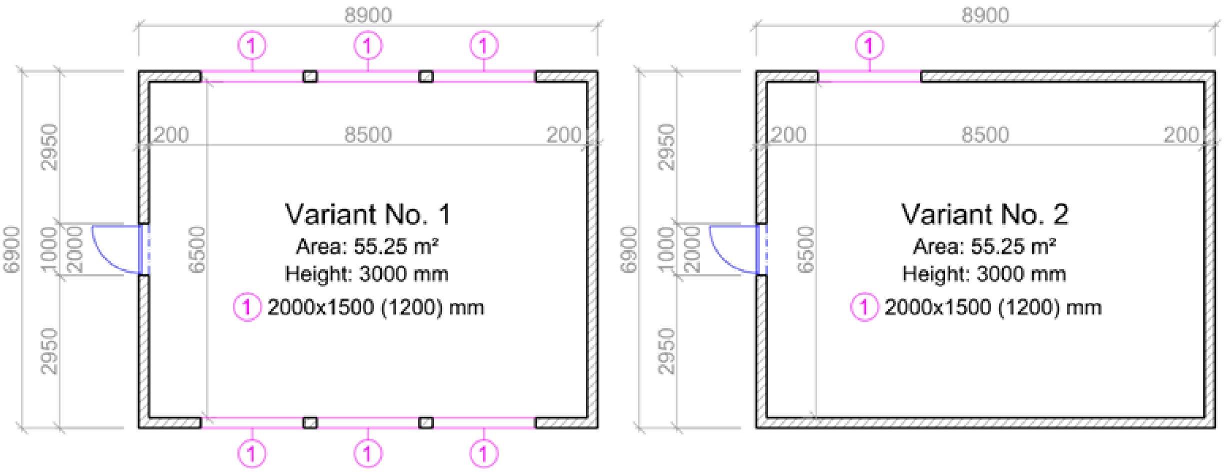

Fig. 1: Scheme of the model fire compartment. Left: variant No. 1; right: variant No. 2.

Table 2: Limits of the employed zone fire modelling software tools: Argos [5], Branzfire [23], B-RISK [24], CFAST [18], OZone [4].

Variant	Burning regime	Max. energy release rate Q_{max} [MW]	Fire growth [minutes]	Fully developed fire [minutes]	Decay [minutes]	Total time [minutes]
No. 1	Fuel-controlled	27.625	13.15	35.12	33.85	82.12
No. 2	Ventilation-controlled	5.144	5.68	210.32	181.83	397.83

The fire simulations were created for both compartment variants in Argos [5], Branzfire [23], B-RISK [24], CFAST [18], and OZone [4] software tools. In each program, the room, its dimensions, window openings, construction materials and their characteristics were defined. The fuel was set as a wooden-based material with the chemical formula $C_{43}H_{37}O_5$ and heat of combustion of 18.5 MJ kg^{-1} [16]. The gas layer mode during a fire was considered according to McCaffrey [10]. Although all programs use zone fire models, each program requires different amount of input parameters. The aim was to create the same model in all programs and to compare the results.

In Argos [5] program, the fire was simulated by defining the HRR curve evolution in a data point form.

In Branzfire [23] and B-RISK [24] programs, the fire was defined by the HRR curve evolution in the data point form, the chemical formula of the burning material and its combustion heat. In addition, a fire load energy density was defined in B-RISK [24] program.

In CFAST [18] program, the fire was simulated using a t-squared HRR curve, defining the maximum HRR value and individual stages of fire, the chemical formula of the burning material and its heat of combustion.

In OZone [4] program, the fire was simulated by defining the HRR curve evolution in the data point form and the fire area.

The outputs obtained by the zone fire modelling software tools were transferred to a spreadsheet. The resulting graphs of the heat release rate and the upper layer temperature are shown in Figs. 2 and 3. The obtained HRR graphs are complemented by the prime HRR curve that were used as the main input to individual programs (“HRR input”), see Fig. 2. The upper layer temperature graphs are complemented by the standard temperature curve ISO 834 (e.g. [6]), see Fig. 3.

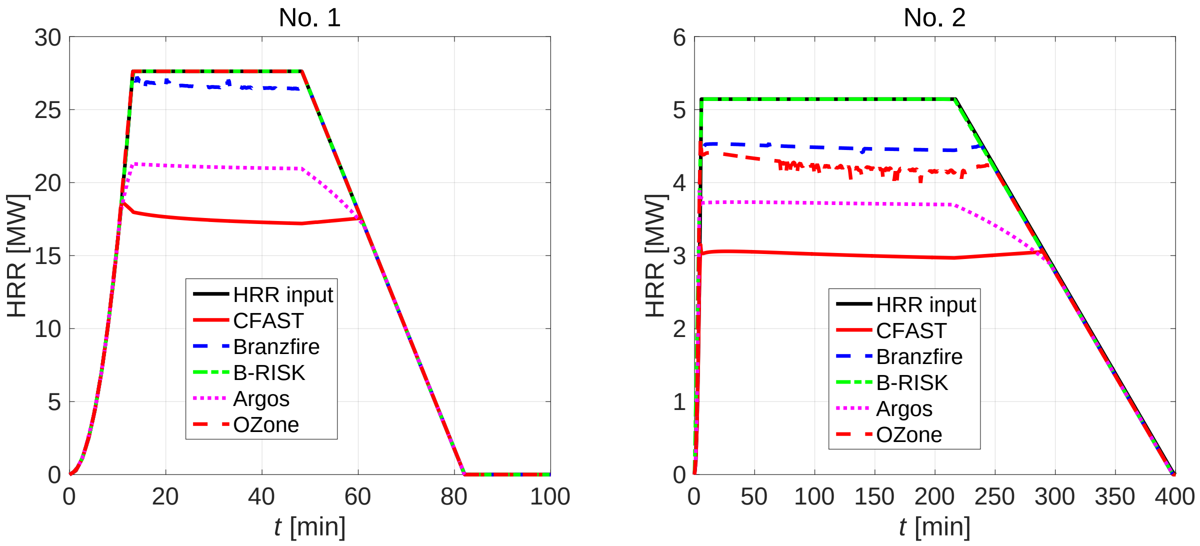

Fig. 2: Heat release rate evolution. Left: variant No. 1; right: variant No. 2.

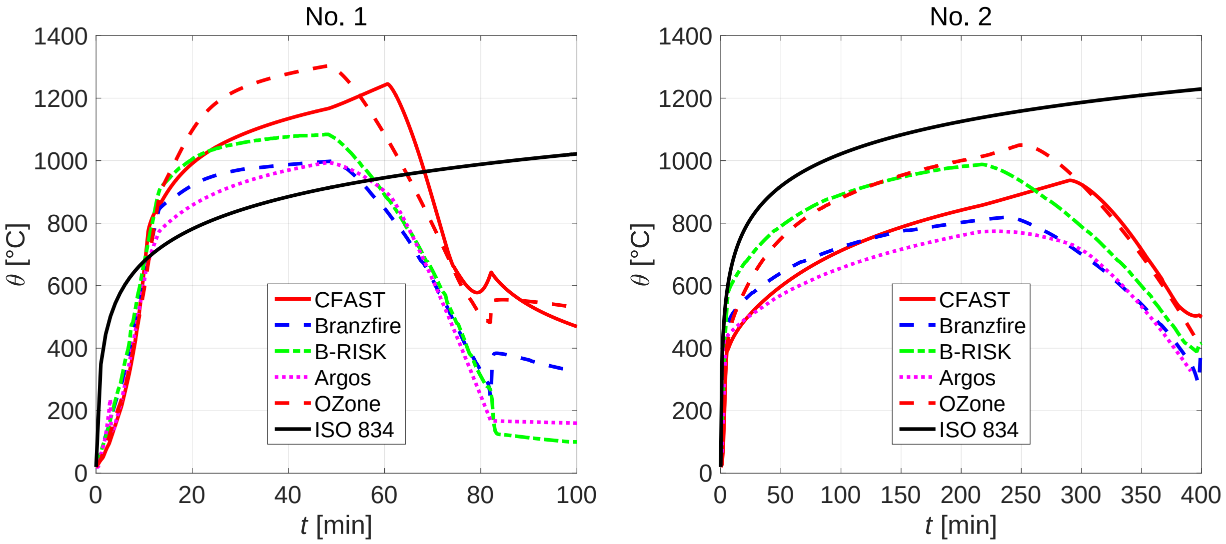

Fig. 3: Upper layer temperature evolution. Left: variant No. 1; right: variant No. 2.

The lowest values of the output HRR curves (in comparison witch the "HRR input" curve) were obtained using the CFAST software, see Fig. 2. However, for variant No. 1, the CFAST software also gives the second-highest upper layer temperature values, see Fig. 3. The value of the heat of combustion and how the CFAST software considers this parameter during the calculation process has a fundamental impact on the course of these graphs. The CFAST software considers in its calculation process a scenario when only a part of the fuel is burned. In this scenario, the HRR curve does not reach its prescribed maximum values according to the EN 1991-1-2 [6]. The heat of combustion of the fuel directly proportionally affects the amount of oxygen consumed in a fire and at the same time the concentration of CO_2 in the upper smoke layer. As the concentration of CO_2 in the upper smoke layer increases, the values of the graphs increase as well. Hence, the higher the value of heat of combustion, the higher the values of the HRR graphs and the upper layer temperatures reach [17]. For the Branzfire and B-RISK software tools, no significant effect of the heat of combustion on the course of the mentioned graphs was noticed. The greatest impact on the decrease of the HRR curve values in the Argos software is probably caused by the fuel parameters considered during the calculation. The Argos and OZone programs do not allow to customize these parameters in the user settings [5, 4].

Fire Resistance Assessment of a Slab Panel

A ceiling structure of the analysed fire compartment (cf. [1, 2]) consists of concrete slab panels with the dimensions of 6900 mm × 1000 mm × 250 mm and the effective span $l = 6700$ mm, see Fig. 4.

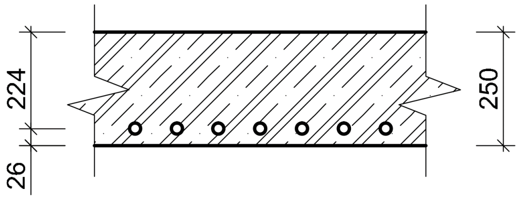

Fig. 4: Cross section of the slab panel.

The slab panels are considered as simply supported panels subjected to an uniformly distributed permanent load (including the self-weight) of a characteristic value $g_k = 7.5\,\mathrm{kN/m^2}$ and a variable load with of a characteristic value $q_k = 2.5\,\mathrm{kN/m^2}$.

The slab panel was designed and assessed at normal temperatures according to EN 1992-1-1 [7]. The main parameters of the element were assumed as follows: concrete class C30/37, reinforcement B500B, concrete cover $c = 20$ mm, main longitudinal reinforcement area $A_{s,prov} = 1131\ \mathrm{mm}^2$ (10 $\varnothing$ 12 mm); the required longitudinal reinforcement area was $A_{s,req} = 888\ \mathrm{mm}^2$. Other reinforcement is neglected in the fire resistance assessment.

The temperature distribution in the slab panel was determined using the TempAnalysis [22] computer program, which is based on finite element solution of the well-known one-dimensional heat transfer problem, see, e.g. [21]. The temperature-dependent material properties of concrete were taken from EN 1992-1-2 [8], assuming the upper limit of thermal conductivity, initial moisture content of 1.5 % by weight of concrete, initial bulk density of $2500\ \mathrm{kg/m^3}$. Parameters of the boundary conditions on the heated surface were taken as follows (see EN 1991-1-2 [6]): heat transfer coefficient of $\alpha_c = 35\ \mathrm{W\,m^{-2}\,K^{-1}}$, emissivity of 0.7, and the fire temperature evolutions were taken from the upper layer temperature graphs determined by the individual zone fire modelling software tools (see above). In addition, the standard temperature curve ISO 834 was also assumed. Zero heat flux was prescribed on the unheated surface of the cross-section. The uniform initial temperature was set as 20 °C. The resulting temperature evolution in the reinforcement for individual upper layer temperature graphs are shown for both compartment variants in Fig. 5.

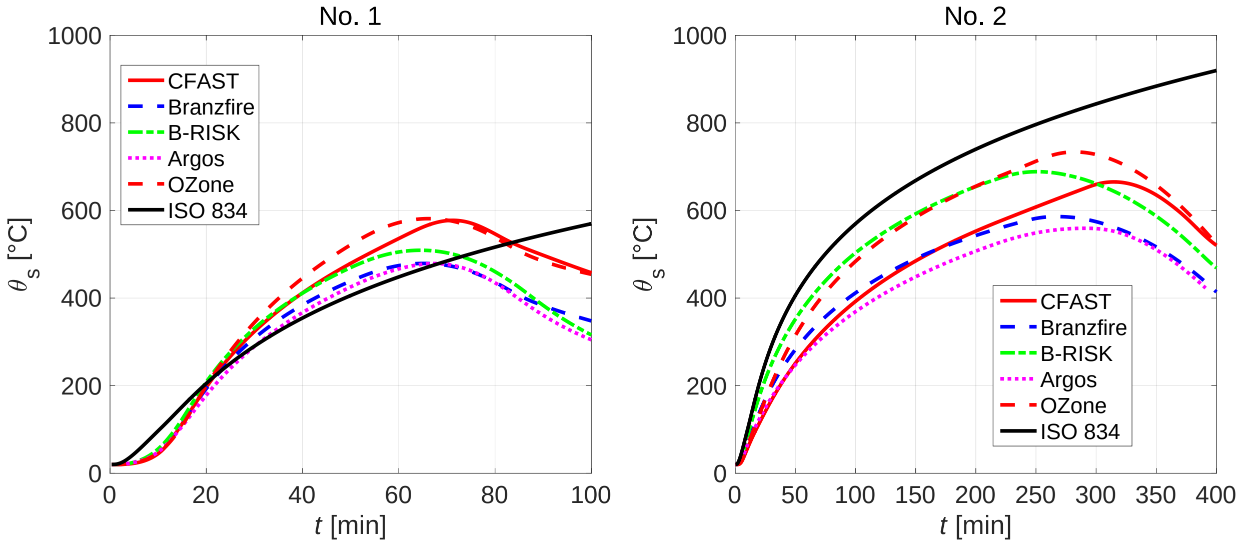

Fig. 5: Temperature evolutions in the reinforcement ($x = 26$ mm). Left: var. No. 1; right: var. No. 2.

To assess the load-bearing capacity of the slab panel in the case of fire, a simplified calculation method for the design of beams and slabs is used according to Annex E in EN 1992-1-2 [8].

In order to provide a sufficient fire resistance for a specific time of fire exposure t, the analysed panel should fulfil condition [8, Cl. 2.4.1 and Cl. E.2(1)]

$$M_{Rd,fi}(t) \geq M_{Ed,fi}. \tag{1}$$

The design value of the bending moment in the fire situation can be determined as [8, Cl. 2.4.2 and Cl. E.2(3)]

$$M_{Ed,fi} = \eta_{fi} M_{Ed} = \eta_{fi} \cdot \frac{1}{8}(g_d + q_d) \cdot b_{eff} \cdot l_{eff}^2. \tag{2}$$

By assuming $\eta_{fi} = 0.7$ [8, Cl. 2.4.2, Note 2] and the other parameters as stated above, we get

$$M_{Ed,fi} = 0.7 \cdot \frac{1}{8} \cdot (7.5 \cdot 1.35 + 2.5 \cdot 1.5) \cdot 1.0 \cdot 6.7^2 = 54.5 \text{ kNm}.$$

The design value of the moment capacity in the fire situation for a specific time of fire exposure t can be calculated as [8, Cl. E.2(4)]

$$M_{Rd,fi}(t) = \frac{\gamma_s}{\gamma_{s,fi}} \cdot k_s(\theta_s(t)) \cdot M_{Ed} \cdot \frac{A_{s,prov}}{A_{s,req}}. \tag{3}$$

In Eq. (3), we assume (see above, see also [1, 6, 8]): $\gamma_s = 1.15$, $\gamma_{s,fi} = 1.0$, $M_{Ed} = 1/8 \cdot (7.5 \cdot 1.35 + 2.5 \cdot 1.5) = 77.9$ kNm, $A_{s,prov} = 1131$ mm^2, $A_{s,req} = 888$ mm^2. Coefficient of the reinforcing steel strength reduction k_s for a given reinforcement temperature θ_s (see Fig. 5) is determined according to EN 1992-1-2 [8, Cl. 4.2.4.3, curve 3].

The above approach was employed for analysis of two problems for each fire modelling software tool data: (i) assessment of the fire resistance of the slab panel for the time of fire exposure corresponding to the maximum temperature reached in the reinforcement (see Fig. 5), (ii) determination of the ultimate fire resistance time of the slab panel. The obtained results are summarized in Table 3.

Table 3: Results of the fire resistance assessment of the analysed slab panel (nvg – no value given).

Software (model)	Var. No.	Max. temp. reached $\theta_{s,max}$ [°C]	Time to reach $\theta_{s,max}$ [minutes]	k_s ($\theta_{s,max}$)	$M_{Rd,fi}$ for $\theta_{s,max}$	Assess-ment for $\theta_{s,max}$	Max. fire resistance [minutes]
Argos	1	478.89	67.33	0.60	68.14	✓	nvg
	2	559.39	290.33	0.43	49.10	×	234
Branzfire	1	479.09	65.00	0.60	68.11	✓	nvg
	2	586.10	266.67	0.37	41.94	×	196
B-RISK	1	509.17	64.67	0.55	62.56	✓	nvg
	2	688.57	251.00	0.13	14.47	×	117
CFAST	1	577.50	71.33	0.39	44.24	×	60
	2	665.22	314.33	0.18	20.73	×	188
OZone	1	581.33	66.33	0.38	43.22	×	52
	2	733.64	282.00	0.09	10.64	×	125
ISO 834	1	569.75	100.00	0.41	46.32	×	87
	2	919.59	400.00	0.06	6.40	×	88

For variant No. 1, the load-bearing capacity of the structure in the case of the fire was satisfactory throughout the fire in the following programs: Argos, Branzfire and B-RISK. For variant No. 2, the load-bearing capacity of the structure for the maximum temperatures reached wasn't satisfactory with any program, which is mainly due to the duration of this fire scenario. Here, it should be noted, that the fire duration for variant No. 2 is unlikely to occur in real world, since the fire would be extinguished earlier. The CFAST program allows defining the highest amount of the input parameters. Therefore, the highest accuracy of the resulting temperature analysis of the selected fire compartment might have been expected. Nevertheless, compared to the other programs, higher temperatures occurred here, and these higher temperatures result in the lower fire resistance of the structure. In contrast, most of the programs do not allow defining as many input parameters as the CFAST program does, assuming more conservative results from these programs compared to the actual burning process in the compartment. Nevertheless, with these programs (especially with the Argos, Branzfire program and with the variant No. 1 of the B-RISK program), lower temperatures were achieved, thus resulting in the higher fire resistance of the structure than with the CFAST program. The analysis shows that the fire resistance of the ceiling structure might be greatly affected by the selected program used for simulating the fire and determining the temperature evolution in the compartment.

Discussion

Since every analysed software requires a different amount and form of input data, obvious differences between individual outputs are evident. It was found that the way the selected software considers in the calculation process with the fuel parameters, especially with the heat of combustion, can have a fundamental impact on the resulting outputs. Further research would be appropriate focusing on the differences in the mathematical basis of the individual programs, or on their comparison with the CFD model, see [9, 13, 15, 20, 25, 26].

In engineering practice, higher values of the temperature profile are always on the safe side of the design process. In some particular cases, it is recommended to perform a more detailed analysis of the burning process. The capabilities of the individual programs are listed in Table 4.

Table 4: Comparison of the zone fire modelling software tools capabilities.

Software capabilities	Argos	Branzfire	B-RISK	CFAST	OZone
Two-zone model	✓	✓	✓	✓	✓
One-zone model only	×	✓	✓	✓	✓
Multiple room option	✓	✓	✓	✓	×
Fire in shafts and corridors	×	✓	✓	✓	×
Time-dependent openings option	✓	✓	✓	✓	✓
Active fire protection (fire extinguishing systems, etc.)	✓	✓	✓	✓	✓
Defined fires database	✓	✓	✓	✓	✓
Multiple fires in a single scenario	×	✓	✓	✓	×
Fire resistance assessment of steel elements	×	×	×	×	✓
Monte Carlo probabilistic module	×	×	✓	×	×
Outputs in graphs	✓	✓	✓	×	✓
Output file in a spreadsheet	×	✓	✓	✓	×
Fire visualization	×	×	✓	✓	×
Free availability	×	✓	✓	✓	✓

Summary

The paper was focused on the comparison of selected fire zone modelling software tools for different burning regimes and the evaluation of their results concerning the fire resistance assessment of a reinforced concrete slab panel. A fire compartment of the office archive room was created. In the individual software tools, two variants of the examined compartment were modelled for two burning regimes, i.e., for the fuel-controlled fire and the ventilation-controlled fire. The outputs from the individual programs were compared and evaluated. A fire resistance assessment of the slab panel was performed for the determined temperature profiles. The individual zone programs were quantitatively evaluated concerning the applicability of the program and the resulting fire resistance of the structure.

From the results presented in this paper, it is evident how the individual outputs may vary depending on the program used. The requirements of each program for the amount of the input data differ. Hence, the suitable program selection and the method of fire modelling is crucial for obtaining relevant results. Therefore, it is necessary to be familiar with the capabilities and limits of the program and to make its selection concerning the nature of the input data.

Acknowledgement

This work has been supported by the Grant Agency of the Czech Technical University in Prague, project No. SGS20/041/OHK1/1T/11. The support is gratefully acknowledged.

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6.8 Paper 4

Reprint of the paper

- Effect of Fire Model Parameter Variability on Determination of Fire Resistance of Concrete Structural Members

Contribution of the author of this thesis to the paper

- M. Benýšek is the author of the text of the paper (that was written under the supervision of J. Procházka and R. Štefan).
- The author’s contribution is 60 %.

Solid State Phenomena
ISSN: 1662-9779, Vol. 309, pp 208-215
doi:10.4028/www.scientific.net/SSP.309.208

Submitted: 2019-11-01
Revised: 2020-01-06
Accepted: 2020-03-03
Online: 2020-08-11

Effect of Fire Model Parameter Variability on Determination of Fire Resistance of Concrete Structural Members

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Keywords: Fire Model, Fire Resistance, Monte Carlo, Latin Hypercube Sampling, MATLAB.

Abstract. The paper is focused on the fire model parameter variability and its effect on the determination of fire resistance of concrete structural members. For the modelling of fire, the parametric temperature-time curve given in EN 1991-1-2 is used. First part of the paper is aimed on the fire model parameter variability in general. First, fire model parameter ranges are described and their combinations are created using two common sampling methods – Monte Carlo and Latin Hypercubes. Then, the combinations are analysed, unreasonable combinations are identified, and viable combinations are illustrated. Moreover, the characteristics of the temperature-time curves obtained using the parameter combinations are discussed. Namely, we focus on the temperature evolution, duration of fire, and the maximum temperature reached. In the second part of the paper, an illustrative example is presented. The example is focused on the analysis of the fire resistance of a concrete slab panel. The panel is placed in a fire compartment with given fire model parameter ranges. In the example, the variability of the fire model parameters is captured using the Latin Hypercubes sampling method. The thermal analysis of the slab panel as well as the subsequent mechanical analysis are both conducted by using numerical methods described in our previous work. The calculations are performed in MATLAB environment. Finally, the obtained results are presented and discussed. It is shown that the Latin Hypercube sampling can be used as an effective tool for the investigation of the effect of fire model parameter variability on the fire resistance.

Introduction

Structural fire design is usually based on simple fire models, such as the standard temperature-time curve (ISO 834 fire) or other nominal curves described in fire design codes, e.g. EN 1991-1-2 [3], see also [2, 11]. For a more detailed simulation of fire in the specific fire compartment, the parametric temperature-time curve given in EN 1991-1-2 [3, Annex A] or more advanced fire models (zone models, computational fluid dynamics models) can be applied. In most cases, the fire model parameters (fire load, fire compartment geometry, material properties of enclosure surfaces, ventilation conditions, etc.) are assumed to be deterministic, i.e. constant, without any variability. However, in recent years, a probabilistic approach to the fire modelling and structural fire design is of significant interest in the scientific community, see e.g. [4, 5, 6, 7, 10, 12, 14, 15, 17].

In our previous work [1], we presented an illustrative example of the fire resistance assessment of a concrete slab panel based on different fire models (the standard temperature-time curve, the parametric temperature-time curve, the two-zone model, and the computational fluid dynamics model). Here, we focus on the same example, except that in this paper, only the standard and parametric-temperature time curves are employed for the modelling of fire, and for the parametric curve, the variability of the fire model parameters are assumed.

Parametric Temperature-Time Curve

Parametric temperature-time curve is described in detail in EN 1991-1-2 [3, Annex A]. Here, we focus on the input parameters, their ranges, combinations, and the temperature evolutions obtained for the created parameter combinations.

Input Parameters

In the mathematical model describing the parametric temperature-time curve in EN 1991-1-2 [3, Annex A], the gas temperature in a fire compartment, θ_g $[°\mathrm{C}]$, is defined in terms of the time (duration of fire), t [s], and four parameters of the specific ranges or values [3, Annex A]:

- the design fire load density related to the surface area, $q_{td} \in [50, 1000]$ $\mathrm{MJ\,m^{-2}}$,
- the opening factor, $O \in [0.02, 0.2]$ $\mathrm{m^{1/2}}$,
- the thermal absorptivity for the total enclosure, $b \in [100, 2200]$ $\mathrm{J\,m^{-2}\,s^{-1/2}\,K^{-1}}$, and
- the time for maximum gas temperature in case of fuel controlled fire, $t_{lim} = 25,\ 20,$ or 15 min, respectively, based on the fire growth rate: slow, medium, or fast.

It should be pointed out that by considering the input parameters in their whole ranges according to EN 1991-1-2 [3, Annex A], see above, and by assuming all possible combinations of these parameters, we can find some parameter combinations that give unreasonable results. For example, assuming $q_{td} = 50$ $\mathrm{MJ\,m^{-2}}$, $O = 0.2$ $\mathrm{m^{1/2}}$, $b = 100$ $\mathrm{J\,m^{-2}\,s^{-1/2}\,K^{-1}}$, and $t_{lim} = 25$ min, we obtain the temperature-time curve shown in Fig. 1.

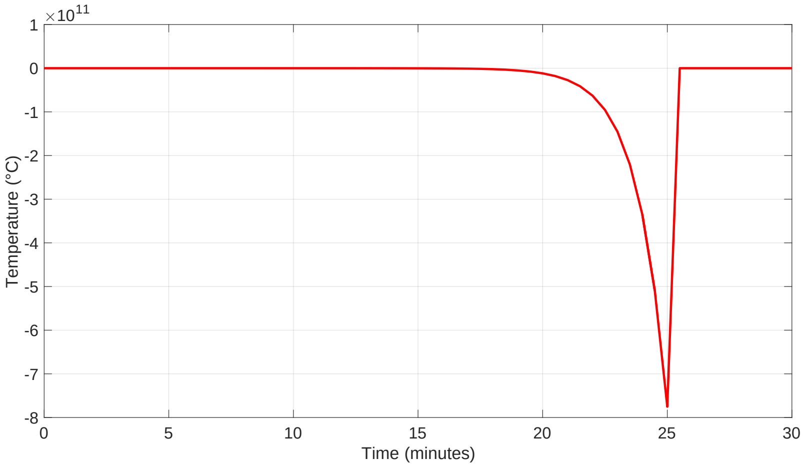

Fig. 1: Parametric temperature-time curve [3, Annex A] obtained by assuming: $q_{td} = 50$ $\mathrm{MJ\,m^{-2}}$, $O = 0.2$ $\mathrm{m^{1/2}}$, $b = 100$ $\mathrm{J\,m^{-2}\,s^{-1/2}\,K^{-1}}$, and $t_{lim} = 25$ min.

As can be seen from Fig. 1, for the aforementioned parameter combination, the model gives negative values of the gas temperature. This inaccuracy is caused by [3, Cl. A(9)]. Other combinations, leading to the positive results, are discussed in the the following section.

Parameter Combinations

In order to illustrate the parametric temperature-time curves for the whole ranges of the input parameters, see above, we create the parameter combinations by two common sampling methods – Monte Carlo and Latin Hypercubes. For the creation of the parameter combinations, uniform distribution of each parameter is assumed. Unreasonable combinations are omitted, see above. In Figs. 2 and 3, the temperature-time curves obtained for the created combinations are illustrated and compared with the standard temperature-time curve (ISO 834 fire), see e.g. [3, Cl. 3.2.1].

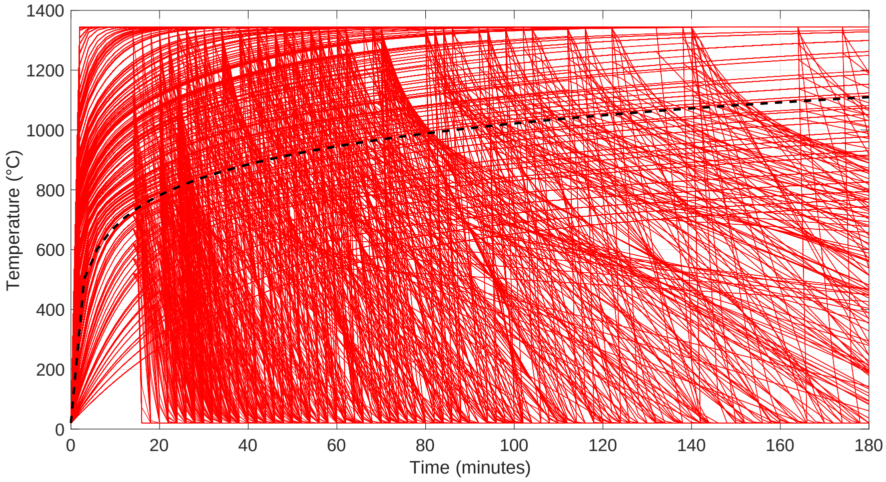

Fig. 2: Parametric temperature-time curves (solid lines) for the whole ranges of input parameters specified in [3, Annex A] assuming the parameter combinations obtained using the Monte Carlo method; comparison with the standard temperature-time curve (dashed line), cf. e.g. [7, 12].

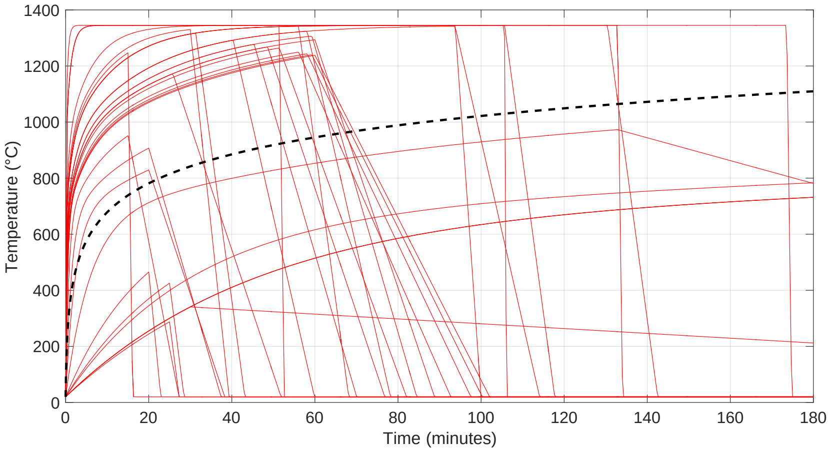

Fig. 3: Parametric temperature-time curves (solid lines) for the whole ranges of input parameters specified in [3, Annex A] assuming the parameter combinations obtained using the Latin Hypercubes method; comparison with the standard temperature-time curve (dashed line), cf. e.g. [7, 12].

As can be seen from Figs. 2 and 3, many of the parametric temperature-time curves reach higher temperatures than the standard temperature-time curve. Based on a more detailed analysis of the curves, it can be mentioned that in most cases, the duration of fire simulated by the parametric temperature-time curve model is, approximately, from 15 to 170 minutes, and the maximum temperatures reach the values, approximately, from 300 °C to 1350 °C.

Illustrative Example

The example below is focused on the illustration of the effect of the fire model parameter variability on the determination of fire resistance of a slab panel placed in a fire compartment shown in Fig. 4. Similar examples can be found, e.g., in [6, 7].

All parameters of the investigated structure (geometry of the fire compartment, loads, materials, reinforcement, dimensions of the analysed slab panel) are taken from our previous work [1] and hence, they are not mentioned here.

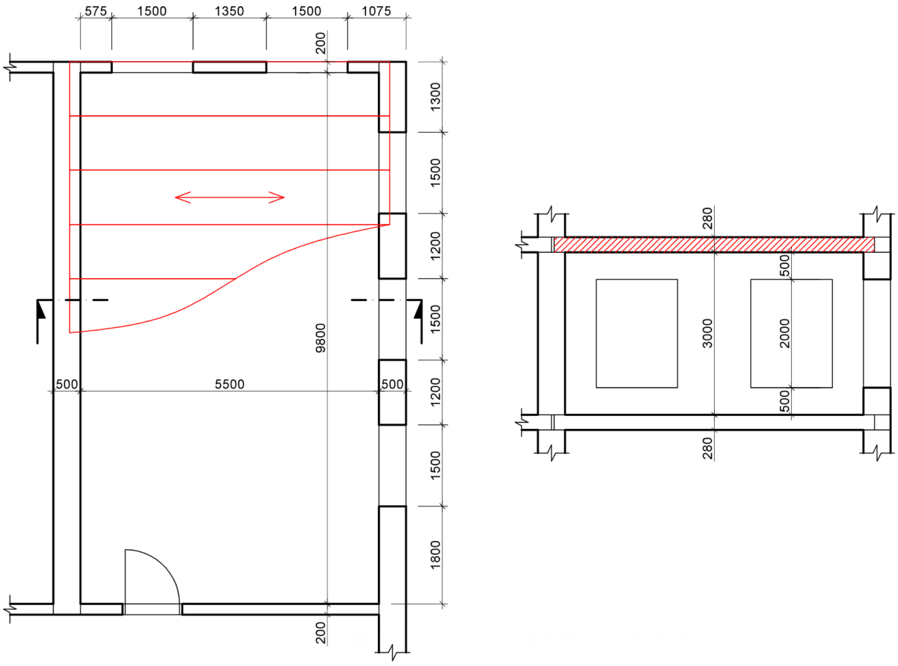

Fig. 4: Scheme of the model fire compartment with the analysed slab panel, taken from [1, Fig. 1].

Modelling of Fire

In our previous work [1], we simulated fire in the analysed compartment by using four different fire models – the standard temperature-time curve, the parametric temperature-time curve, the two-zone model, and the computational fluid dynamics model. Here, we utilize only the standard and parametric-temperature time curves. However, for the parametric curve, we take into account the variability of the fire model parameters.

The ranges of the fire model parameters are assumed as follows: the design fire load density is taken in the range $[q_{td}, 2q_{td}]$, the opening factor is taken in the range $[O/2, O]$, and the thermal absorptivity for the total enclosure is taken in the range $[0.9b, 1.1b]$, where q_{td}, O, and b are the original values of the fire model parameters given in paper [1].

These ranges were determined based on the following assumptions. For the fire load, it is necessary to take into account a real equipment of today's buildings. Nowadays, lot of office devices such as computers, printers, and chairs are made of plastic materials. Currently, the furniture is usually not made of solid wood, but there are used light plywood or agglomerated wood, which is full of glue. This can lead to 100 % increase in the fire load. For the opening factor, we follow the findings presented in [8], where it is stated that the double or triple glass filling can withstand the thermal stress during fire without any or with only limited destruction. For the thermal absorptivity of the total enclosure, we consider high quality of modern building materials with small deviations in the thermal properties.

For the creation of the parameter combinations, uniform distribution of each parameter is assumed and two common sampling methods are utilized – Monte Carlo and Latin Hypercubes.

More sophisticated approaches to the analysis of the parameter variability and randomness can be found in literature, e.g. [4, 5, 6, 7, 10, 12, 14, 15, 17], and they will be employed in our future work.

In Figs. 5 and 6, the temperature-time curves obtained for the created combinations are illustrated and compared with the standard temperature-time curve (ISO 834 fire), see e.g. [3, Cl. 3.2.1]. For the following thermal and mechanical analysis of the slab panel, we use only the parametric temperature-time curves depicted in Fig. 6 (obtained using the Latin Hypercubes method).

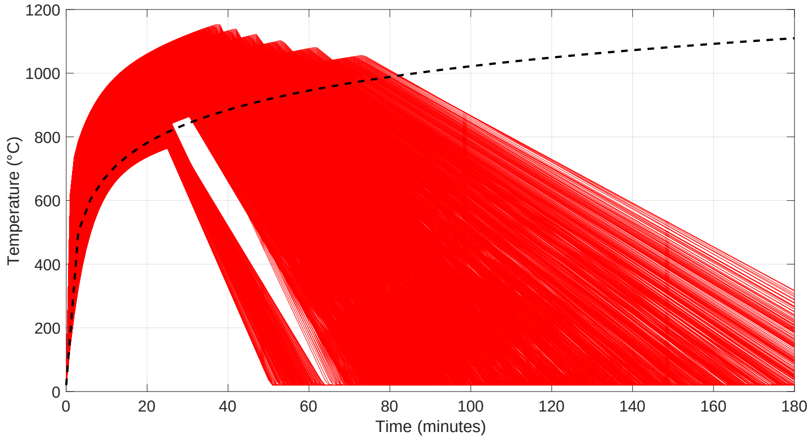

Fig. 5: Parametric temperature-time curves (solid lines) for the illustrative example assuming the parameter combinations obtained using the Monte Carlo method; comparison with the standard temperature-time curve (dashed line), cf. e.g. [7, 12].

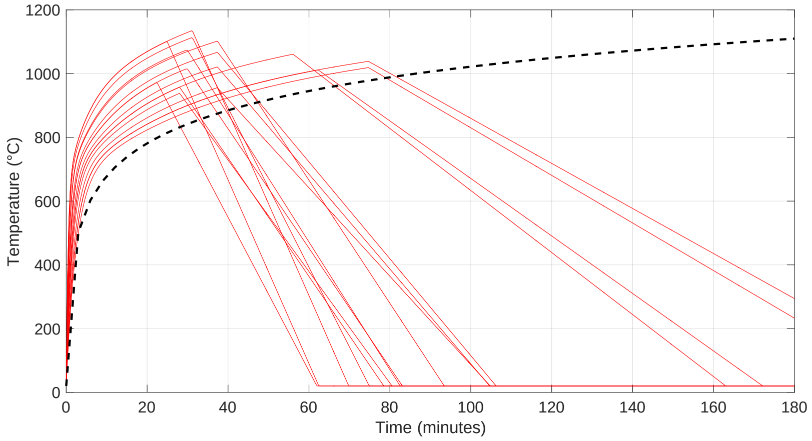

Fig. 6: Parametric temperature-time curves (solid lines) for the illustrative example assuming the parameter combinations obtained using the Latin Hypercubes method; comparison with the standard temperature-time curve (dashed line), cf. e.g. [7, 12].

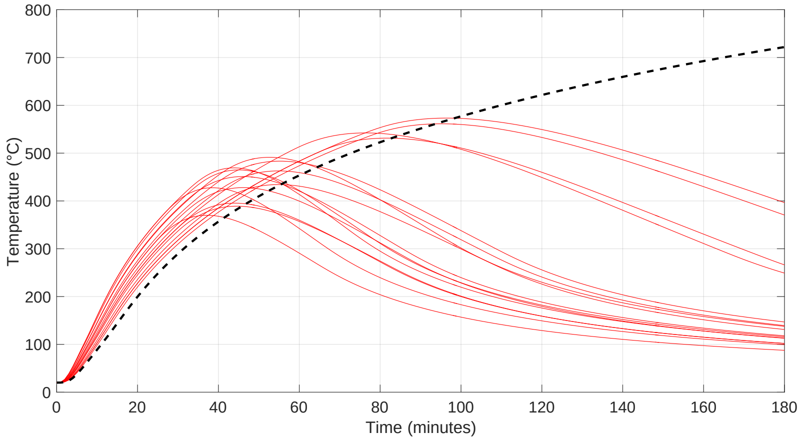

Fig. 7: Temperature evolutions in the reinforcement ($x = 25$ mm) for the parametric fire curves assuming the parameter combinations obtained using the Latin Hypercubes method (solid lines); comparison with the reinforcement temperature for the standard curve (dashed line), cf. e.g. [6, 7].

Thermal Analysis

The thermal analysis of the slab panel was performed by using a MATLAB code developed by the authors of this paper. The code is based on a one-dimensional heat transfer model discretized in space by the finite element method and in time by a semi-implicit difference scheme, as described in [1] and references therein. The total time of heating was set to 180 minutes. The results of the thermal analysis are shown in Fig. 7.

Mechanical Analysis

For the mechanical analysis of the slab panel, an iterative procedure based on the moment-curvature approach was used. The algorithm of the procedure is given in Algorithm 1 and described in detail, e.g., in [1].

Algorithm 1 Algorithm for the fire resistance assessment (see [9, 13, 16], see also [1])

```
1: determine the applied bending moment in fire situation, $M_{Ed,fi}(t)$
2: determine the temperature distribution across the analysed cross-section for the full duration of fire
3: for each time step, determine all the positions of neutral axis satisfying the equilibrium of internal forces, calculate the appropriate bending moments and find the maximum value, $M_{Rd,fi}(t)$
4: display and compare the time evolutions of $M_{Ed,fi}$ and $M_{Rd,fi}$
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The comparison of the applied moment $M_{Ed,fi}$ and the ultimate moments $M_{Rd,fi}$ is shown in Fig. 8.

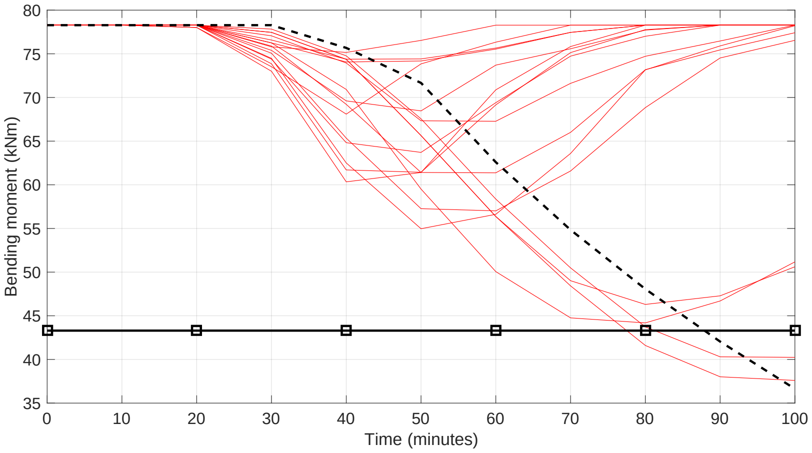

Fig. 8: Applied moment $M_{Ed,fi}$ (solid line with square markers), the ultimate moments $M_{Rd,fi}$ for the parametric fire curves assuming the parameter combinations obtained using the Latin Hypercubes method (solid lines) and for the standard temperature-time curve (dashed line).

Results and Discussion

In Figs. 5 and 6, the possible temperature-time curves for the analysed fire compartment are presented. These curves were obtained using combinations of fire model parameters created by the Monte Carlo and the Latin Hypercubes methods from defined ranges of the parameters. The maximum fire temperatures in the analysed fire compartment reach the values from 800 °C to 1150 °C at the time of 25–75 minutes. As can be seen in Figs. 5 and 6, although the fire curves obtained by the Monte Carlo and the Latin Hypercubes sampling methods are comparable, significantly lower number of combinations is needed when using the Latin Hypercubes method. Hence, for the subsequent thermal and mechanical analysis of the slab panel, only the fire curves obtained using the Latin Hypercubes method were utilized.

The possible temperature evolutions in the reinforcement in the analysed slab panel are illustrated in Fig. 7. The maximum temperatures in the reinforcement reach the values from 380 °C to 580 °C at the time of 35–95 minutes.

As illustrated in Fig. 8, failure of the panel due to fire exposure occurred only in two scenarios simulated by the parametric temperature-time curve. The failure occurred at the time of 80 minutes. For the other fire scenarios simulated by the parametric temperature-time curve, the panel withstood the full fire exposure without loosing its load bearing capacity. For comparison, by assuming the standard fire exposure, the fire resistance of the panel was determined to be 87 minutes, see also [1].

Summary

In the paper, the fire model parameter variability and its effect on the determination of fire resistance of concrete structural members were discussed.

For the modelling of fire, the parametric temperature-time curve given in EN 1991-1-2 was used.

In the first part of the paper, we focused on the fire model parameter variability in general. First, fire model parameter ranges were described and their combinations were created using two common sampling methods – Monte Carlo and Latin Hypercubes. Then, the combinations were analysed, unreasonable combinations were identified, and viable combinations were illustrated and discussed.

In the second part of the paper, an illustrative example was presented. The example was focused on the analysis of the fire resistance of a concrete slab panel. The panel was placed in a fire compartment with given fire model parameter ranges. In the example, the variability of the fire model parameters was captured using the Latin Hypercubes sampling method. For the creation of the parameter combinations, uniform distribution of each parameter was assumed.

It was illustrated that although the fire curves obtained by the Monte Carlo and the Latin Hypercubes sampling methods were comparable, significantly lower number of combinations was needed when using the Latin Hypercubes method. Hence, for the subsequent thermal and mechanical analysis of the slab panel, only the fire curves obtained using the Latin Hypercubes method were utilized.

It was shown that the variability of the fire model parameters strongly affects the predicted fire resistance of the analysed slab panel.

In our future work, we will focus on a detailed analysis of the fire model parameter variability and randomness.

Acknowledgement

This work has been supported by the Czech Science Foundation, project No. GA16-18448S, and by the Grant Agency of the Czech Technical University in Prague, project No. SGS19/034/OHK1/1T/11. The support is gratefully acknowledged.

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6.9 Paper 5

Reprint of the paper

- Timber Beam in Virtual Furnace

Contribution of the author of this thesis to the paper

- M. Benýšek is the co-author of the numerical simulations of the virtual furnace stated in Section 2 of the paper.
- The author’s contribution is 15 %.

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Timber beam in virtual furnace

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Received 15 January 2019
Revised 17 March 2020
Accepted 10 May 2020

Abstract

Purpose – This paper aims to present a part of a coupled numerical model for prediction the fire resistance of elements in a horizontal furnace. Temperatures calculated inside the timber beam are compared to measured values from the fire test.

Design/methodology/approach – The paper presents a part of a coupled numerical model for prediction the fire resistance of elements in a horizontal furnace. The presented part lies in a virtual furnace which simulates temperature environment around tested elements in the furnace. Comparison of results show good agreement in the case when burning of timber is included in the numerical model.

Findings – The virtual furnace presented in this paper allows to calculate temperature environment around three timber beams. After validation of the fire dynamics simulator (FDS) model, the temperature conditions are passed to the FE model which solves heat transfer to the tested element. Temperatures inside the timber beam which are solved in software Atena Science are compared to measured temperatures from the fire test. The comparison of temperatures in three control points shows good accuracy of the calculation in the point closer to the heated edge. An inaccuracy is shown in points located deeper in the beam cross-section – below the char layer.

Research limitations/implications – In conclusion, the virtual furnace has a great potential for investigating the thermal behaviour of fire-resistance tests. A huge advantage inheres in the evaluation of the thermal effect throughout the volume of the furnace, which allows an accurate prediction of fire-resistance tests and evaluation of large number of technical alternatives and boundary conditions. However, passing the temperature field from the FDS model into FE model may decrease the level of accuracy. The solution lies in a coupled CFD-FE model. A weakly coupled model including fluid dynamics, heat transfer and mechanical behaviour is under development at Faculty of Civil Engineering, Czech Technical University in Prague. The fluid dynamics part which is presented in this paper is solved by FDS and the thermo-mechanical part is computed by object-oriented finite element model (OOFEM). The interconnection of both software is made owing to MuPIF python library.

Practical implications – The virtual furnace takes advantage of great possibilities of computational fluid dynamics code FDS. The model is based on an accurate representation of a real fire furnace of fire laboratory PAVUS a.s. located in the Czech Republic. It includes geometry of the real furnace, material properties of the furnace linings, burners, ventilation conditions and tested elements. Gas temperature calculated in the virtual furnace is validated to temperatures measured during a fire test.

Social implications – The virtual furnace has a great potential for investigating the thermal behaviour of fire-resistance tests. A huge advantage inheres in the evaluation of the thermal effect throughout the volume of the furnace, which allows an accurate prediction of fire-resistance tests and evaluation of large number of technical alternatives and boundary conditions.

Originality/value – The virtual furnace has a great potential for investigating the thermal behaviour of fire-resistance tests. A huge advantage inheres in the evaluation of the thermal effect throughout the volume of the furnace, which allows an accurate prediction of fire-resistance tests and evaluation of large number of technical alternatives and boundary conditions. However, passing the temperature field from the FDS model into FE model may decrease the level of accuracy. The solution lies in a coupled CFD-FE model. A weakly coupled model including fluid dynamics, heat transfer and mechanical behaviour is under development at Faculty of Civil Engineering, Czech Technical University in Prague. The fluid dynamics part which is

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The work on this paper was supported by project n. 19-22435S in the frame of the Czech science foundation GACR.

Journal of Structural Fire Engineering
© Emerald Publishing Limited
2040-2317
DOI 10.1108/JSFE-01-2019-0007

presented in this paper is solved by FDS and the thermo-mechanical part is computed by OOFEM. The interconnection of both software is made thanks to MuPIF python library.

Keywords Finite element model, Computational fluid dynamics, Coupled CFD-FE model, Fire-resistance test, Timber beam, Virtual furnace

Paper type Research paper

1. Introduction

Testing by standard fire test is the common method of obtaining fire-resistance rating of structural elements, see (Buchanan and Abu, 2017). Despite fire-resistance tests are very common, they can be time consuming. The cost of the test is also very high. Because of these drawbacks a numerical model of a horizontal furnace (virtual furnace) which can save both time and money, is developed. The model solves a problem including fluid dynamics. Heat transfer into a tested element and mechanical behaviour of the element can be then solved in FE model. A decrease of accuracy caused by manual data transfer from CFD to FE model may be solved by interconnection of both models. Therefore, a coupled model including fluid dynamics, heat transfer and mechanical behaviour (CFD-FE model) which presents relatively new approach how to tackle multi-physical problem of fire-exposed structural behaviour, has a great potential in the fire-resistance testing.

In this paper, the virtual furnace which was prepared to calculate thermal environment during fire-resistance tests for coupled CFD-FE model is presented. The temperature of environment in the horizontal furnace during the fire-resistance test of timber beams which is solved by computational fluid dynamics method creates boundary conditions for the thermal model. The fluid dynamics part is solved by fire dynamics simulator (FDS) (McGrattan *et al.*, 2014) and the thermal part is computed separately by software Atena Science (Červenka *et al.*, 2014). Results of the FDS model are manually transferred into FE model in this case. The accuracy of calculated temperature environment in FDS as well as accuracy of calculated temperature inside the timber beam from the FE model is validated to measured values from a fire tests executed in horizontal furnace of fire laboratory PAVUS a. s., Czech Republic.

1.1 Current state

First attempt to apply CFD modelling in standard testing is described in (Welch and Rubini, 1997). In this study, a computer code SOFIE (Simulation Of Fires In Enclosures) was used to simulate a fire-resistance test of a steel plate in a wall furnace. Next application of CFD to standard fire testing can be found in Piloto *et al.* (2009). Authors of this study modelled a 1 m3 fire resistance test furnace in ANSYS Fluent computer program. The furnace was heated according to the standard time-temperature curve. The model was used for calculation of adiabatic surface temperature inside the furnace. Results of the numerical analysis were compared with experimental results. In Cayla *et al.* (2011), a model of the vertical furnace of Efectis laboratory in France was presented. FDS computational code was used to simulate temperature conditions inside the furnace. Except the FDS model the fire furnace simulator created by coupling the CAST3M and FDS code were also described. The coupled CAST3M and FDS simulator was used to calculate the fire resistance of a sandwich composite panel composed of glass reinforced polyester laminate (GRP) and a polyisocyanurate rigid foam (PIR) (Auguin, 2013). The application of CAST3M-FDS model is shown also in Cueff (2014). In Karabaş *et al.* (2016), CFD analysis of the fire testing furnace is done with ANSYS Fluent program to evaluate and determine the temperature distribution inside the fire test furnace. A 1 m3 cubic fire resistance test furnace with four burners and one exhaust was designed.

Gathered data from the CFD analysis was compared with standard temperature curve. A study on coupling of CFD and thermo-mechanical analysis for analysis of fire-exposed structural behavior is introduced in Silva *et al.* (2016).

Modelling of timber exposed to fire has been solved for the past decades, while various material models have been described and proposed (Buchanan and Abu, 2017; König, 2006) and other. Following (EN 1995–1-2 Eurocode 5 , 2006), when modelling timber exposed to fire conditions, it is accepted to modify the thermal properties to gain the results comparable with the experimental ones. This proves the fact, that the standard thermal properties of burning timber are not precise sufficiently and improved or upgraded material models need to be proposed and implemented. Behaviour of timber at elevated temperatures considering the mechanical properties of charred sub-layers, chemical processes and consequent modifications in thermal and mechanical properties are described and well-known (Reinprecht, 2008; Lange *et al.*, 2014), and other. However, as the processes are rather complex, a material model suitable for numerical simulations in final element models is needed and requested. Simplified and conservative material models of burning timber are applied these days (Fragiacomo, 2010). Many others, however, this leads to structures being over-designed and so timber as a natural source not being used efficiently. One of the very beneficial features of timber in fire is its self-protection ability (Reinprecht, 2008; Aseeva *et al.*, 2014), and others, which makes timber a very competitive structural material.

2. Gas temperature analysis

2.1 Model of temperature environment in the furnace

Temperature environment inside the furnace is simulated by the aid of the computational fluid dynamics code FDS version 6.4.0. Geometry of the furnace, material properties of furnace linings, burners and ventilation conditions corresponds to the horizontal furnace of fire laboratory PAVUS a.s. Inside the furnace three timber beams of dimensions 100 × 250 × 3000 mm are located below the ceiling. The location of the beams is shown in Figures 1 and 2.

Considering dimensions of the real furnace, time needed for numerical solution and sufficient level of accuracy of results, size of the general mesh of 100 × 100 × 100 mm is selected. In the region of timber beams the mesh is finer, 50 × 50 × 50 mm, see Figure 2. Material properties of the furnace linings are taken from data sheets of manufacturers. These include density, specific heat capacity and thermal conductivity of high alumina bricks, thermally insulating bricks, calcium silicate boards, blocks of refractory ceramic

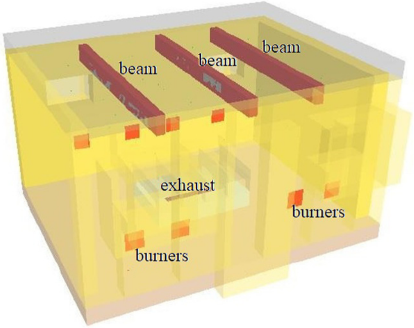

Figure 1.
FDS model of the furnace with timber beams

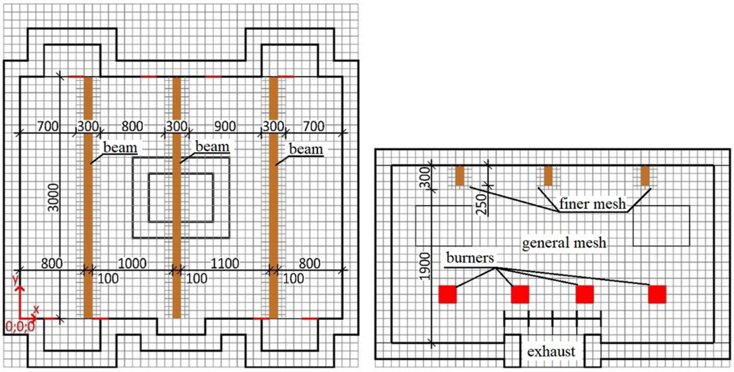

Figure 2.
Location of timber beams and meshing in the FDS model

fibers, steel and insulating refractory concrete. Material properties of the tested beams corresponds to GL24h timber.

In the model, burners are simulated as eight square surfaces of type VENT of dimension 250 × 250 mm, which are located 0.5 m above the floor. In Figures 1 and 2, the burners are illustrated as red squares. The fuel in the real furnace is composed of the mixture of natural gas and air, just as the case of the virtual furnace with the prescribed reaction of burning of this mixture. Power of the burners in the model is gradually increased in dependence on time according to the power of burners calculated from the fire test. During the test percentage of power of each burner was recorded. The maximal power of one burner guaranteed by producer of the furnace is 266 kW. For the purpose of numerical model, the maximal power is divided by area of a burner. Then the maximal power of one burner equals to 4256 kW/m2. In the model, the power is defined by a ramp function of heat release rate per unit area (HRRPUA).

In the model burning of timber is simulated by specified RAMP_Q function. After reaching the ignition temperature of the timber, the energy from the timber beams is released according to the function of heat release rate per unit area (HRRPUA). Detailed description is presented in Welch and Rubini (1997).

In the bottom part of the model, the mesh is enlarged to simulate the conduit of the gas exhaust system. The hole leading into the conduit is protected with welded steel structures. A niche of the door (0.5 × 1.75 m) and four visors are also simulated.

In the model gas temperature is calculated by device type THERMOCOUPLE. Properties of the device are modified in the model to correspond to properties of coated thermocouple used in the validation fire test. Then, device type ADIABATIC SURFACE TEMPERATURE is used in the model to simulate a weighted average value of the radiation temperature and the gas temperature. The adiabatic surface temperature also allows later calculation of temperature inside the timber beam.

2.2 Validation of the temperature environment

For standard fire testing, it is important to meet requirements of European standard EN 1363–1: 2013, which defines the conditions of fire resistance tests. The average temperature in the furnace is monitored and controlled to follow the standard temperature-time curve. According to EN 1363–1 there are specified tolerances for the temperature distribution in the furnace, where it is allowed to vary by ± 100°C. Development of the adiabatic surface temperature (AST) below the ceiling of the furnace calculated in FDS model is shown in

Figure 3. The development of gas temperature from the model is compared with the standard temperature-time curve and with the curve measured during the fire test. In the figure, there are also two curves showing the upper and the lower tolerance according to EN 1363 – 1. Based on the diagram it may be stated that after 5 min the gas temperature is within the acceptable tolerance given in EN 1363 – 1.

2.3 Contribution of burning of timber beams

During the fire test, gas burners are automatically controlled based on the temperature measured on the plate thermometers (PT) located 100 mm below the furnace ceiling to match the standard temperature curve. Each burner is regulated separately using an average temperature of two PTs. The rapid increase of power of the burners in the first 2 min is usual during the fire test due to the need to follow the sharp increase of temperature in the first minutes of the normal temperature curve. The burners reach their maximum power during this time. Subsequently, the power is abruptly reduced to regulate the temperature within the curve limits, and after approximately 13 min the power of all burners stabilizes and there are no large fluctuations. In the case of a timber beam model where the test specimens burn (burning of the beams during the fire test is shown in Figure 4), the control of the burner power is even more complicated, as the energy from the combustion of these beams contributes to the overall temperature increase inside the furnace. The fluctuations of the power of burners measured during the first minutes of the fire test with timber beams is shown in Figure 5. Peaks in the power observed in 4 , 7.5 and 9 min of the test are caused by difficulties with regulation of the burners power which is aggravated by the presence of additional inner heat source. In Figure 5, the power of burners from the fire test with timber beams is compared to the power measured during a fire test of empty furnace (no structural element present). Both curves refer to average value of the power of all burners. The difference of both curves after 13 min which refers to contribution of energy coming from burning timber beams is about 500 kW/m^2 (Piloto *et al.*, 2009).

With the purpose of showing the contribution of burning of timber beams, FDS model with no timber burning (energy from timber is not released, the beams serve as obstacles only) was prepared. In Figure 6, results of gas temperatures calculated in both FDS models (including burning of timber and with no burning of timber) are presented. Full grey curve refers to FDS model which reflects burning of timber. Dashed grey curve is the temperature calculated in FDS model where is no timber burning. The two curves of gas temperature calculated in FDS are compared to the standard temperature-time curve. In the same diagram there is also development of temperature measured during the fire test.

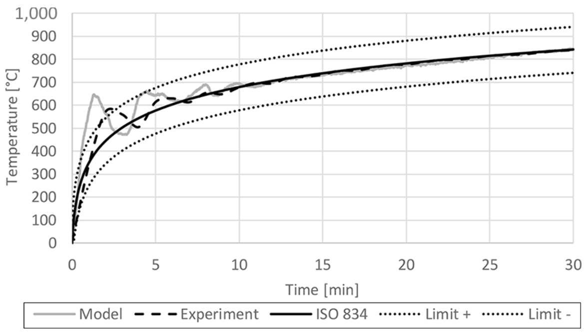

Figure 3.
Comparison of gas temperature

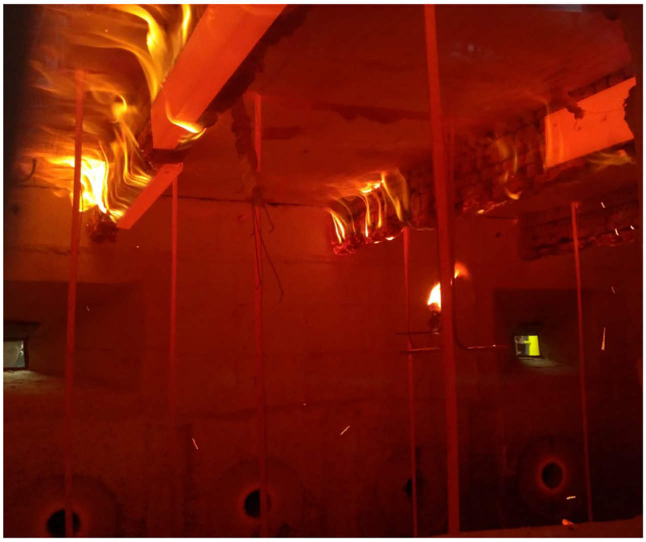

Figure 4. Burning of timber beams during the fire test

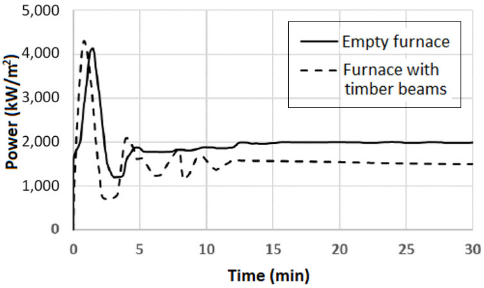

Figure 5. Power of burners measured during fire tests

The comparison of all results in Figure 6 shows that burning of timber has to be included in FDS model.

3. Temperature of timber beam

3.1 Description of finite element model

After validation of the FDS model, temperature environment in means of AST values could be used as boundary conditions in FE model of the timber beam. To solve the heat transfer into the timber beam software Atena Science V.513 is used. Input values of the model are set by the aid of pre-processor GiD 12.0.8.

In the FE model, properties of timber follows that as per recommendations in (EN 1995–1–2 Eurocode 5, 2006). These properties may be used for structures exposed to standard temperature curve. Initial moisture contain of the timber is 12%. Its density equals to 530 kg/m^3. In the model decrease of the moisture contain and decrease of the density with increasing temperature of timber is included. Specific heat capacity and coefficient of thermal conductivity are set as temperature dependant properties. The dependence of both properties which also follows (EN 1995–1–2 Eurocode 5, 2006) are shown in Figure 7. The

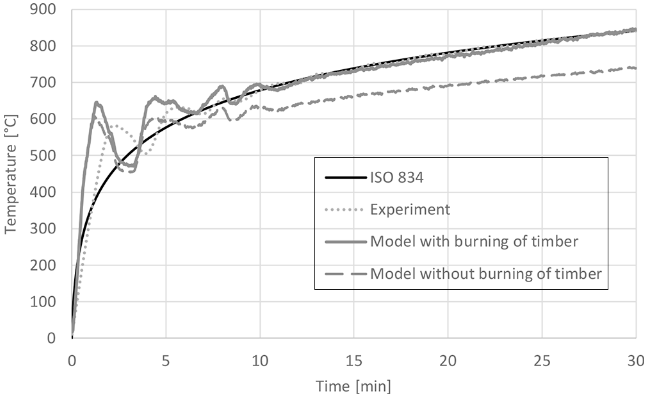

Figure 6.
Comparison of gas temperature for different FDS models

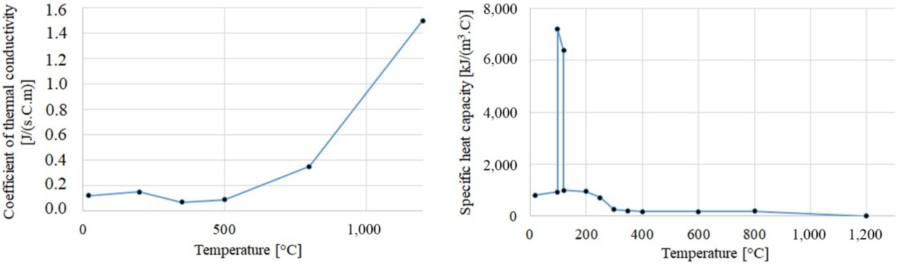

Figure 7.
Temperature dependant properties of timber used in the model

temperature dependence reflects change of properties in charring layer and due to drying cracks in timber. Coefficient of thermal conductivity takes into account the increased heat transfer caused by drying cracks above about 500°C and the loss of the char layer at about 1000°C. For the need of Atena software specific heat capacity must be inserted in kJ/(m^3.C). Therefore, values of specific heat capacity taken from (EN 1995–1–2 Eurocode 5, 2006) are multiplied by density for each temperature. For the thermal analysis, a material model CCTransportMaterial is chosen. Gas temperatures originated from the FDS model are applied to three boundary lines of the timber cross-section. Figure 8 shows dimensions of the timber beam cross-section. The beam is 100 mm width and 240 mm high. Figure 8 also informs about a size of 2 D mesh elements of the model. Two sizes of the mesh are used – 2

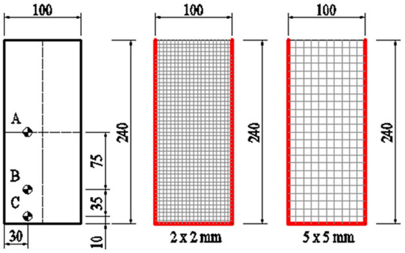

Figure 8.
Timber beam cross-section with locations of control points and meshing of the model

and 5 mm to check convergence of the results to the same solution. Calculation time step is set to 6 s. Calculation time is 1800 s.

To compare results from the model with temperatures measured during the fire test, temperature is calculated at the same positions as it was during the fire test – control point A, B and C. As it is illustrated in Figure 8, all points are located in depth of 30 mm. Each of them lies in different height of the beam – 10, 45 and 120 mm from the lower edge of the beam.

3.2 Results and comparison

Figure 9 shows distribution of temperature inside the timber beam in 30 min for models with both sizes of mesh. As the convergence criterion the temperature in all control points must not exceed 50°C. Development of temperature in all control points A, B and C introduced in Figure 10 shows that temperature difference does not exceed a given criterion when comparing the model with 5- and 2-mm mesh. The maximal difference of temperatures in point C is 46°C in 13 min of the calculation. Therefore, in later comparison only results coming from the model with 2 mm mesh is presented.

Developments of temperatures at highlighted control points A, B and C are presented in Figure 11. The results come from the model with mesh of 2 mm. The highest temperature is

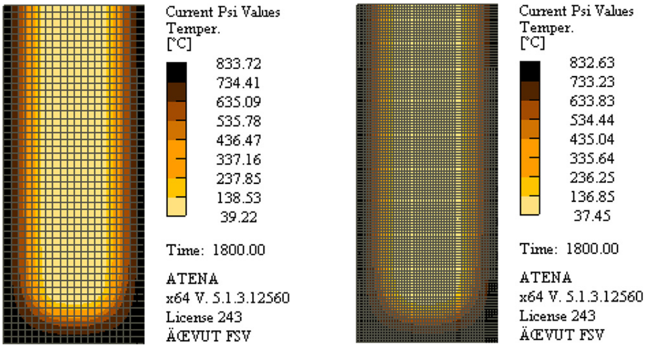

Figure 9. Distribution of temperature across the timber beam in 30 min – 5- and 2-mm mesh

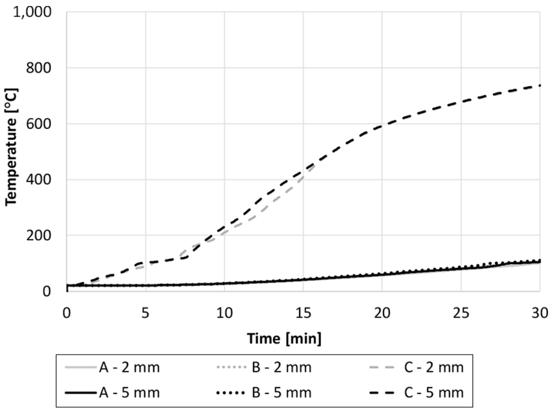

Figure 10. Comparison of calculated temperatures in control points A, B and C – 5- and 2-mm mesh

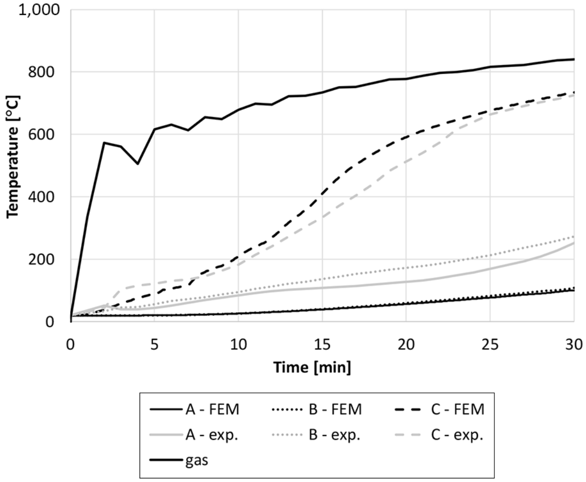

Figure 11. Comparison of calculated temperatures and measured temperatures in control points A, B and C

reached in point C which was the closest point to the lower edge of the beam. The depth of the point C was too small to be protected by a char layer. From Figure 11, it is clear that points A and B are protected by a char layer. The temperature is noticeably lower in these points. Figure 11 also shows temperatures measured during the fire test. Results of the comparison show the best agreement in point C which was located in height of 10 mm from the lower edge of the beam. In points A and B difference between calculated and measured temperatures is about 100°C. These two points are more complicated for numerical solution as they lie below the char layer. The mistake may be caused by material model used in the FE simulation. For the purpose of more accurate results material properties from (EN 1995–1–2 Eurocode 5, 2006) should be modified according to need of given test.

4. Conclusions

The paper presents the virtual furnace which was prepared to calculate thermal environment during fire-resistance tests for coupled CFD-FE model. In this case, the virtual furnace was used to calculate temperature environment around three timber beams. After validation of the FDS model, the temperature conditions are passed to the FE model which solves heat transfer to the tested element. Temperatures inside the timber beam which are solved in software Atena Science are compared to measured temperatures from the fire test. The comparison of temperatures in three control points shows good accuracy of the calculation in the point closer to the heated edge. An inaccuracy is shown in points located deeper in the beam cross-section – below the char layer.

In conclusion, the virtual furnace has a great potential for investigating the thermal behaviour of fire-resistance tests. A huge advantage inheres in the evaluation of the thermal effect throughout the volume of the furnace, which allows an accurate prediction of fire-resistance tests and evaluation of large number of technical alternatives and boundary conditions. However, passing the temperature field from the FDS model into FE model may decrease the level of accuracy. The solution lies in a coupled CFD-FE model. A weakly coupled model including fluid dynamics, heat transfer and mechanical behaviour is under development at Faculty of Civil Engineering, Czech Technical University in Prague. The fluid dynamics part which is presented in this paper is solved by FDS and the thermo-mechanical part is computed by OOFEM (Borek Patzák, 2012). The interconnection of both software is made owing to MuPIF python library. Details of the coupled CFD-FE model are described in Šulc *et al.* (2019).

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6.10 Paper 6

Reprint of the paper

- Analysis of Fire Resistance of Concrete Structural Members Based on Different Fire Models: An Illustrative Example of the Slab Panel Assessment

Contribution of the author of this thesis to the paper

- M. Benýšek is the author of the text of the paper (that was written under the supervision of J. Procházka and R. Štefan).
- The author’s contribution is 60 %.

Solid State Phenomena
ISSN: 1662-9779, Vol. 292, pp 173-182
doi:10.4028/www.scientific.net/SSP.292.173

Submitted: 2018-10-16
Revised: 2018-11-18
Accepted: 2019-02-03

Analysis of Fire Resistance of Concrete Structural Members Based on Different Fire Models: An Illustrative Example of the Slab Panel Assessment

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Keywords: Concrete, Slab panel, Fire resistance, Fire model, MATLAB, CFAST, FDS.

Abstract. The paper deals with the analysis of fire resistance of concrete structural members exposed to fire based on different fire models. An illustrative example of the assessment of a slab panel is presented. Several fire models are employed in order to predict the evolution of temperature in a selected fire compartment. Some of these fire models, namely the ISO fire curve and the parametric fire curve, are implemented in an in-house MATLAB code. For the more comprehensive fire models, external scientific software tools are used, namely the CFAST software for the zone model and the FDS software for the CFD (computational fluid dynamics) model. By employing the results of the fire simulations, the fire resistance of the slab panel is assessed. It is performed by a one-way coupled numerical procedure based on a well-known heat transfer finite element model and iterative sectional mechanical analysis. The procedure is implemented in an in-house MATLAB code. It is shown that (i) the numerical procedure can be employed in connection with different fire models and (ii) the fire resistance prediction can be strongly influenced by the type of selected fire model.

Introduction

In structural fire engineering practice, the assessment of fire resistance of structural members is usually based on simplified fire models, that are represented by less or more sophisticated temperature-time curves, such as the nominal and parametric curves given in EN 1991-1-2 [12], see e.g. [7, 25]. However, the current progress in computational mechanics has enabled to apply the advanced fire modelling approaches, such as the computational fluid dynamics (CFD) simulations, in connection with the numerical models of structural behaviour (both thermal and mechanical), usually based on finite element method [8, 23].

The selected fire scenario and the type of fire model can influence the results of the related fire resistance assessment, which has been studied by many researchers, e.g. [5, 10, 17, 18, 27, 33].

In the paper, an illustrative example of the fire resistance assessment of a slab panel is presented. Several fire models are employed in order to predict the evolution of temperature in the selected fire compartment. By employing the results of the fire simulations, the fire resistance of the slab panel is assessed by a one-way coupled numerical procedure implemented in an in-house MATLAB [19] code.

Illustrative Example

The illustrative example is focused on the fire resistance assessment of a slab panel. The panel is situated in the model office space designed as one separate fire compartment depicted in Fig. 1. The walls enclosing the compartment are made of lightweight concrete masonry. The slab panel of the dimensions of $5900\,\text{mm} \times 1000\,\text{mm} \times 280\,\text{mm}$ is considered as a simply supported beam of the effective span $l = 5700\,\text{mm}$. The characteristic values of the uniformly distributed loads acting on the panel are $g_k = 8.5\,\text{kN/m}^2$ and $q_k = 2.5\,\text{kN/m}^2$, with g_k being the permanent load (including the self-weight) and q_k being the variable load.

For the ultimate and serviceability limit states at normal temperature, the panel was designed according to EN 1992-1-1 [13]. The main parameters of the panel can be summarized as follows: concrete class C30/37, reinforcement B500B, concrete cover $c = 20$ mm, main longitudinal reinforcement area $A_s = 628 \text{ mm}^2$ ($8\ \phi\ 10$ mm); the other reinforcement is neglected in the fire resistance assessment and hence, it is not mentioned here.

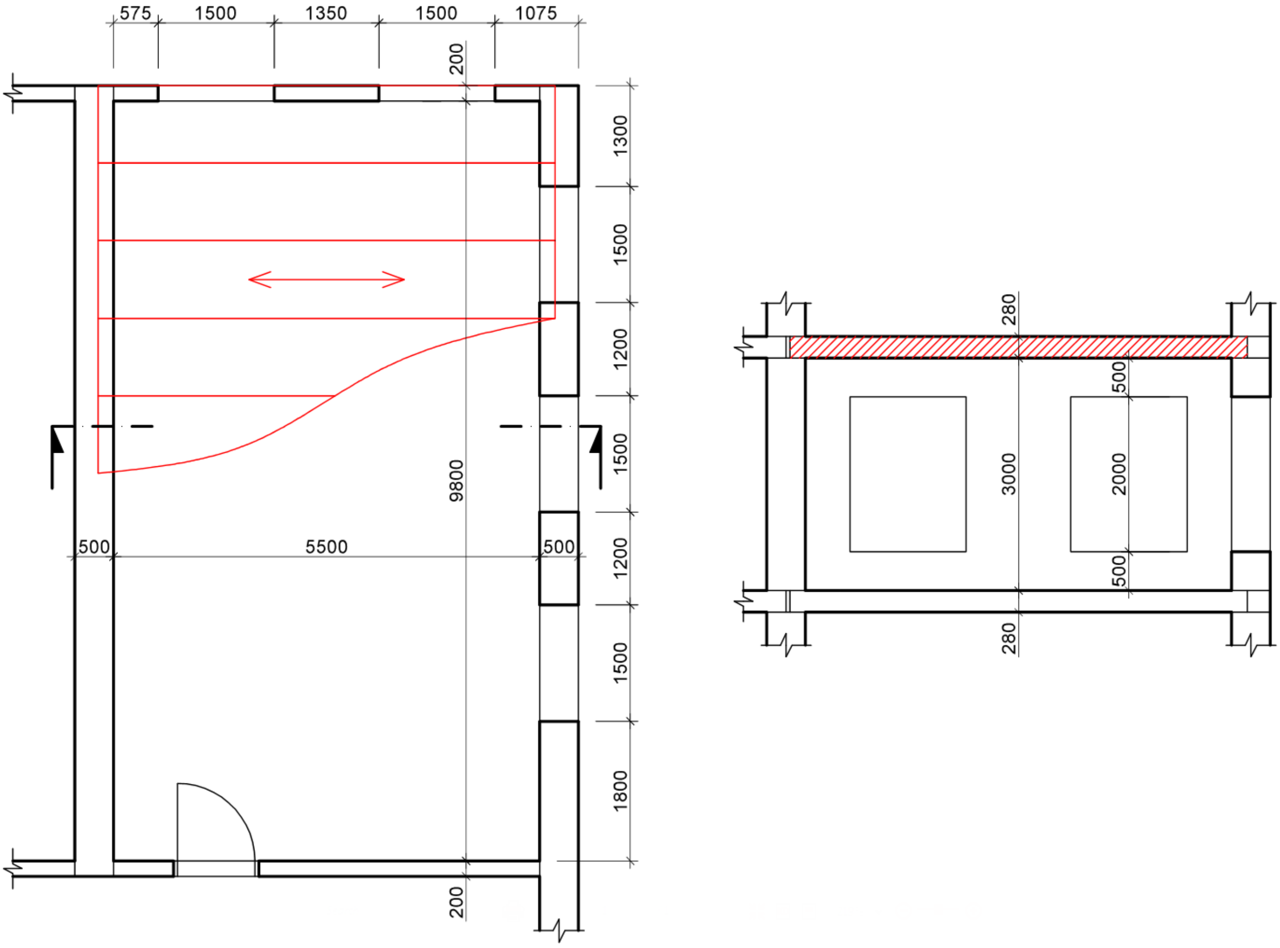


Fig. 1: Scheme of the model fire compartment with the analysed slab panel

Modelling of Fire

For the modelling of fire in the analysed fire compartment, the following fire models and computational tools were utilized:

- the standard temperature-time curve (ISO 834 fire) described, e.g., in EN 1991-1-2 [12, Cl. 3.2.1] and implemented in an in-house MATLAB code (see also [6, 30]);
- the parametric temperature-time curve given by EN 1991-1-2 [12, Annex A] and implemented in an in-house MATLAB code (see also [6, 30]);
- the two-zone fire model implemented in external scientific software tool CFAST [22];
- the CFD (computational fluid dynamics) model implemented in external scientific software tool FDS [20].

The input parameters for the fire models are set as follows: characteristic fire load density $q_{f,k} = 511\ \mathrm{MJ/m^2}$, [12, Table E.4], the design value, $q_{f,d}$, was calculated from [12, Eq. (E.1)] assuming no active fire fighting measures; the rate of heat release was determined according to EN 1991-1-2 [12, Annex E.4], with fire growth rate - medium, $t_\alpha = 300$ s, and $RHR_f = 250\ \mathrm{kW/m^2}$ [12, Table E.5]; the geometry of the compartment (enclosure area, floor area, openings area, openings height, etc.) is obvious from Fig. 1, all the windows were assumed to be open for the full duration of fire, the door was not included in the openings area; the thermal properties of the materials of enclosure were set as: $\lambda = 0.083\ \mathrm{W\,m^{-1}\,K^{-1}}$, $\rho = 300\ \mathrm{kg\,m^{-3}}$, and $c = 1000\ \mathrm{J\,kg^{-1}\,K^{-1}}$ for the light weight concrete masonry (the compartment walls, see [1]), and $\lambda = 1.951\ \mathrm{W\,m^{-1}\,K^{-1}}$, $\rho = 2500\ \mathrm{kg\,m^{-3}}$, and $c = 900\ \mathrm{J\,kg^{-1}\,K^{-1}}$ for concrete (the compartment floor and ceiling, see [20]).

The heat release rate curve used as an input for the CFAST and FDS calculations was determined by the in-house MATLAB application FMC [6], implementing the procedure described in [12, Annex E.4].

For generating the input files and visualizing the results of the CFAST a FDS models, external software tools Smokeview [15] and PyroSim [2] were employed.

In the FDS model, the temperatures in the compartment were monitored by 1520 thermocouples (TCs) in total. The positions of the thermocouples are shown in Fig. 2.

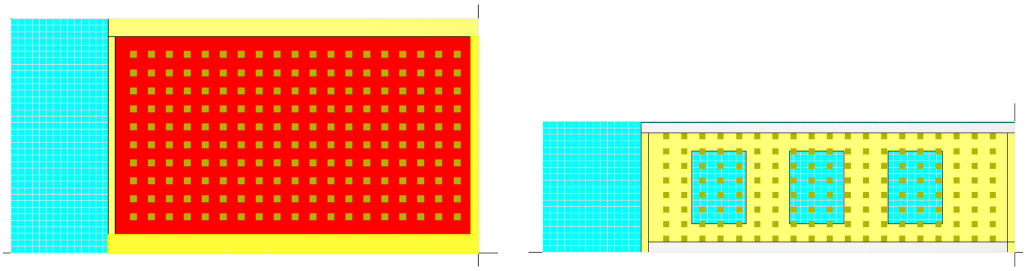


Fig. 2: Thermocouples in the CFD model [20]

The results obtained by the aforementioned fire models are displayed in Figs. 3–5.

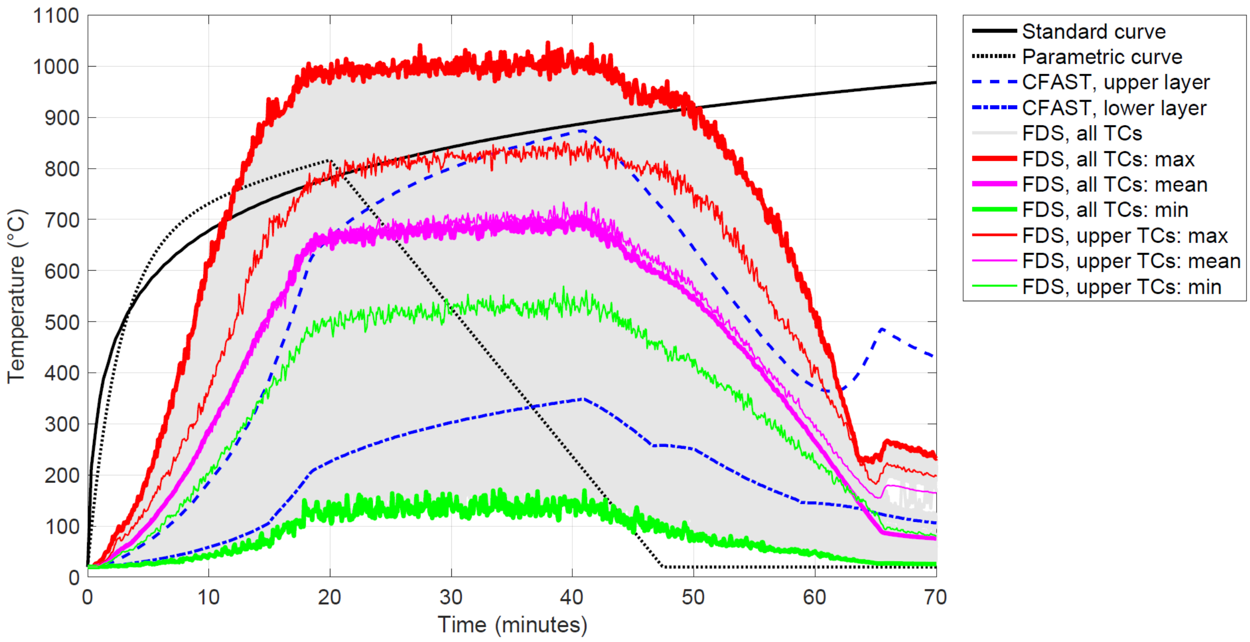
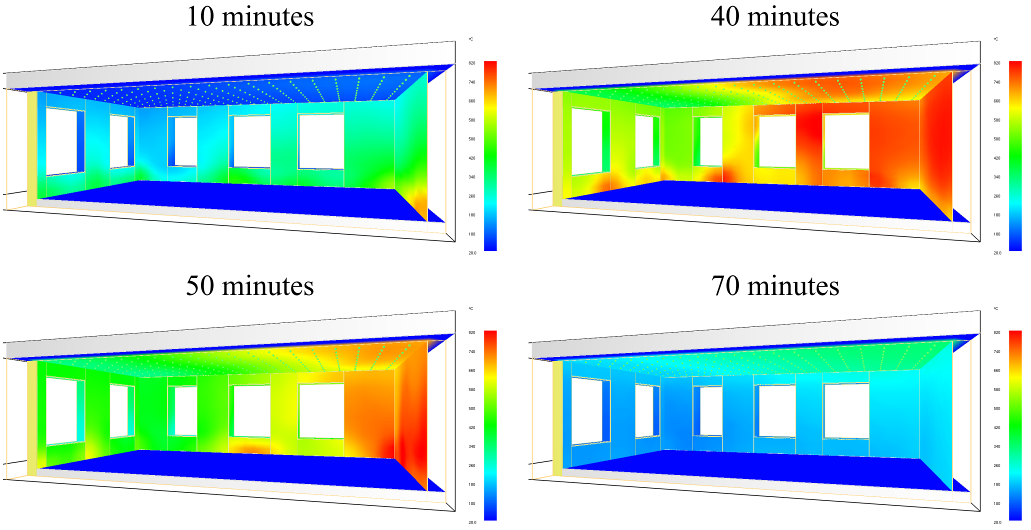


Fig. 3: Temperature-time curves for the analysed fire compartment obtained by the selected fire models

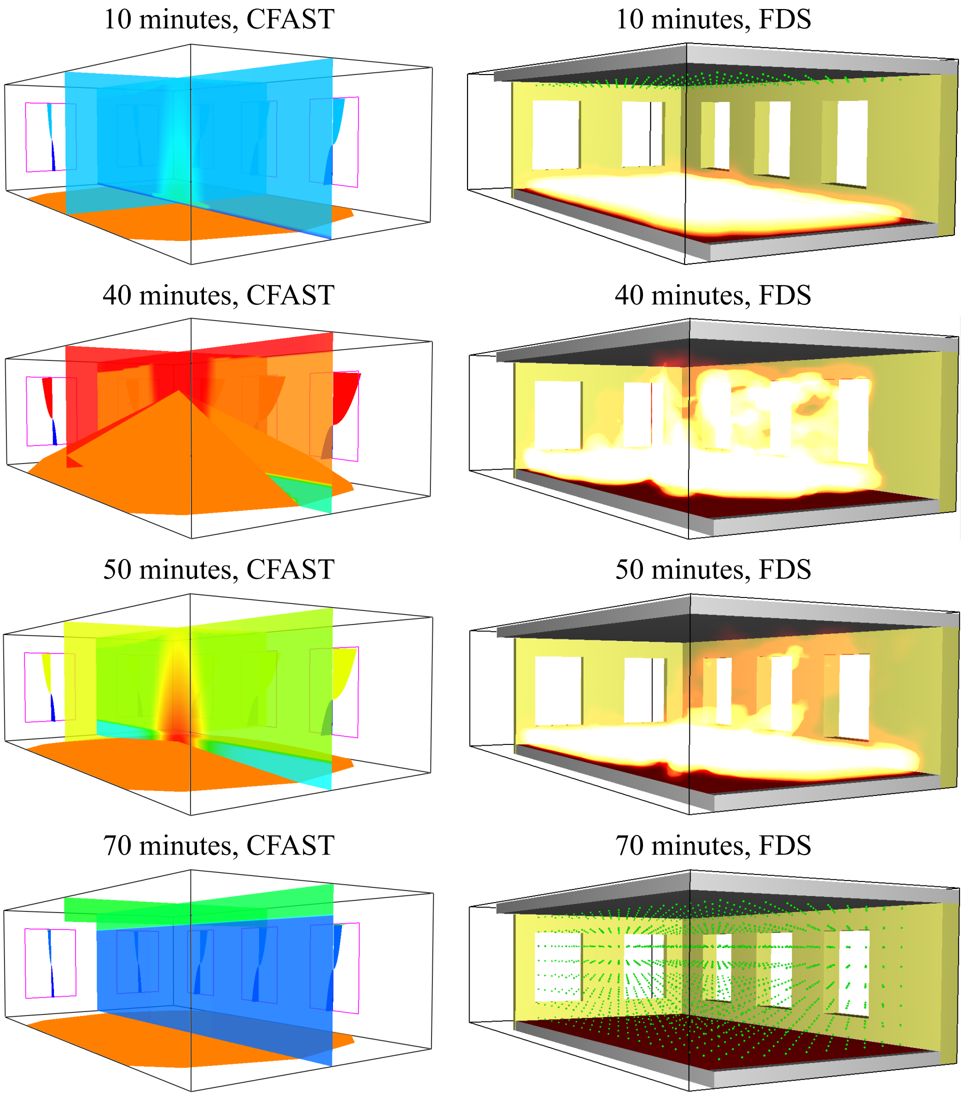

10 minutes

40 minutes

50 minutes

70 minutes

Fig. 4: Surface temperatures obtained by the CFD model [20]


10 minutes, CFAST

10 minutes, FDS

40 minutes, CFAST

40 minutes, FDS

50 minutes, CFAST

50 minutes, FDS

70 minutes, CFAST

70 minutes, FDS

Fig. 5: Visualization of fire in the analysed fire compartment obtained by the CFAST [22] and FDS [20] software tools

The temperature-time curves shown in Fig. 3 were determined as follows: for the standard and parametric fires, the curves are given directly by the models. In the CFAST zone model, the temperature evolutions for the upper and lower layers are simulated (see [22]), which can be illustrated by the appropriate temperature-time curves. For the FDS CFD model, the temperature evolution was monitored by the thermocouples placed in the analysed fire compartment, see Fig. 2. The temperature time-curves were calculated from (i) all the thermocouples (highlighted in Fig. 5 – 70 minutes FDS) and (ii) the upper thermocouples, placed near the analysed slab panels (highlighted in Fig. 5 – 10 minutes FDS). For both of these variants, the maximum, minimum, and mean temperatures were determined, see Fig. 3.

For the subsequent thermal and mechanical analysis, the following temperature-time curves were assumed: (i) the standard curve, (ii) the parametric curve, (iii) the curve obtained by the CFAST software for the upper layer - i.e. "CFAST, upper layer", and (iv) the curve obtained by the FDS software as the maximum temperature for the upper thermocouples, i.e. "FDS, upper TCs: max", see Fig. 3.

For reading and visualising the .csv files generated by the CFAST and FDS software tools, an in-house MATLAB code was written (see [29]), that also enables to connect these external software tools with an in-house code for the subsequent thermal and mechanical analysis.

Thermal Analysis

The thermal analysis of the panel was performed by solving the well-known one-dimensional heat transfer problem described in detail, e.g., in [28, 31].

The thermal properties of concrete (thermal conductivity, specific heat, density) were taken from EN 1992-1-2 [14, Cl. 3.3], assuming the upper limit of the thermal conductivity, the initial moisture content in concrete of 1.5 % of concrete weight, and the initial density of concrete of 2500 kg/m^3. In the cooling phase, the thermal properties of concrete were considered as irreversible [11].

The effect of the reinforcement on the temperature distribution was neglected [14, Cl. 4.3.2(4)].

The uniform initial temperature was set as $\theta_0 = 20$ °C.

The heat flux on the heated boundary was determined according to EN 1991-1-2 [12, Cl. 3.1], with $\alpha_c = 25\,\mathrm{W\,m^{-2}\,K^{-1}}$, $\Phi = 1$, $\varepsilon_m = 0.7$, $\varepsilon_f = 1$, and $\theta_g = \theta_r$ assumed according the appropriate temperature-time curve displayed in Fig. 3. On the unexposed boundary, zero heat flux was conservatively prescribed [28].

The model was solved by the finite element method implemented in an in-house MATLAB code. The spatial discretization was performed by 56 1D two-node linear elements (the element size of 5 mm). For the discretization in time, a semi-implicit difference scheme was used, with the time step of 20 s [28, 30, 31]. The total time of heating was set to 70 minutes, see Fig. 3.

The result of the thermal analysis are depicted in Figs. 6–7.

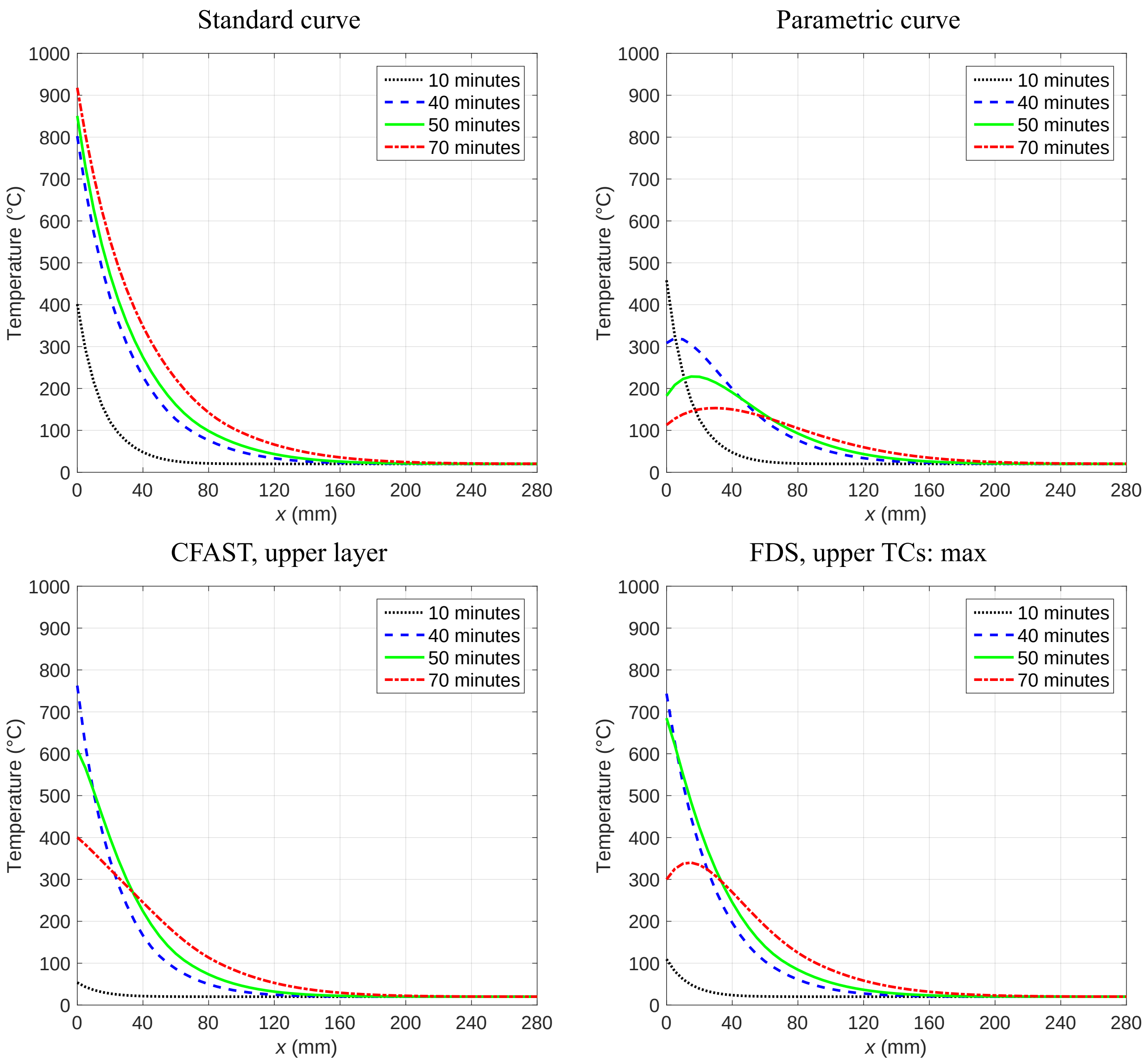
Mechanical Analysis

For the mechanical analysis, an iterative procedure based on moment-curvature approach was used to determine the maximum moment capacity for a given time of fire exposure. The procedure is described in detail, e.g., in [21, 26] (see also [32]). Hence, for this particular case, it is only briefly summarised in Algorithm 1.

In **Step 1**, the design value of the applied bending moment for the analysed slab panel is determined. In this case, the panel is considered as simply supported beam and the effect of mechanical restraint on the resulting bending moment is neglected, cf. [5, 18, 24]. Hence, the constant value of $M_{Ed,fi}$ can be simply calculated as (see [14, Cl. 2.4.2])

$$M_{Ed,fi} = \eta_{fi} M_{Ed} = 0.7 \cdot (g_d + q_d)/8 \cdot l^2 = 0.7 \cdot (8.5 \cdot 1.35 + 2.5 \cdot 1.5)/8 \cdot 5.7^2 = 43.3\,\mathrm{kNm}. \quad (1)$$

In **Step 2**, the thermal analysis of the analysed cross-section for the full duration of fire is performed, as described in the previous section.


Standard curve

Parametric curve

CFAST, upper layer

FDS, upper TCs: max

Fig. 6: Temperature profiles across the analysed cross-section for the selected fire models

In **Step 3**, an iterative procedure is applied in order to determine all the positions of neutral axis satisfying the equilibrium of internal forces for each time step (see [21, 32]). It is assumed that the total strain can be divided in two strain components: the thermal strain and the mechanical strain (see [32] and references therein for more detail). The stress-strain relations for concrete and reinforcing steel (cold-worked) as well as the formulas for the thermal strain of the materials are taken from EN 1992-1-2 [14]. In the cooling phase, the stress-strain relation for concrete is considered as irreversible, while for reinforcing steel, it is assumed as fully reversible [11]. For each time step, the maximum bending moment is determined, which can be denoted as $M_{Rd,fi}(t)$ [21]. Alternatively, the ultimate moment capacity could be determined by simplified calculation methods, as described, e.g., in [9, 14, 17, 26].

In the last **Step 4**, the resulting time dependencies of bending moments $M_{Ed,fi}$ and $M_{Rd,fi}$ are displayed and compared in order to perform the final fire resistance assessment [3, 4, 9, 16, 17, 18].

The comparison of the applied moment $M_{Ed,fi}$ and the ultimate moments $M_{Rd,fi}$ appears in Figs. 8 and 9.

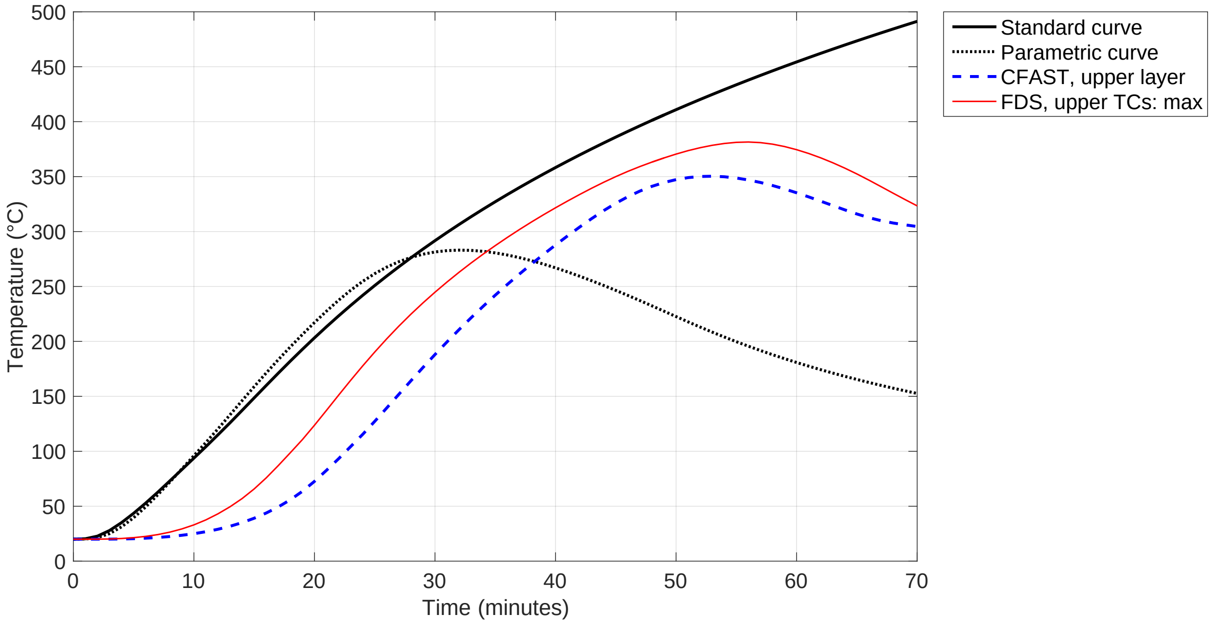


Fig. 7: Temperature evolutions in the reinforcement ($x = 25$ mm) for the selected fire models

Algorithm 1 Algorithm for the fire resistance assessment (see [21, 32])

```
1: determine the applied bending moment in fire situation, $M_{Ed,fi}(t)$
2: determine the temperature distribution across the analysed cross-section for the full duration of fire
3: for each time step, determine all the positions of neutral axis satisfying the equilibrium of internal forces, calculate the appropriate bending moments and find the maximum value, $M_{Rd,fi}(t)$
4: display and compare the time evolutions of $M_{Ed,fi}$ and $M_{Rd,fi}$
```

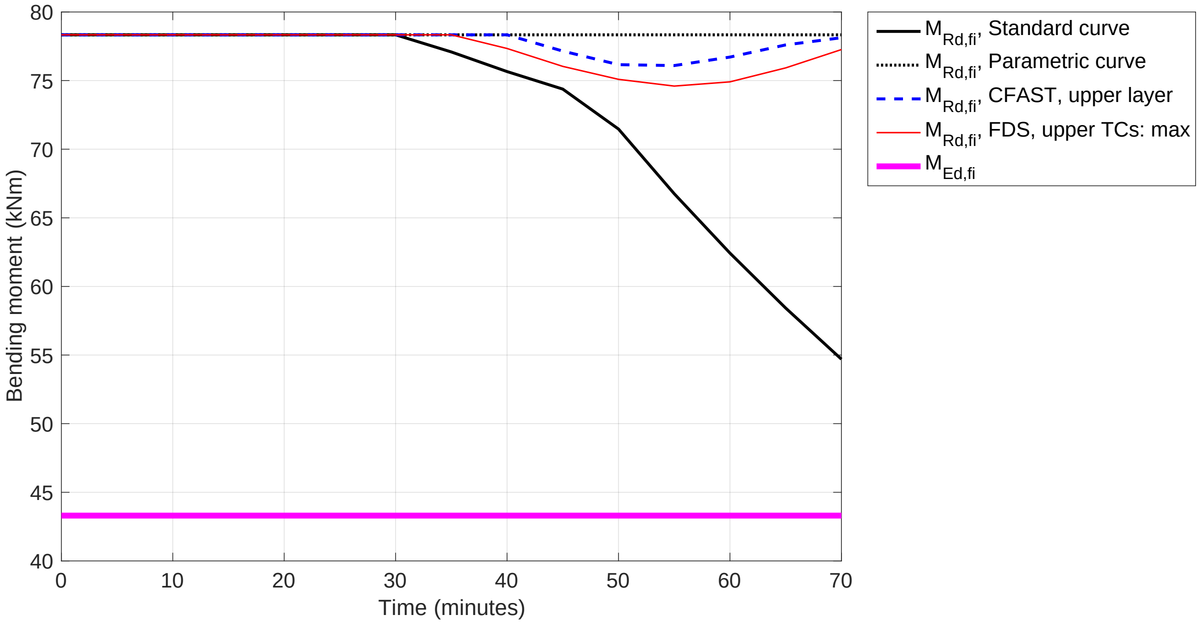


Fig. 8: Applied moment $M_{Ed,fi}$ and the ultimate moments $M_{Rd,fi}$ for the selected fire models

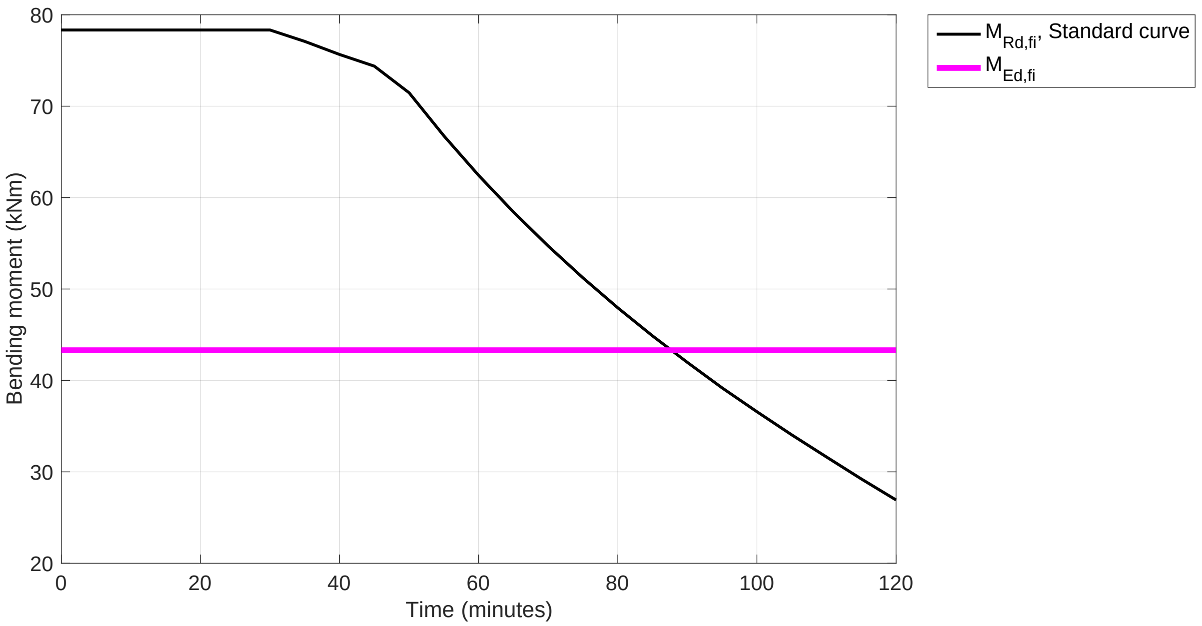


Fig. 9: Applied moment $M_{Ed,fi}$ and the ultimate moment $M_{Rd,fi}$ for the standard fire exposure

Results and Discussion

From Figs. 8 and 9, it is obvious that the resulting fire resistance behaviour of the analysed slab panel is strongly influenced by the type of model employed for the simulation of fire. By using the standard fire curve, the most conservative results were obtained, with the fire resistance reached at the time of fire exposure of 87.7 minutes, see Fig. 9. For all of the other fire models, the slab panel maintained its load bearing function for the full duration of fire.

Summary

In the paper, an illustrative example of the fire resistance assessment of a slab panel was presented. Several fire models were employed in order to predict the evolution of temperature in the selected fire compartment. By employing the results of the fire simulations, the fire resistance of the slab panel was assessed by a one-way coupled numerical procedure implemented in an in-house MATLAB code.

Based on the results obtained by the fire models and with respect to the computational costs, it can be concluded that in this case, the CFAST zone model was the most convenient, since the standard temperature-time curve was too conservative, the parametric curve underestimated the temperature evolution, mainly in the cooling phase of fire, and the FDS CFD model required too time-consuming simulations.

For the fire resistance assessment of the analysed slab panel, the most conservative results were obtained assuming the standard fire curve (with the resulting fire resistance of 87.7 minutes). For all of the other fire models, the slab panel maintained its load bearing function for the full duration of fire.

Acknowledgement

This work has been supported by the Czech Science Foundation, project No. GA16-18448S, and by the Grant Agency of the Czech Technical University in Prague, project No. SGS18/038/OHK1/1T/11. The support is gratefully acknowledged.

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6.11 Short papers presented at PhD workshop

6.11.1 Paper 7

Reprint of the paper

- Software Tools for Fire Engineering

Contribution of the author of this thesis to the paper

- M. Benýšek is the author of the text of the paper (that was written under the supervision of J. Procházka and R. Štefan).
- The author's contribution is 100 %.

SOFTWARE TOOLS FOR FIRE ENGINEERING

BENYSEK Martin

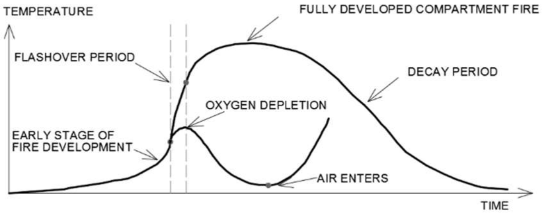
Abstract:

This paper is focused on the analysis and algorithmization of fire models for fire engineering. Based on the complicated process of obtaining results from the sophisticated fire models – zone models (e. g. software CFAST – Consolidated Fire and Smoke Transport Model) and Computational Fluid Dynamics models (e. g. software FDS – Fire Dynamics Software), a software tool DataPlot was developed. This tool serves for elaboration, display, and comparison of the resulting values of the temperature curves. In literature, there are available many simplified fire models. In order to simplify the usage of these models, a software tool FMC (Fire Models Calculator) was developed. This software tool contains selected simplified fire models. The software tools are developed in the MATLAB environment and they work as standalone applications.

Keywords: fire engineering, fire models, MATLAB, FDS, CFAST

1. Introduction

Fire was a significant phenomenon in the past and is still an important scientific branch. With extending knowledge, scientists and researchers in fire safety engineering, can leave standard approaches and can apply advanced methods. A typical fire has four stages. Each stage can be investigated separately (Pokorný 2018).



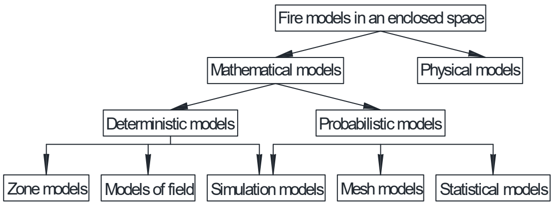


Fig. 1: *Phases of fire.* (Karlsson 2000)

Fig. 2: *Types of fire models.* (Kučera 2010)

Fire can be described by the models of fire. They can be deterministic (Benýšek et al. 2018) or probabilistic (Benýšek et al. 2019). This paper is mainly focused on the algorithmization of the deterministic fire models. These models can be simplified, e. g. nominal temperature-time curves (standard temperature-time curve, external fire, etc.), parametric temperature-time curves, or simplified, e. g. zone and CFD (Computational Fluid Dynamics) models, see Fig.2.

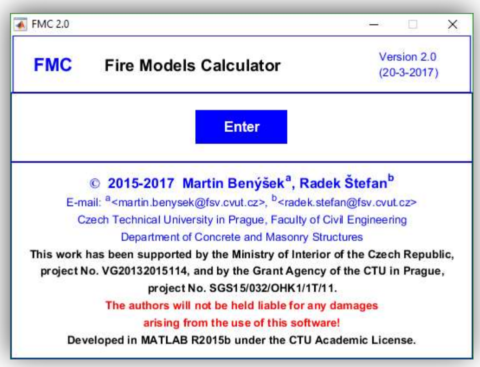
Currently, there is a tendency to use advanced fire models with sophisticated models for assessment of the fire resistance of structures for complicated buildings. However, this process is time-dependent so that there is a tendency to speed up it by automatization. That is the reason why two software tools were developed in MATLAB environment – DataPlot – tool for visualization of csv data (Štefan, Benýšek 2017) and FMC – Fire Models Calculator (Benýšek, Štefan 2018).

2. Software FMC – Fire Models Calculator

This program, see Fig. 3, was developed in MATLAB R2015b under the Czech Technical University academic license. It contains simplified and frequently used fire models. The main window of the program is shown below.

FMC is divided into four general parts – type of model, see Fig. 4:

- Flashover
- Nominal temperature-time curves
- Natural fire models
- Equivalent time of fire exposure



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This work has been supported by the Ministry of Interior of the Czech Republic, project No. VG20132015114, and by the Grant Agency of the CTU in Prague, project No. SGS15/032/OHK1/1T/11.
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Fig. 3: *FMC.* (Benýšek, Štefan 2018)

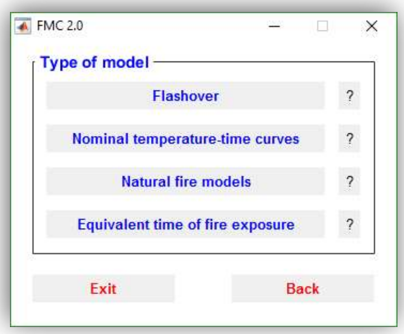
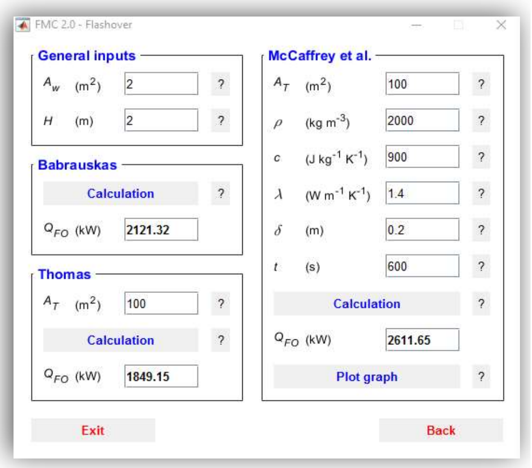


Fig. 4: *FMC- Type of Model.* (Benýšek, Štefan 2018)

2.1 FMC - Flashover

The flashover effect can be determined by the empirical equations according to three models (Babrauskas, Thomas, McCaffrey et.al.). In this section of FMC, according to inputs, the program can determine the value of the heat release rate (HRR or RHR) which is required for the flashover effect. It also allows plotting a graph of the required HRR for the flashover effect on time according to McCaffrey et.al., see Fig. 5.

FMC is equipped with input control. Limits of fire models and formats of inputs are checked. In case that the input is incorrect, the input window becomes red, see Fig. 6. This is set up in the whole FMC software.



A_w (m^2) 2

H (m) 2

Babrauskas: Q_{FO} (kW) 2121.32

Thomas: A_T (m^2) 100

Thomas: Q_{FO} (kW) 1849.15

McCaffrey et al.: A_T (m^2) 100

ρ (kg m^{-3}) 2000

c (J kg^{-1} K^{-1}) 900

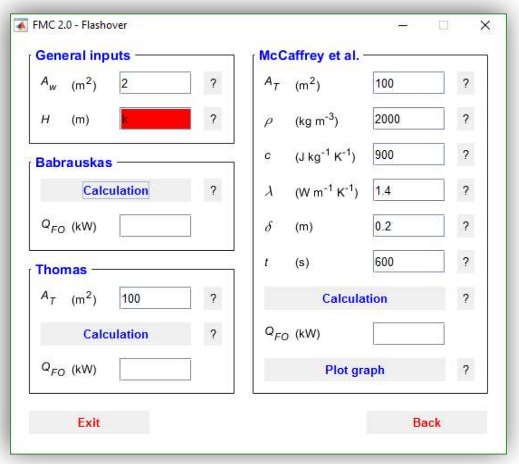
λ (W m^{-1} K^{-1}) 1.4

δ (m) 0.2

t (s) 600

McCaffrey et al.: Q_{FO} (kW) 2611.65

Fig. 5: *FMC – Flashover.* (Benýšek, Štefan 2018)



A_w (m^2) 2

H (m)

Q_{FO} (kW)

Thomas: A_T (m^2) 100

Q_{FO} (kW)

McCaffrey et al.: A_T (m^2) 100

ρ (kg m^{-3}) 2000

c (J kg^{-1} K^{-1}) 900

λ (W m^{-1} K^{-1}) 1.4

δ (m) 0.2

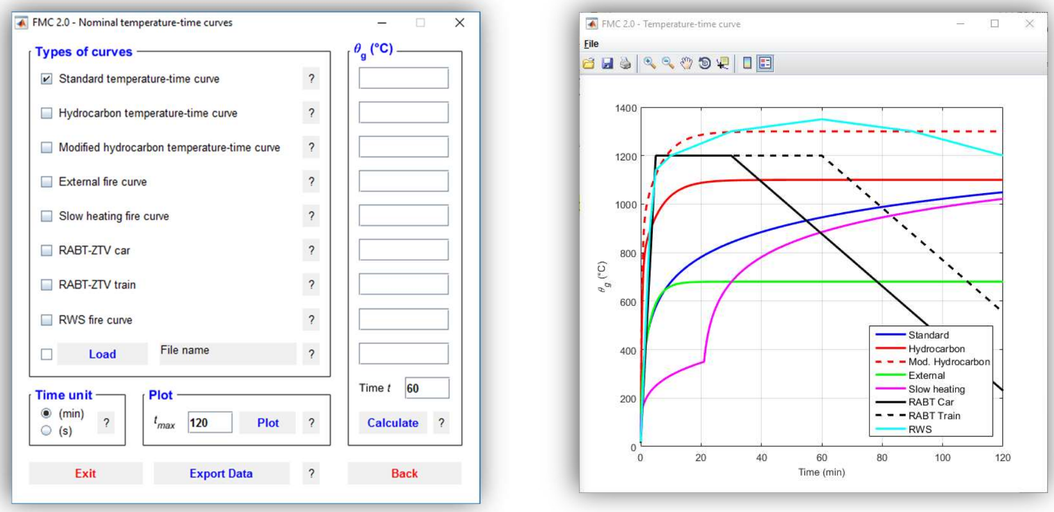
t (s) 600

Q_{FO} (kW)

Fig. 6: *FMC – inputs control.* (Benýšek, Štefan 2018)

2.2 FMC – Nominal temperature-time curves

The program in this section allows plots up to eight nominal temperature-time curves. The plot is made according to the checkboxes for a given time. With regard to the possible comparison of the temperature-time curves with the temperature processes from sophisticated programs (e.g. CFD fire models, zone fire models) or fire experiments, it is available to load variable temperature curve(s) in *.xls* format, see Fig. 7. The load temperature curve(s) must have only one time-vector and a variable amount of temperature-vectors. The variable curve can be compared with the variable numbers of the nominal temperature-time curves. Nominal temperature-time curves could be also exported to a *.xls* format and, however, it is possible to choose time-units.



☑ Standard temperature-time curve

☐ Hydrocarbon temperature-time curve

☐ Modified hydrocarbon temperature-time curve

☐ External fire curve

☐ Slow heating fire curve

☐ RABT-ZTV car

☐ RABT-ZTV train

☐ RWS fire curve

☐ Load

Time unit: ● (min) ○ (s)

t_{max} 120

Time t 60

(a) (b)

Fig. 7: *FMC – (a) Nominal temperature-time curves, (b) graph of the temperature-time curves.* (Benýšek, Štefan 2018)

2.3 FMC – Natural fire models

Section Natural fire models is divided into five sub-programs, see Fig. 8:

- Heat Release Rate (HRR or RHR)
- HRR with activation of sprinkler nozzle
- HRR of flammable liquids
- Parametric temperature-time curve (EN 1991-1-2, Annex A)
- Localised Fires

FMC can calculate the maximum value and plot the graph of the heat release rate. The program allows the export of the data in *.xls* format for the following applications (e.g. for CFD models of fire), see Fig 9.

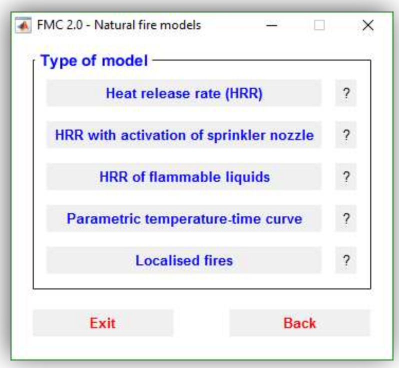
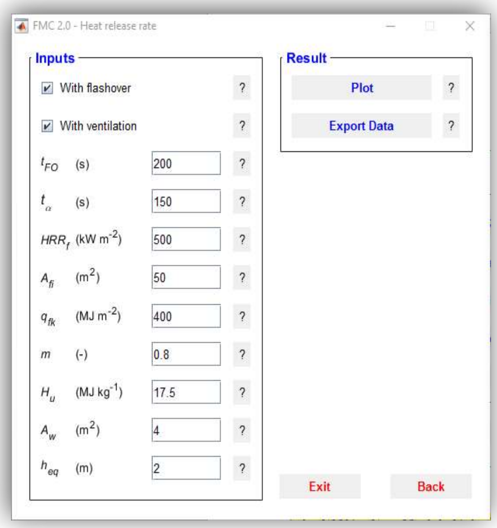


Fig. 8: *FMC – Natural Fire Models. (Benýšek, Štefan 2018)*



☑ With flashover

☑ With ventilation

t_{FO} (s) 200

t_{α} (s) 150

HRR_f (kW m^{-2}) 500

A_{fi} (m^2) 50

q_{fk} (MJ m^{-2}) 400

m (-) 0.8

H_u (MJ kg^{-1}) 17.5

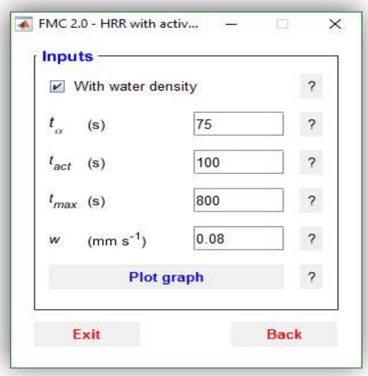
A_w (m^2) 4

h_{eq} (m) 2

Fig. 9: *FMC – Natural Fire Models – HRR.* (Benýšek, Štefan 2018)

Program FMC can automatically determine the type of the HRR according to inputs (fuel-controlled fire, ventilation-controlled fire, fuel-controlled fire with flashover, ventilation-controlled fire with flashover). The HRR with activation of a sprinkler nozzle, see Fig. 10, can calculate both models (Madrzykowski, D., & Vettori, R. L. (1992); Evans (1993)). The result of this fire model is a graph with a given maximum value of the HRR.

The HRR of flammable liquids can determine the maximum value of the HRR according to the inputs. The calculation works for two different shapes (square and circle) where flammable liquids are located. FMC contains some input values, see Fig. 11.


FMC 2.0 - HRR with activ...

Inputs

☑ With water density

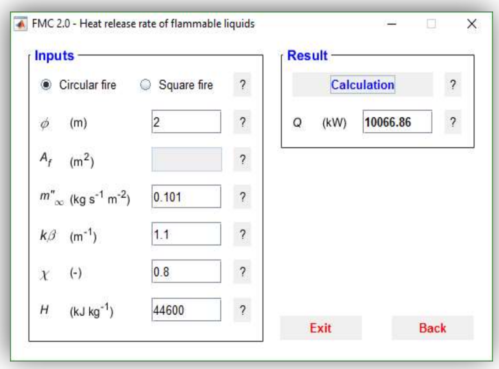
t_α (s) 75

t_{act} (s) 100

t_{max} (s) 800

w (mm s^{-1}) 0.08

Fig. 10: *FMC – Natural Fire Models – HRR with activation of sprinkler nozzle.* (Benýšek, Štefan 2018)


FMC 2.0 - Heat release rate of flammable liquids

Inputs

● Circular fire ○ Square fire

ϕ (m) 2

A_f (m^2)

m''_∞ (kg s^{-1} m^{-2}) 0.101

$k\beta$ (m^{-1}) 1.1

χ (-) 0.8

H (kJ kg^{-1}) 44600

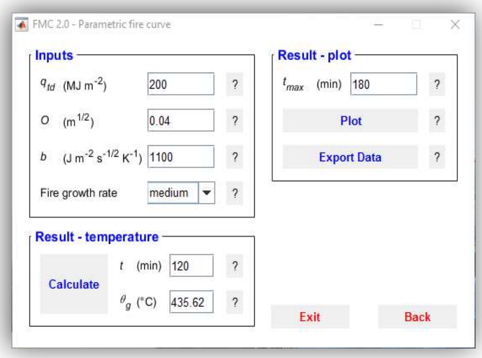
Result

Q (kW) 10066.86

Fig. 11: *FMC – Natural Fire Models – HRR of flammable liquids.* (Benýšek, Štefan 2018)

The parametric fire curve is also included (EN 1991-1-2). FMC can plot the graph of this curve, calculate the temperature in variable time and export data in *.xls* format, see Fig. 12.

The next fire model is localised fire. FMC contains both models (the flame is impacting the ceiling; the flame is not impacting the ceiling). According to the inputs, FMC determines the shapes of the flame and the heat flux from localised fire, see Fig. 13.


FMC 2.0 - Parametric fire curve

Inputs

q_{td} (MJ m^{-2}) 200

O ($m^{1/2}$) 0.04

b (J m^{-2} $s^{-1/2}$ K^{-1}) 1100

Fire growth rate medium

Result - plot

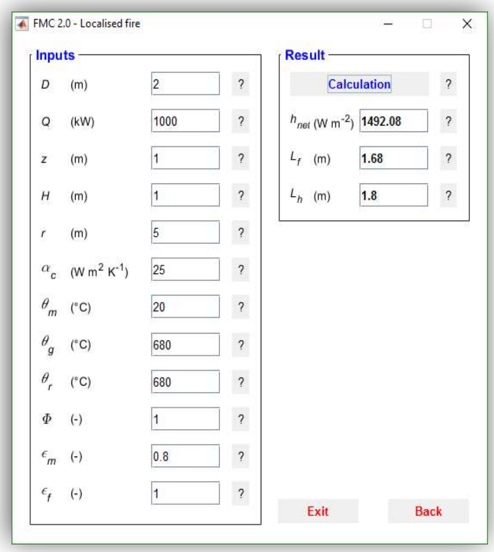
t_{max} (min) 180

Result - temperature

t (min) 120

θ_g (°C) 435.62

Fig. 12: *FMC – Natural Fire Models – Parametric temperature-time curve.* (Benýšek, Štefan 2018)


FMC 2.0 - Localised fire

Inputs

D (m) 2

Q (kW) 1000

z (m) 1

H (m) 1

r (m) 5

α_c (W m^2 K^{-1}) 25

θ_m (°C) 20

θ_g (°C) 680

θ_r (°C) 680

Φ (-) 1

ϵ_m (-) 0.8

ϵ_f (-) 1

Result

h_{net} (W m^{-2}) 1492.08

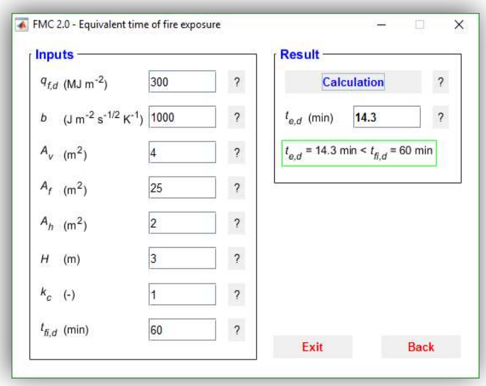
L_f (m) 1.68

L_h (m) 1.8

Fig. 13: *FMC – Natural Fire Models – Localised fire.* (Benýšek, Štefan 2018)

2.4 FMC – Equivalent time of fire exposure

The last section of the FMC serves for determination of the Equivalent time of fire exposure, see Fig. 14. The program according to the inputs can assess the condition if the equivalent time of fire exposure is larger or smaller than the equivalent time of ISO-fire exposure assessed according to Eurocodes.



$q_{f,d}$ (MJ m^{-2}) 300

b (J m^{-2} s$^{-1/2}$ K^{-1}) 1000

A_v (m^2) 4

A_f (m^2) 25

A_h (m^2) 2

H (m) 3

k_c (-) 1

$t_{fi,d}$ (min) 60

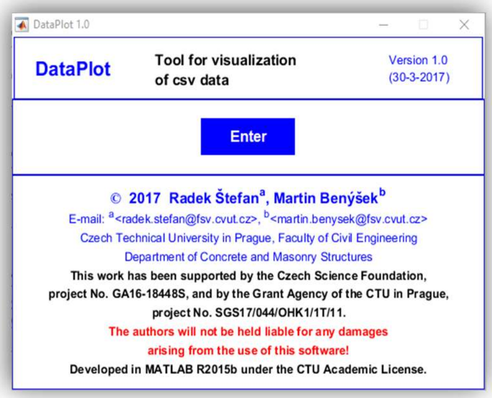
$t_{e,d}$ (min) 14.3

$t_{e,d}$ = 14.3 min < $t_{fi,d}$ = 60 min

Fig. 14: *FMC – Equivalent time of fire exposure.*
(Benýšek, Štefan 2018)

3. Software DataPlot – tool for visualization of csv data

Software DataPlot – tool for visualization of csv data (*csv* = Comma-Separated Values) is a simple tool for reformatting of the *.csv* files into user-friendly *.xls* files and, of course, it is for creating graphs. It is mainly created for support of the output files of the FDS and CFAST software. The main window is shown in Fig. 15.



Tool for visualization
of csv data

Version 1.0
(30-3-2017)

© 2017 Radek Štefan[a], Martin Benýšek[b]
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This work has been supported by the Czech Science Foundation,
project No. GA16-18448S, and by the Grant Agency of the CTU in Prague,
project No. SGS17/044/OHK1/1T/11.
The authors will not be held liable for any damages
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Developed in MATLAB R2015b under the CTU Academic License.

Fig. 15: *DataPlot.* (Štefan, Benýšek 2017)

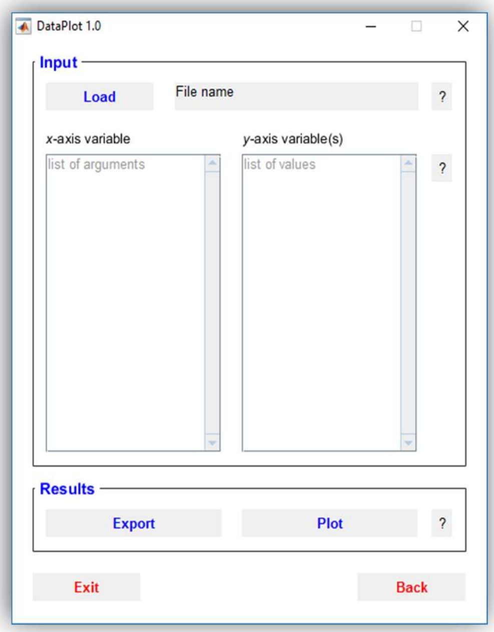

Fig. 15: *DataPlot – main window.* (Štefan, Benýšek 2017)

This program was also developed in MATLAB R2015b under the Czech Technical University academic license. After the main window of the program, there is a prime window, see Fig. 16. This window is separated into two main parts – Input and Results.

Load the data (e. g. the output from the Fire Dynamics Simulator) respecting the following rules:

- the input file must be in .csv format (the first sheet is assumed for the calculation),
- the first row must contain the units of variables separated by "comma",
- the second row must contain the names of variables separated by "comma",
- the third and the others must contain the variables data.

DataPlot contains input control and helps as well as FMC. Using the button "Load", it is available to load a random *.csv* file (output from FDS software). DataPlot loads all the data to columns (in DataPlot marked as x-axis variable and y-axis variable(s)), see Fig. 16, where the user can choose the axis "x" and the axis "y" for a graph. It can be marked only one value for the axis x and a variable amount of values for the axis y. Then the program DataPlot can plot the required graph.

DataPlot can also export the data to *.xls* file. This exported *.xls* file can be loaded in FMC software. This connection of FMC and DataPlot is appropriate for comparison, for example, the temperatures from FDS software with nominal temperature-time curves.

4. Conclusions

Modelling fire is a complicated process. There are simplified models (e. g. nominal temperature-time curves, parametric temperature-time curves, localised fires, etc.), and advanced fire models (zone models and CFD models). For complicated buildings and for the economic design of the structure and fire safety design, there is a tendency to apply an advanced approach.

Two software tools have been developed: FMC – Fire Models Calculator and DataPlot – tool for visualization of csv data. FMC contains simplified and frequently used fire models. DataPlot is a simple tool for reformatting of the *.csv* files into user-friendly *.xls* files and, of course, it is for creating graphs. Both software tools were developed in MATLAB R2015b under the Czech Technical University academic license. FMC and DataPlot are useful in engineering practise and for future scientific purposes.

Acknowledgements

This work has been supported by the Grant Agency of the Czech Technical University in Prague, project No. SGS20/041/OHK1/1T/11. The support is gratefully acknowledged.

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6.11.2 Paper 8

Reprint of the paper

- Fire Resistance Assessment of Reinforced Concrete Columns (*in Czech*)
- in Czech, translated to English

Contribution of the author of this thesis to the paper

- M. Benýšek is the author of the text of the paper (that was written under the supervision of J. Procházka and R. Štefan).
- The author's contribution is 100 %.

FIRE RESISTANCE ASSESSMENT OF REINFORCED CONCRETE COLUMNS

BENYSEK Martin

Abstract:

This paper is focused on the fire resistance assessment of reinforced concrete columns. There is briefly described a method for a determination of the required fire resistance which is based on design standards for the fire safety. There are also stated fire models which describe the theoretical process of this phenomenon. Fire models serve as a boundary condition for the heat transfer. Subsequently, there are described options for the fire resistance assessment of concrete structures with an aim at the tabular assessment of reinforced concrete columns. Based on described methods, there were created three software – it is about an assessment of the fire resistance according to the Method A, Method B, and Method for slender columns. These software tools were developed in the MATLAB.

Keywords: fire resistance, columns, fire models, heat transfer

1. Introduction

The main part of the fire safety solution is to design structures that resist for a specific time fire spreading and withstand the temperatures which occur during the fire. Active and passive protections are available in the fire safety engineering. Building structures are considered as a passive fire protection – structures can have a fire separation function (mostly slabs and walls) – they separate building into the fire compartments. Structures also can be only load-bearing (e.g. columns, beams) and they are placed in fire compartments. The fire compartment is a space which is separated by the constructions fulfil fire resistance. Active fire protections are the electric detection and signalization, sprinkler systems or the fire ventilation. The fire is for needs of fire safety described by the fire models (ČSN 73 0802, Kučera a kol. 2010).

2. Models of fire

Models of fire describe the dynamics of this phenomenon in a space. It is a theoretical description of a fire which can occur. This description is usually described by the temperature curve which serves as a boundary condition for the heat transfer. Based on this boundary condition, the temperature in a structure can be solved.

Among basic types of fire models belong the mathematical and physical models. The mathematical are divided according to their accuracy into:

1) Nominal temperature-time curves
    a) Standard temperature-time curve
    b) External fire curve
    c) Hydrocarbon temperature-time curve
    d) Modified hydrocarbon temperature-time curve
    e) Slow heating fire curve, etc.
2) Natural fire models – simplified fire models
    a) Parametric temperature-time curves
    b) Thermal actions for external members
    c) Heat release rate

d) Local fires
3) Natural fire models – advanced fire models
a) Zone models (one or two zones)
b) Computational fluid dynamics – CFD models.

The physical models are e.g. fire experiments which can be small-scale or full-scale. The parametric temperature-time curve and nominal temperature-time curves are shown below, see Fig. 1 (Benýšek et al. 2018, EN 1991-1-2).

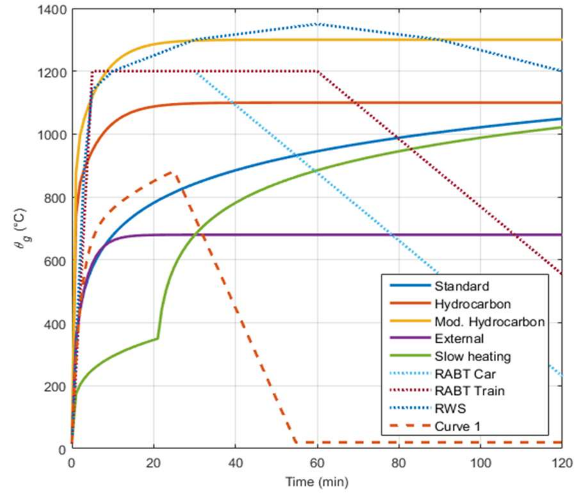


Fig 1: *Nominal temperature-time curves and the parametric temperature-time curve (Curve 1)* (FMC 2015-2017)

In engineering practise, the nominal temperature-time curves are commonly used. This approach is sufficient namely for concrete structures with required fire resistance up to 90 minutes. In a case of the high demand for the fire resistance (more than 90 minutes) or if the structural are old (or historical), it is preferable to use advanced natural fire models – zone models or CFD models (Benýšek et al. 2018). Zone models are user-friendly and they work quickly for acceptable accuracy. CFD models are the most sophisticated fire models, however they are very consuming for the inputs and for the length of calculation time. Modelling of fire is well described in (Wald et al. 2015).

3. Determination of the required fire resistance

The fire resistance is a period for which the building structures are able to resist effects of the fire. It is characterized by the limit states (load-bearing criterion R, integrity criterion E, insulation criterion I, fire separation criterion EI, etc.). In the Czech Republic, it is used an additional marking of type of structural parts, marked as DP1, DP2 and DP3. Type of structural part is dependent on the classification of the materials – the class of reaction to fire tests according to EN 13501-1. This class is defined by the letters A1 (non-flammable), A2, B, C, D, E and F (flammable). For example, concrete is non-flammable – class of reaction is A1. Concrete structural part is DP1 (created from the material class of reaction A1). For example, a concrete column has a required fire resistance R 30 DP1.

The value of the required fire resistance of building structures is dependent on the thermal (fire) load, type of the building, type of the structure and the fire hight. The required fire resistance is determined in the fire safety design, in the Czech Republic according to the standards ČSN 73 08xx (ĆSN 73 0802, ČSN 73 0810, Kučera et al. 2010).

4. Assessment of structures exposed to fire

Although the concrete is non-flammable material, during the high temperatures the concrete strength and reinforcement strength is decreased and the integrity and cohesion are compromised. Simplified and advanced methods can be used for the fire resistance assessment. These methods are described in EN 199x-1-2, x ∈ 1,2,3,4,5,6,9 where the number means the material, for example 2 = concrete structures.

If the advanced models for assessment of fire resistance are assumed (or required), it is necessary to know the temperature distribution in a structural member. Three types of heat transfer can occur – conduction, convection and radiation. Heat transfer is well described for example in (Štefan 2015). The boundary condition for heat transfer is commonly a temperature-time curve which is determined based on an appropriate model of fire. The Eurocodes describe only simplified methods for assessment of fire resistance quite well. The scheme of the design of structures exposed to fire is shown below and it shows opportunities in the process (EN 1992-1-2).

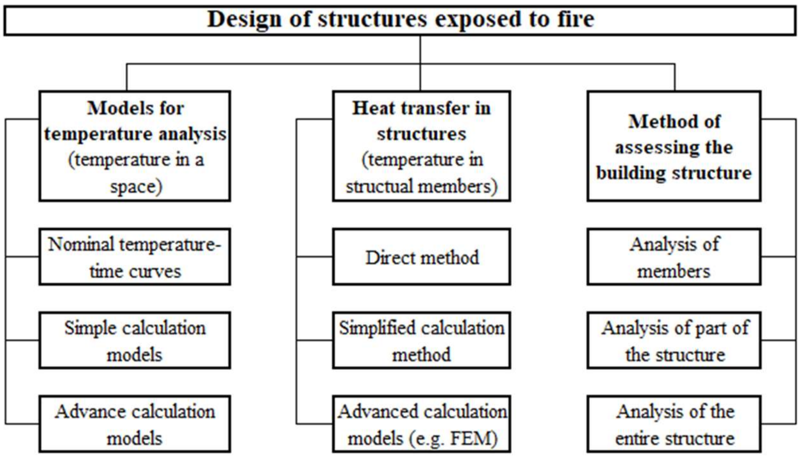


Fig 2: *Design of structures exposed to the fire* (EN 1992-1-2).

Assessment of fire resistance is possible to provide in different ways, according to the time, temperature and load-carrying capacity. The standard EN 1992-1-2 describes several methods for the fire resistance assessment. The simplest method is the assessment by the table values. For load-bearing criterion (R) and fire separation criterion (EI), the values of minimum width and minimum axis distance of reinforcing or prestressing steel from the nearest exposed surface are given in these tables. More sophisticated methods are the simplified calculation methods (e. g. the 500 °C isotherm method or the zone method) or advanced methods (EN 1992-1-2 describes only basic limits) (Kučera et al. 2010, EN 1992-1-2, Benýšek et al. 2018).

5. Fire resistance assessment of columns according to the tables

Columns are commonly used as structural items. With respect to the fire resistance, the best material is concrete or masonry. Steel is normally sufficient only up to 15 minutes of fire resistance and wood is a flammable material (but it is better than steel). However, this does not mean that the concrete (reinforced concrete) is not affected by the temperatures. During the high temperatures, mechanical, physical and chemical processes occur in concrete which leads to reversible or irreversible changes of properties (Wald 2005, Kučera et al. 2010).

The standard EN 1992-1-2 describes three methods for assessment of the fire resistance of concrete structures in total: Method A, Method B and Method for slender columns (Kučera et al. 2010, EN 1992-1-2).

5.1 Assessment of columns by the table values

For tabular assessment, several values are needed to be assessed. It is the simplest approach for assessment of the fire resistance. Table values are in many cases limited by the additional conditions. These tables were created based on calculations and experiments so as to safely covered a common range of other parameters, e.g. thermal and physical properties of parameters etc., which are not in tables directly expressed. That is the reason why the table values are in many cases conservative. However, it is a very good approach to determining fire resistance, especially for low required fire resistance.

Table values correspond to the effect of the standard temperature-time curve, see Fig. 1. It is valid for concrete with the density of 2000 to 2600 kg/m^3 with silica aggregate. If the member fulfils the table values, it is not necessary to do any additional assessment relating to the shear, torsion etc. However, additional requirements must be applied in a case when the axis distance of reinforcing or prestressing steel from the nearest exposed surface is equal or higher than 70 mm – the surface reinforcement must be added.

The load bearing function of items (criterion R) is ensured if table values (minimum width and minimum axis distance of reinforcing or prestressing steel from the nearest exposed surface) are fulfilled, see Fig 3.

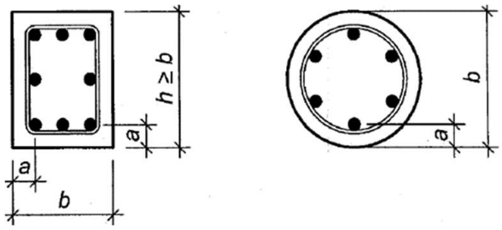


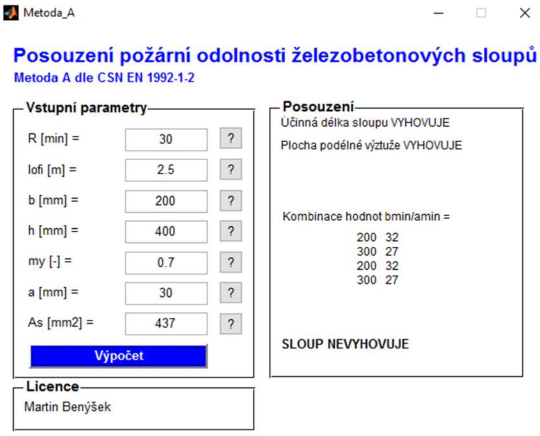
Fig. 3: *Parameters of the cross-section* (Procházka et al. 2010).

The table values amin must be increased if the prestressing bars (+ 10 mm) or prestressing wires and strands (+ 15 mm) are used. The values amin are increased with respect to the critical reinforcement temperature according to the type of the reinforcement (Procházka et al. 2010, EN 1992-1-2).

For assessment of concrete columns by the table values, three software tools were developed. These tools were created in MATLAB and subsequently, they were validated according to EN 1992-1-2. Tools are described below in detail.

5.2 Method A

Method A is applicable for concrete columns loaded mainly by the pressure. This method has, of course, some restrictive criteria, e. g.: effective length of the column under the fire conditions $l_{0,fi} \leq 3{,}0$ m; first order eccentricity under fire conditions $e = M_{0Ed,fi}/N_{0Ed,fi} \leq e_{max}$; and amount of reinforcement $A_s < 0.04\ A_c$. Combinations of minimal values $b_{min}\ /\ a_{min}$ are determined by the required fire resistance and mechanical reinforcement ratio. The main window of the program is shown in Fig. 4.



Posouzení požární odolnosti železobetonových sloupů
Metoda A dle CSN EN 1992-1-2

Vstupní parametry
R [min] = 30
lofi [m] = 2.5
b [mm] = 200
h [mm] = 400
my [-] = 0.7
a [mm] = 30
As [mm2] = 437

Posouzení

```
Účinná délka sloupu VYHOVUJE
Plocha podélné výztuže VYHOVUJE

Kombinace hodnot bmin/amin =
          200  32
          300  27
          200  32
          300  27

SLOUP NEVYHOVUJE
```

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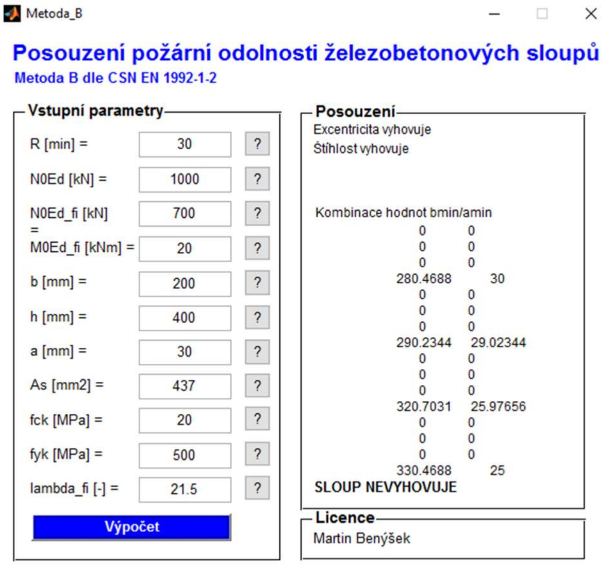
Fig. 4: *Method A* (Benýšek 2018).

Alternatively to Method A, it is possible to use a simplified calculation method based on equations which are described in EN 1992-1-2. The result of these relations is the time of the actual fire resistance. Described software tool does not consider this alternative approach. (Procházka et al. 2010, EN 1992-1-2).

5.3 Method B

The Method B can be applied for reinforced columns which fulfil the conditions for eccentricity, slenderness and for the required fire resistance R 90 and higher the reinforcement must be applied equally. The value combination b_{min}/a_{min} is determined according to the required fire resistance, mechanical reinforcement ratio and load level of a column at normal temperature conditions. The main window of the software tool for this method is shown in Fig. 5. (Procházka et al. 2010, EN 1992-1-2).



Posouzení požární odolnosti železobetonových sloupů
Metoda B dle CSN EN 1992-1-2

Vstupní parametry
R [min] = 30
N0Ed [kN] = 1000
N0Ed_fi [kN] = 700
M0Ed_fi [kNm] = 20
b [mm] = 200
h [mm] = 400
a [mm] = 30
As [mm2] = 437
fck [MPa] = 20
fyk [MPa] = 500
lambda_fi [-] = 21.5

Posouzení

```
Excentricita vyhovuje
Štíhlost vyhovuje

Kombinace hodnot bmin/amin
            0        0
            0        0
            0        0
        280.4688       30
            0        0
            0        0
            0        0
        290.2344   29.02344
            0        0
            0        0
            0        0
        320.7031   25.97656
            0        0
            0        0
            0        0
        330.4688       25
SLOUP NEVYHOVUJE
```

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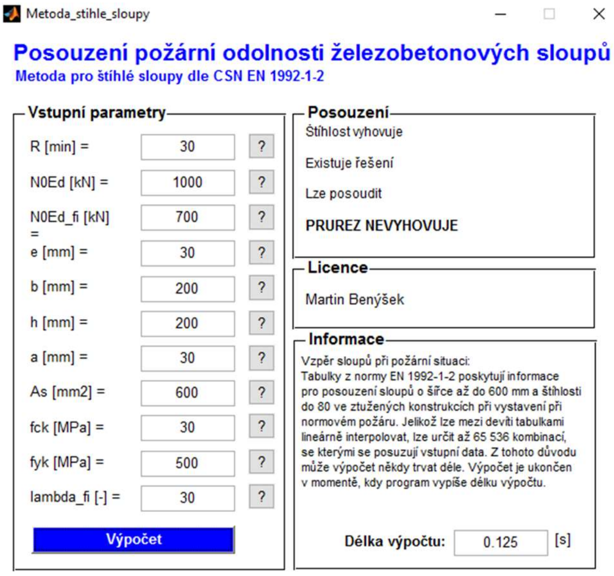
Fig 5: *Method B* (Benýšek 2018).

5.4 Method for slender columns

This method is the most sophisticated table method. It contains nine tables, size A4. The appropriate table is chosen in dependence on the value of mechanical reinforcement ratio and eccentricity. The value combination b_{min}/a_{min} is determined based on the required fire resistance, slenderness and load level of a column at normal temperature conditions. The main window of the software tool for this method is shown in Fig. 6.



R [min] = 30
N0Ed [kN] = 1000
N0Ed_fi [kN] = 700
e [mm] = 30
b [mm] = 200
h [mm] = 200
a [mm] = 30
As [mm2] = 600
fck [MPa] = 30
fyk [MPa] = 500
lambda_fi [-] = 30

Štíhlost vyhovuje
Existuje řešení
Lze posoudit
PRUREZ NEVYHOVUJE

Martin Benýšek

Vzpěr sloupů při požární situaci:
Tabulky z normy EN 1992-1-2 poskytují informace pro posouzení sloupů o šířce až do 600 mm a štíhlosti do 80 ve ztužených konstrukcích při vystavení při normovém požáru. Jelikož lze mezi devíti tabulkami lineárně interpolovat, lze určit až 65 536 kombinací, se kterými se posuzují vstupní data. Z tohoto důvodu může výpočet někdy trvat déle. Výpočet je ukončen v momentě, kdy program vypíše délku výpočtu.

Délka výpočtu: 0.125 [s]

Fig. 6: *Method for slender columns* (Benýšek 2018).

During the fire resistance assessment according to this method, nine tables can be used. Between tables, a linear interpolation may be used. In a limit case, it can be created up to 65 536 liner combinations and the only one can be appropriate. For a hand calculation, this method can be sometimes too complicated (Procházka et al. 2010, EN 1992-1-2).

6. Conclusions

Fire safety is a significant branch for the protection of people and property. For assessment of the fire resistance of structures, which is an integral part of the project documentation for buildings, it is necessary to know the required fire resistance and subsequently know the design approaches which are described in Eurocodes. Fire resistance can be approved by table values. This type of assessment is very conservative but it is a very quick method. Alternatively, the simplified or advanced method can be also applied. Simplified methods are described in the Eurocode 2 in detail; for advanced methods, only basic conditions are mentioned. The important boundary condition for the assessment of structures is the model of fire which can be characterized by a curve. Fire resistance of structures can be proved by software tools which were described herein. These tools were created in MATLAB.

Acknowledgements

The work has been supported by the Grant Agency of the Czech Technical University, project No. SGS18/038/ OHK1/1T/11. The support is gratefully acknowledged.

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6.11.3 Paper 9

Reprint of the paper

- Heat Transfer in Fire Safety (*in Czech*)
- in Czech, translated to English

Contribution of the author of this thesis to the paper

- M. Benýšek is the author of the text of the paper (that was written under the supervision of J. Procházka and R. Štefan).
- The author’s contribution is 100 %.

HEAT TRANSFER IN FIRE SAFETY

BENYSEK Martin

Abstract:

This paper focuses on the description of convection, conduction and radiation, which are types of heat transfer. Heat transfer is very important in fire safety, especially for an assessment of a fire resistance of structural members. Radiation is crucial for an assessment of separation distances, which is a significant factor for checking the fire transfer to other buildings. For this phenomenon, the software "Calculation of separation distances" was developed.

Keywords: concrete structures, fire models, heat transfer, fire transfer, configuration factor, separation distance

1. Introduction

The inseparable part of fire safety design is the assessment of structures exposed to fire - structures must fulfil the required fire resistance. It is necessary to use the appropriate model of fire. The design fire scenario is a specific fire scenario, which is used for a temperature analysis in an area. It is necessary to know the temperature profiles in structures. For assessment of a fire resistance, simplified and advanced models are possible to use. Conduction, convection and radiation have a negative effect on structures, see Fig. 1. Due to increased temperatures, materials degrade. The fire resistance is characterized by the ultimate limit states, which are determined by one to three letters and a number, which determines minutes (e.g. R 30 - fire resistance class for the load-bearing criterion for 30 minutes in standard fire exposure) [1, 2, 6].

2. Assessment of the structures exposed to fire

The table values or calculation (simplified or advanced) methods can be applied for the assessment of the structures exposed to fire. If the calculation methods are used, it is necessary to know the temperature distribution in structural members. Three items of the heat transfer are considered: conduction, convection and radiation. The thermal load of the structure is usually defined by a temperature-time curve which is determined by an appropriate model of fire (e.g. standard temperature-time curve or CFD model). The fire resistance is characterized by the fire resistance classes, so-called limit states, which are marked by the letters (e.g. EI – fire resistance class of integrity and insulation – fire separation function; R – fire resistance class for the load-bearing criterion) and by the number which defines minutes for which the fire resistance class is valid (e.g. R 60 – fire resistance class for the load-bearing criterion for 60 minutes in standard fire exposure) [3, 7].

3. Heat transfer

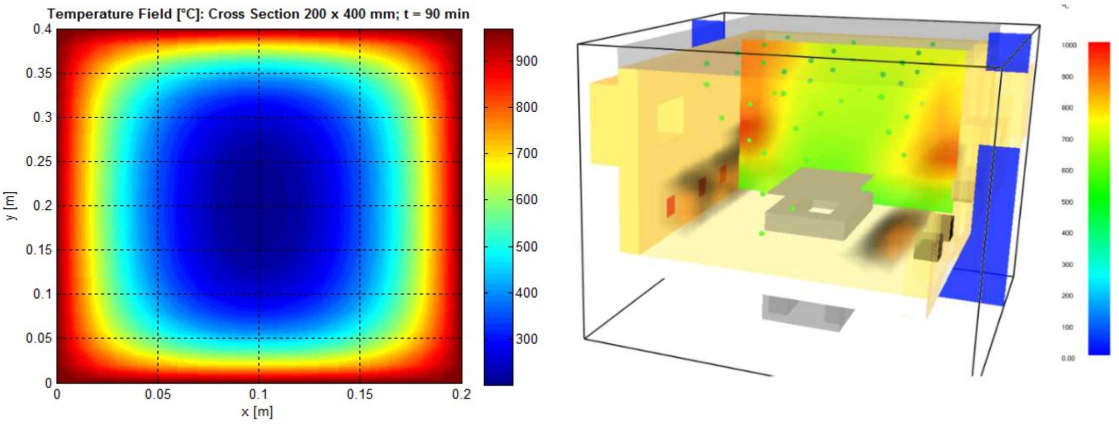
Three items of the heat transfer are considered: conduction, convection and radiation. During the fire, radiation and convection on the surface of building items (walls, ceilings, etc.) are most often expected. Subsequently, the conduction is considered inside of the building items.

If the structure is in direct contact with the hot gasses (e.g. during fire in an enclosed space after the spatial ignition – “flashover effect”), the heat is transferred to the surface by the radiation and convection. However, if the structure is in a specific distance from the flames or hot gases (e.g. the fire in a neighbouring building), surfaces can be heated by the radiation but cooled down by the convection. The conduction and the convection is shown in Fig. 1. The radiation is described in detail in following sections of this paper [4,5].

3.1 Conduction and convection

The heat from hot surfaces is transferred into the item by the conduction. The transfer of energy in solid items takes place through the interaction and exchange of energy between the elementary particles of the item. Conductive heat transfer can cause, for example, evaporation of water contained in the structure or thermal degradation of the structure. These processes are commonly endothermic and therefore slow down the heat transfer [5].

The heat transfer by convection is a significant factor during a flame spread. Smoke and hot combustion products transfer. During the fluid flow around the surface of the structure, an area of flow is created where the external flow speed is changing continuously. This area is marked as a limit layer which can be laminar or turbulent. During the fire, the area of flow is dependent on dimensions of the fire compartment, a temperature difference between the surrounding and item surface (e.g. wall), and the gas speed inside of the fire compartment. This process is considered in heat transfer coefficient which enters into the boundary condition in heat transfer model [4,5].



(a) (b)

Fig. 1 Forms of heat transfer: (a) conduction – output from FiDeS [8], (b) convection – output from FDS [9].

The heat transfer is well described in following sources [11, 12, 15].

3.2 Radiation

Radiation is a transfer of energy by electromagnetic waves. It is a very important effect in a case of fire because it is the main mechanism for a heat transfer from flames to a fuel surface or other structures in a building or to another building [4,5]. During a fire, a heat radiation from fire open areas occurs. Open areas are holes (or windows) or structures (e.g. walls) without a fire resistance and they can lead to a fire transfer to the adjacent building. It is an important assessment during the fire design of buildings. The fire separation distances define a fire dangerous area [13].

For a calculation of fire separation distances, a software tool according to EN 1991-1-2, see Fig. 5, was developed and it was created in MATLAB.

4. Fire separation distances

The basic equation for the radiative heat flux is used. This heat flux is marked as q_r or I [W/m^2], see equation (1). For a calculation of fire separation distances, a basic equation for a heat flux is used, based on the Stefan-Boltzmann law, where $\varepsilon = 1{,}0$ [-] is fire emissivity, $\sigma = 5{,}67 \,.\, 10^{-8}$ [W/m^{2}K^4] is Stephan-Boltzmann constant [5, 6].

$$q_r^{"} = I = \varepsilon \times \sigma \left(T_g^{\,4} - T_0^{\,4} \right) \tag{1}$$

$$T_g = 20 + 345 \cdot \log\left(8t + 1\right) \tag{2}$$

For calculation of fire separation distances, a conservative relation is considered and the initial temperature T_0 is commonly neglected (this value is normally considered as 20 °C). The gas temperature is expressed by the standard temperature-time curve (ISO 834), see Fig. 2, and it is calculated according to the equation (2).

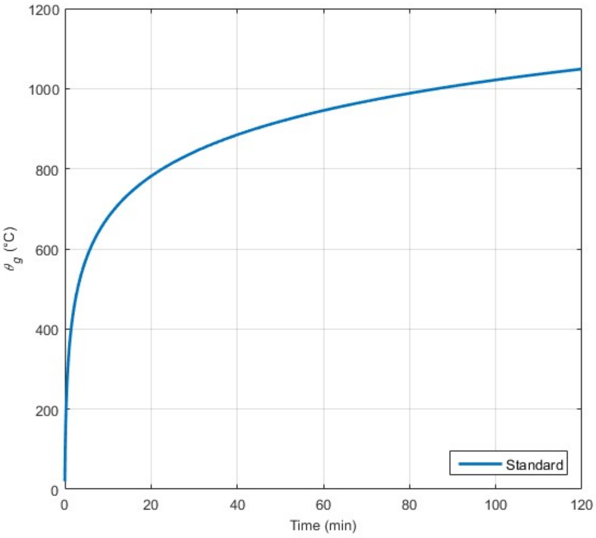


Fig. 2 Standard temperature-time curve – output from FMC [14]

The value t in eq. (2) is a fire risk expressed by the fire load or equivalent duration of fire [6].

The part of a radiated heat flux, which reaches a receiving surface, is expressed by the configuration factor ϕ [-], see equations (3,4,5). The configuration factor determines the proportion of the total radiant heat generated from the radiant surface which reaches on the given receiving surface. Its value depends on the radiant surface, distance receiving surface from the radiating surface and their orientation [1].

$$\phi_i = \frac{1}{2\pi}\left[\frac{a}{\left(1+a^2\right)^{0,5}} \tan^{-1}\left(\frac{b}{\left(1+a^2\right)^{0,5}} \right) + \frac{b}{\left(1+b^2\right)^{0,5}} \tan^{-1}\left(\frac{a}{\left(1+b^2\right)^{0,5}} \right) \right] \tag{3}$$

$$a = \frac{h}{s} \tag{4}$$

$$b = \frac{w}{s} \tag{5}$$

The value *s* is the distance between *X* and *P*; it is a variable parameter; *h* and *w* are the dimensions of the radiative area (fire open area). This surface is commonly divided into four parts (areas), see Fig. 3 [1, 5].

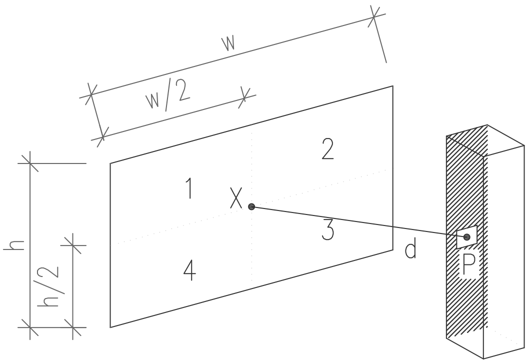


Fig. 3 Schema of the calculation of the configuration factor [1]

Configuration factor is determined as a sum of these four configuration factors, see eq. (6) [1].

$$\phi = \phi_1 + \phi_2 + \phi_3 + \phi_4 \tag{6}$$

Critical value of the heat flux density is considered $I_{0cr} = 18{,}5$ [kW/m^2] for the calculation of the fire separation distances. Critical value of the configuration factor ϕ_{cr} is determined according to eq. (7) [1, 6].

$$\phi_{CR} = \frac{I_{0,CR}}{I} \tag{7}$$

The resulting value of the fire separation distances must be done by the iteration process, where the finding value is just the fire separation distance *d*, for equality eq. (8) [1, 13].

$$\phi \approx \phi_{CR} \tag{8}$$

Fig. 4 shows the schema of the fire separation distance. For calculation of fire separation distances, a software tool in MATLAB was created. This tool can calculate these distances, the step of the calculation process is given by the value 0,0001 m. The initial window of the software tool *„Calculation of separation distances“* is shown in Fig. 5 [1, 6].

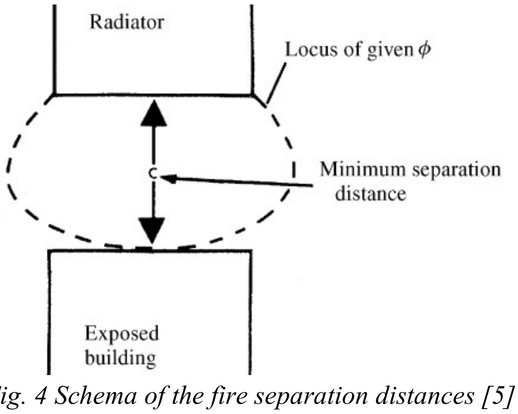
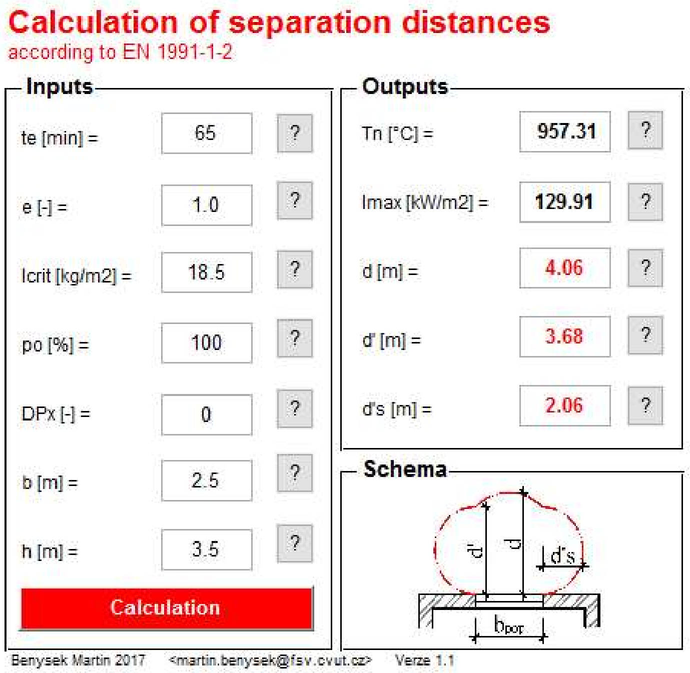


Fig. 4 Schema of the fire separation distances [5]

The fire separation distances are commonly calculated in the centre of the fire open areas, where the highest heat flux occurs. In other cases, it is necessary to calculate the configuration factor according to equations (G.3) or (G.4) in [Annex G, 1].


Calculation of separation distances
according to EN 1991-1-2

Inputs
te [min] = 65
e [-] = 1.0
lcrit [kg/m2] = 18.5
po [%] = 100
DPx [-] = 0
b [m] = 2.5
h [m] = 3.5

Outputs
Tn [°C] = 957.31
Imax [kW/m2] = 129.91
d [m] = 4.06
d' [m] = 3.68
d's [m] = 2.06

Benysek Martin 2017 <martin.benysek@fsv.cvut.cz> Verze 1.1

Fig. 5 Developed software: Calculation of separation distances [10].

5. Conclusions

Fire safety is a significant branch for personal and property protection. It is necessary to carry out fire experiments so that the fire will be well described and understood.

For an assessment of the fire resistance of structures, which is an inseparable part of a project documentation, it is necessary to know the temperature profiles of members. Temperature profiles are determined by the solution of the heat transfer problematics. Conduction, convection and radiation are the three types of the heat transfer. As a boundary condition, an appropriate model of fire is used (e.g. ISO curve, or CFD model), which is characterized by a temperature curve. The radiation is a significant factor for checking the fire transfer to other buildings. It is one of the factors, which must be verified in the fire safety design. For a calculation of separation distances, a software called „*Calculation of separation distances*“ was developed, see Fig. 5, which was created in MATLAB.

Acknowledgements

The work has been supported by the Grant Agency of the Czech Technical University, project No. SGS17/044/OHK1/1T/11. The support is gratefully acknowledged.

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6.11.4 Paper 10

Reprint of the paper

- Comparison of Zone and CFD Fire Model (*in Czech*)
- in Czech, translated to English

Contribution of the author of this thesis to the paper

- M. Benýšek is the author of the text of the paper (that was written under the supervision of J. Procházka and R. Štefan).
- The author’s contribution is 100 %.

COMPARISON OF ZONE AND CFD FIRE MODEL

BENYSEK Martin

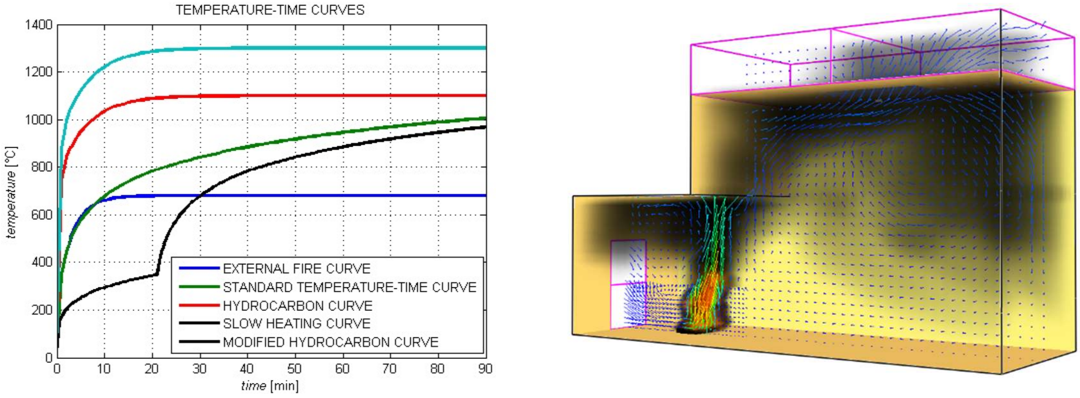
Abstract:

This paper is focused on the zone and CFD (Computational Fluid Dynamics) fire model. The description of fire models and approaches to assessment of fire resistance are presented. The results of two programs are compared – Consolidated Model of Fire Growth and Smoke Transport (CFAST based on a zone model) and Fire Dynamics Simulator (FDS based on a CFD model), developed by the National Institute of Standards and Technology in the USA.

Keywords: concrete structures, mathematical fire models, fire resistance, Fire Dynamics Simulator, Consolidated Model of Fire Growth and Smoke Transport

1. Introduction

Fire safety is one of the most important branches of science in the building design. As a part of this evaluation, it is necessary to assess the fire compartments, evacuation, installation of the fire safety equipment and also the fire resistance of load bearing and fire separating structures. In order to assess the fire resistance of structures, it is necessary to determine a fire's risk, which can occur in a designated space, and a fire scenario. Fire scenarios describe the presumed process of fire in a fire compartment. Fire can be described mathematically by the nominal temperature-time curves (standard temperature-time curve, hydrocarbon temperature-time curve etc.) or the natural models of fire (CFD, see Fig. 1a), zone models, see Fig. 1b), etc.) [1,2].



(a) (b)

Fig. 1Mathematical models of fire: (a) nominal temperature-time curves [3]; (b) Advanced fire model – Computational Fluid Dynamics in the FDS software [4,12]

2. Fire resistance assessment

Concrete is a composite material. Although concrete is a non-flammable material, in a case of exposure to fire the strength of the concrete and reinforcement is decreased and the integrity and cohesion is disturbed [5].

The required fire resistance is generally determined by the Czech Standards. The simplified method, such as tabulated values, simplified computational methods (e. g. 500 °C isotherm method, zone method), and advanced methods, e.g. thermal response model, mechanical response model, can be used for the assessment of the fire resistance [6].

Advanced calculation methods for thermal response shall be based on the acknowledged principles and assumptions of the theory of heat transfer. Advanced calculation methods for mechanical response shall be based on the acknowledged principles and assumptions of the theory of structural mechanics, considering the changes of mechanical properties with temperature [5,6].

It is always necessary to choose an appropriate fire scenario and consider the fire performance if the advanced fire models are used. For simple structures with common fire risk, it is appropriate to use nominal temperature-time curves. For complicated structures or buildings, it is more convenient to use advanced fire models, such as Zone or CFD models. If the advanced fire models are used and if the simplified methods for fire resistance assessment are used, it is necessary to consider the Equivalent time of fire exposure [6].

2.1 Zone models of fire

Zone models express the ideal shape of fire in an enclosed space. It is a commonly used methodical process for simplified determination of the temperatures and the smoke height. This method uses empirical relations. Zone models can be one-zone or two zones. The application is dependent on the type of the solved task.

Initially, the model describes the fire in an enclosed space before the flashover – it assumes a creation of two separate zones (smoke layers) – two zone model, see Fig. 3a). One zone model is a limit state after the flashover effect. Afterward in the fire compartment, the homogeneous temperature, density, energy and gas pressure is assumed.

The temperature should be calculated considering:

- the resolution of mass conservation and energy conservation equations,
- the exchange of mass between the internal gas, the external gas (through openings) and the fire (pyrolysis rate),
- the exchange of energy between the fire, internal gas, walls and openings.

A two-zone model is based on the assumption of accumulation of combustion products in a layer beneath the ceiling, with a horizontal interface. Different zones are defined: the upper layer, the lower layer, the fire and its plume, the external gas and walls. In the upper layer, uniform characteristics of the gas may be assumed. The exchanges of mass, energy and chemical substance may be calculated between these different zones.

In a given fire compartment with a uniformly distributed fire load, a two-zone fire model may develop into a one-zone fire in one of the following situations:

- if the gas temperature of the upper layer gets higher than 500 °C,
- if the upper layer is growing so to cover 80% of the compartment height [6].

Commonly used programs are ARGOS, ASET B, CFAST, OZONE, SMOKE PRO, BRISK, BRANZFIRE etc.

For detailed comparison of the zone and CFD model of fire, programs CFAST and FDS were chosen, see chap. 2.2 and 3.

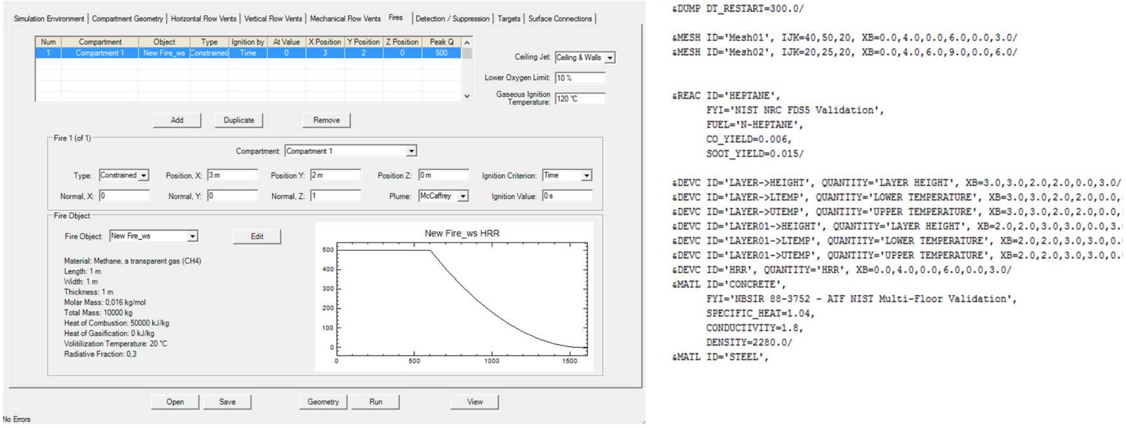
Software CFAST (Consolidated Fire and Smoke Transport) has been developing by the American Company NIST (National Institute of Standards and Technology) since 1990. It is a zone fire model which predicts the temperature environment caused by the fire. The area is divided into the upper and lower layer of gases, see Fig. 3a). The calculation is based on the differential equations derived from the laws of conservation of matter and energy. The transfer of gas and heat is determined by the empirical correlations. The pre-processor of the CFAST is shown in Fig. 2. The biggest limit for this type of fire model is the shape of compartments. Zone models are not convenient for line constructions or buildings (e.g. shafts). Fire can be determined only by simplifying the Heat Release Rate (HRR). CFAST uses SmokeView as a post-processor, see Fig. 3a). The biggest advantage of zone models is the speed of calculation, which usually takes a few seconds (depends on the size of the area, etc.) [8].

2.2 CFD models of fire

CFD mathematical models are the most sophisticated software tools which can be applied. This technology is a powerful tool mainly for the simulation of fluid flow. The principle of the CFD models is based on the partition of the space into 3-D elements, so-called controlled volumes. Zone models assume only two controlled volumes but CFD models assume n-controlled volumes. For each controlled volume, equations of conservation of mass, energy, momentum and particle composition are computed. This is so-called Navier-Stokes equations (N-S equations) which are 3-D, time-dependent, non-linear, partial differential equations.

Common software uses this technology are e.g. FDS, FLUENT, SMARTFIRE, SOFIE etc. [7].

Fire Dynamics Simulator (FDS), is a computational fluid dynamics (CFD) model of fire-driven fluid flow. FDS, developed by NIST (National Institute of Standards and Technology), solves numerically a form of the Navier-Stokes equations appropriate for low-speed (Ma < 0.3), thermally-driven flow with an emphasis on smoke and heat transport from fires. First version was released in 2000. FDS does not have a pre-processor, all functions are defined by commands, see Fig. 2b). The advantage of this CFD method is almost unlimited usage. The significant disadvantage is the length of the simulation calculation. It is also dependent on the amount of the input parameters. Fires can be defined by simplified or advanced methods; it depends on the required accuracy [10].



Num	Compartment	Object	Type	Ignition by	At Value	X Position	Y Position	Z Position	Peak Q
1	Compartment 1	New Fire_ws	Constrained	Time	0	3	2	0	500

Ceiling Jet: Ceiling & Walls
Lower Oxygen Limit: 10 %
Gaseous Ignition Temperature: 120 °C

Fire 1 (of 1)
Compartment: Compartment 1
Type: Constrained
Position, X: 3 m
Position Y: 2 m
Position Z: 0 m
Ignition Criterion: Time
Normal, X: 0
Normal, Y: 0
Normal, Z: 1
Plume: McCaffrey
Ignition Value: 0 s

Fire Object
Fire Object: New Fire_ws
Material: Methane, a transparent gas (CH4)
Length: 1 m
Width: 1 m
Thickness: 1 m
Molar Mass: 0,016 kg/mol
Total Mass: 10000 kg
Heat of Combustion: 50000 kJ/kg
Heat of Gasification: 0 kJ/kg
Volitilization Temperature: 20 °C
Radiative Fraction: 0,3

No Errors

```
&DUMP DT_RESTART=300.0/

&MESH ID='Mesh01', IJK=40,50,20, XB=0.0,4.0,0.0,6.0,0.0,3.0/
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&REAC ID='HEPTANE',
      FYI='NIST NRC FDS5 Validation',
      FUEL='N-HEPTANE',
      CO_YIELD=0.006,
      SOOT_YIELD=0.015/

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&DEVC ID='LAYER->UTEMP', QUANTITY='UPPER TEMPERATURE', XB=3.0,3.0,2.0,2.0,0.0,
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      FYI='NBSIR 88-3752 - ATF NIST Multi-Floor Validation',
      SPECIFIC_HEAT=1.04,
      CONDUCTIVITY=1.8,
      DENSITY=2280.0/
&MATL ID='STEEL',
```

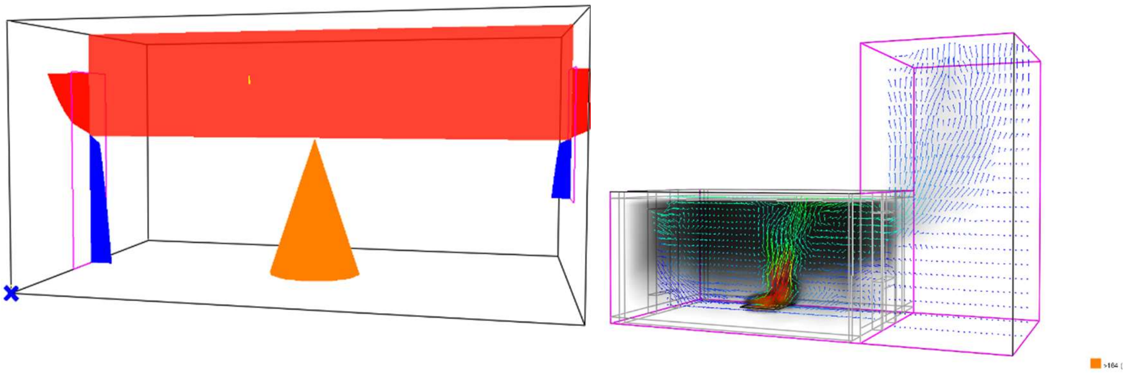
(a) (b)

Fig. 2 Pre-processors of the software: (a) CFAST [9]; (b) FDS [4]

3. Comparison of Zone and CFD model

For a comparison of the zone and the CFD fire model the following illustration was assumed: an emergency sump 1.0 x 1.0 m for flammable liquids in a room 6.0 x 4.0 x 3.0 m, where the walls, ceiling and floor are made of concrete. It assumed a value of the heat release rate of 500 kW. The room has one open window 1.0 x 1.5 m and one open door 1.0 x 2.0 m.

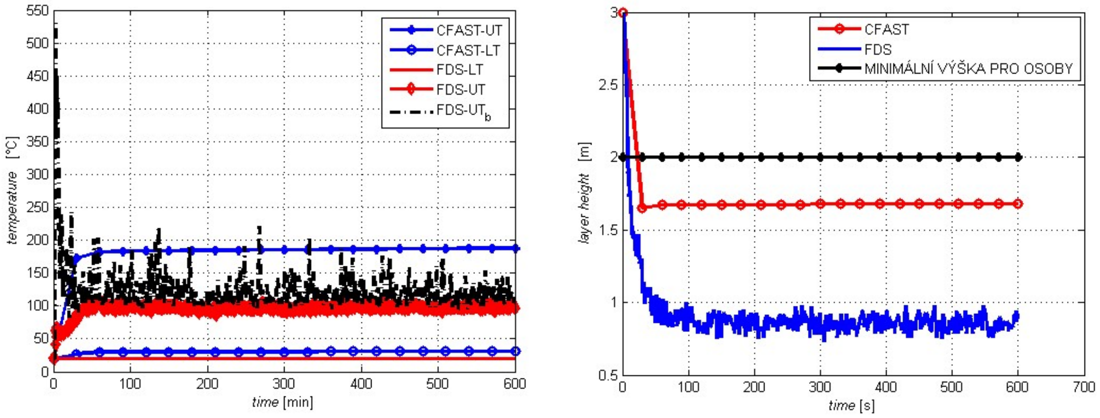
The zone model-based software CFAST and the CFD model-based software FDS were applied for this fire scenario. The upper temperatures designated as UT (temperatures of the upper smoke layer; lower temperatures are designated as LT) and the layer height (height of the neutral axis) were monitored values. It was measured in two locations in FDS software. The results are shown in Fig. 3.



(a) (b)

Fig. 3 Mathematical models of fire: (a) the zone model of fire in CFAST [9]; (b) CFD model of fire in FDS [4]

Temperatures in upper layers are the key values for the fire resistance design. The height of smoke layers are the key values for the evacuation processes. It is commonly considered that the neutral axis should be 2.0-2.5 m above the floor [4,7,9].



(a) (b)

Fig. 4 Comparison of CFAST and FDS software: (a) temperatures (UT – upper temperatures; LT – lower temperatures; (b) layer height

If the nominal temperature-time curve (ISO 834) is conservatively used for the selected fire scenario, the resulting values of temperatures are higher. This can have a significant influence for the subsequent fire resistance assessment because the boundary condition for the heat transfer is the temperature in an enclosed space. The temperature difference between ISO 834 and the zone model in 600 seconds, see Fig. 4, is approx. 480 °C. For this solved case, it is convenient to determine the temperatures based on advanced models of fire. The probability of fire origin and spread must be always analysed.

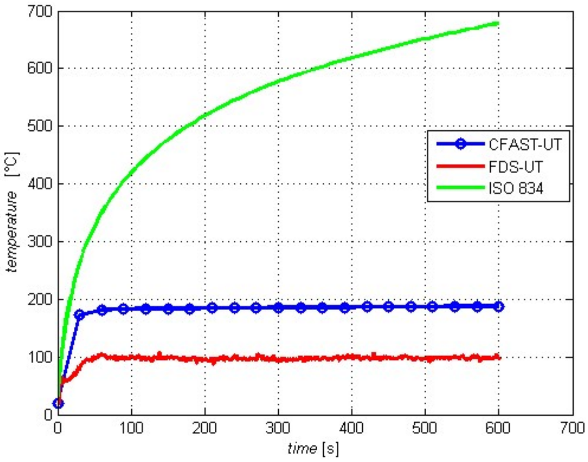


Fig. 5 Comparison of the Standard temperature-time curve with temperatures from the CFAST and FDS software [4,9]

4. Conclusions

The results indicate that the temperatures in the zone model are higher in comparison with the CFD model. The zone model in the whole room assumes a constant temperature in the upper smoke layer. In the CFD, which assumes unsteady temperatures in upper smoke layers, depend on location, where monitored values are measured. The neutral axis of the smoke layer is higher in CFAST than in FDS. The FDS software better reflects the problems of fluid dynamics and therefore there are probably different values. The zone software CFAST conservatively considers vertical fire plumes – tilting of flames due to the convection is not considered.

It is necessary to mention the fact that the duration of simulation is approximately 3 seconds in CFAST software and 1 hour, 58 minutes, 46 seconds in FDS software (using the same computer). For simplified tasks the zone models are preferable. For advanced tasks the CFD models are more preferable. Moreover, CFD models don't have as many limitations, but the big unknown is the input data. Zone models calculate very quickly and their accuracy is sufficient. CFD models are the most sophisticated fire models with almost no limits. However, their computation can take a disproportionately long time. More details about the results and assessment of concrete structures exposed to fire are described in a longer version of this paper.

Generally, it is possible to use the nominal temperature-time curves or the natural fire models. Nominal temperature-time curves are conservative – these curves are only a function of time; the application is useful for simple buildings where the fire resistance requirements are not high. Natural fire models are more convenient for a) specific buildings and, specific places in a building, b) for a significant reduction of costs for the evaluation of fire safety.

Acknowledgements

The work has been supported by the Grant Agency of the Czech Technical University, project No. SGS16/039/OHK1/1T/11. The support is gratefully acknowledged.

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6.11.5 Paper 11

Reprint of the paper

- Physical and Mathematical Models of Fire (*in Czech*)
- in Czech, translated to English

Contribution of the author of this thesis to the paper

- M. Benýšek is the author of the text of the paper (that was written under the supervision of J. Procházka and R. Štefan).
- The author's contribution is 100 %.

PHYSICAL AND MATHEMATICAL MODELS OF FIRE

BENÝŠEK Martin

Abstract:

This paper focuses on the physical and mathematical models of fire. There is a description of models of fire and their use in fire engineering. Mathematical models in Fire Dynamics Simulator (FDS) for a flammable liquid and a wooden crib are introduced. The results of the heat release rate obtained by FDS are compared with calculations by hand.

Keywords: mathematical fire models, physical fire models, flammable liquids, software FDS, wooden crib, fire experiments

1. Introduction

Fire models describe the dynamics of this phenomenon in a determined area. The basic types of fire models are mathematical and physical models, see Fig. 1.

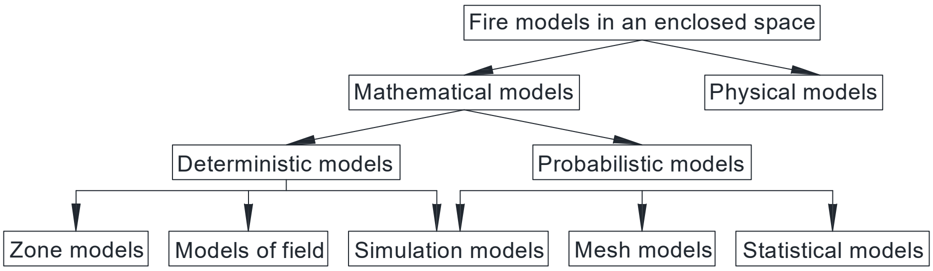


Fig.1: Types of fire models [1]

These models are used primarily as fire scenarios for determining the temperatures or as boundary conditions for the assessment of the evacuation or for heat transfer for fire resistance assessment of structures. This is an important physical phenomenon which must be correctly specified.

2. Fire Models

2.1 Mathematical Models of Fire

Mathematical models are based on mathematical processes, which use the advantages of computational technology and solve individual fire scenarios by means of a set of equations that describe the behaviour of physical systems in the fire. The results of mathematical models are mainly used for forecasts of the behaviour of real physics [1].

Several fire models are well known in fire engineering. Basic fire models are nominal temperature-time curves which are only time-dependent. That is the reason why these curves are the most conservative description of fire. Natural simplified fire models are represented by parametric temperature-time curves and localised fires, zone models and Computational Fluid Dynamics models belong into the natural advanced fire models.

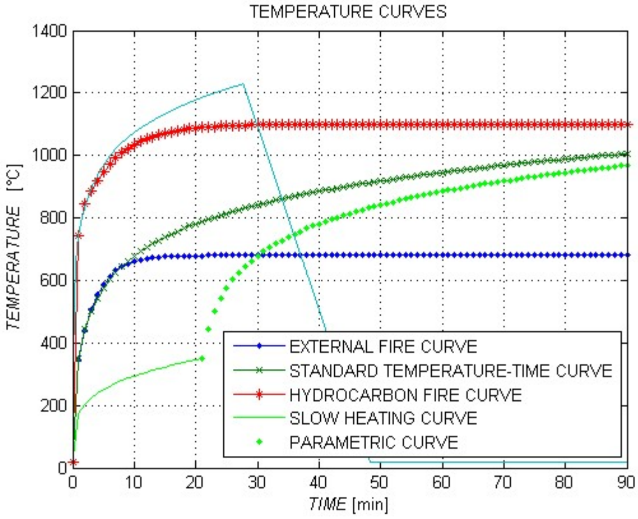
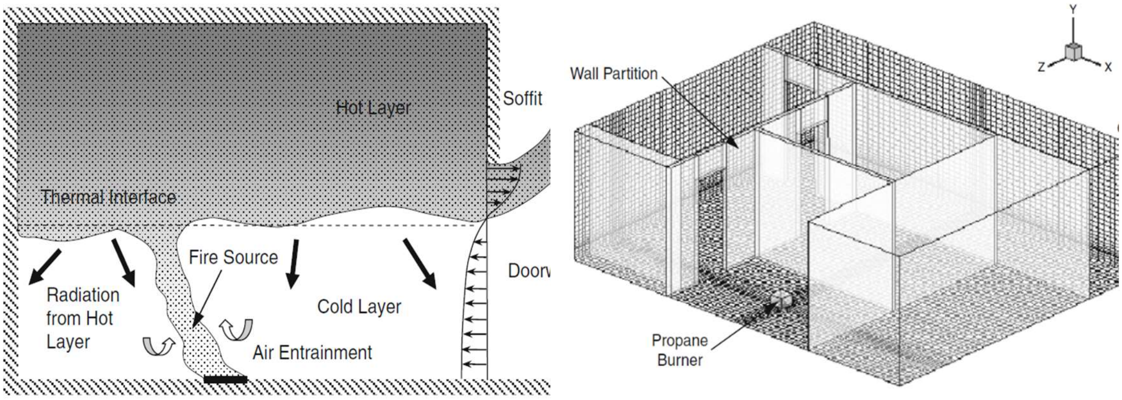


Fig.1: Overview of the curves – parametric and nominal temperature-time curves [2]

Simplified models are based on specific physical parameters with a limited area of use. During fires in fire compartments, a uniform distribution of time-dependent temperatures is assumed, where the temperature of gases should be determined by physical parameters which should consider the fire load density and ventilation at least. During localised fires, an unsteady distribution of time-dependent temperatures is assumed, the spatial ignition (flashover effect) is not possible.

Advanced models should consider the gas properties, mass exchange and energy exchange.

Zone models can be one-zone (uniform and time-dependent distribution of temperatures in fire compartments) or two-zone (the upper layer with a time-dependent thickness and with uniform time-dependent temperature; the lower layer with a uniform time-dependent lower temperature than the upper layer). Computational Fluid Dynamics (CFD) models describe temperatures, evaluated in fire compartments entirely in terms of time and they are spatially independent [2].



(a) (b)

Fig.3: Advanced fire models: (a) two-zone model, (b) CFD model [3].

In fire safety engineering, the nominal temperature-time curves are commonly used, because with them the fire is described very quickly and easily. However, these curves are not precise. Curves do not consider material and physical parameters, ventilation conditions, the process of combustion etc. That is the reason why the curves are not appropriate for complicated buildings or complicated fire-technical phenomena. In those cases, it is recommended to apply the natural fire models (zone or CFD).

2.2 Physical Models of Fire

Physical models are artificially created objects, which can clarify some physical phenomena or new pieces of knowledge. Models aimed at the description of the fire try to reproduce the fire phenomena in simplified conditions.

Physical models cannot describe all aspects of the real phenomenon. These models are usually more expensive and time-consuming than mathematical models. The sense of physical models is an imitation of the fire under simplified conditions.

Real fire phenomena are always more sophisticated and complicated than their models.

The main purpose of the physical models (PM) is to imitate fire in the case of the simplified physical conditions. The PMs are also appropriate for validation of the mathematical models. The dimensions of these models vary widely. The full-scale experiments are close to real fires; however, their main disadvantage is their price. That is the reason why the PMs are not feasible sometimes.

For that reason, the research leads to simplification – only single phenomena are separately investigated in a small-scale testing. Fire experiments, which are conducted in certified fire laboratories and serve the purpose of determining the fire resistance, are representative of the physical fire models [1,4].

3. Utilization of Fire Models in Fire Engineering

The fire load, according to Czech Standards, in fire compartments is considered to be spruce wood and it is routinely substituted for wooden cribs. This simplification can be useful for mathematical models due to savings in the time length of the simulation. Because the heat release rates from the fire experiments can be subsequently used as an input for some additional simulations. This simplification can lead to a decrease in the quality of the results but the simulation time length is shortened.

Flammable liquids, often found in production buildings, increase the risk of the fire inception. It is necessary to pay attention to flammable liquids and wooden cribs.

The values of the fire technical properties of materials and the results of the fire experiments are an insufficient commodity. That is the reason why it is necessary to provide all kinds of experiments and publish them in detail.

3.1 Wooden cribs

Solid materials combustion needs chemical decomposition – pyrolysis, where the production of vapour occurs, leads to the flame burning.

The available amount of oxygen has an increasing tendency for pyrolysis. Wood is an inhomogeneous material which is also non-isotropic which means that its properties are different in the direction in which it is measured. Wood is a polymer natural mixture of high molecular weight, where the most significant are cellulose (≈ 50 %), hemicellulose (≈ 25 %) and lignin (≈ 25 %).

Wooden cribs are commonly used as a replacement of the fire load during full-scale experiments. It could be also used for fire simulations [5].

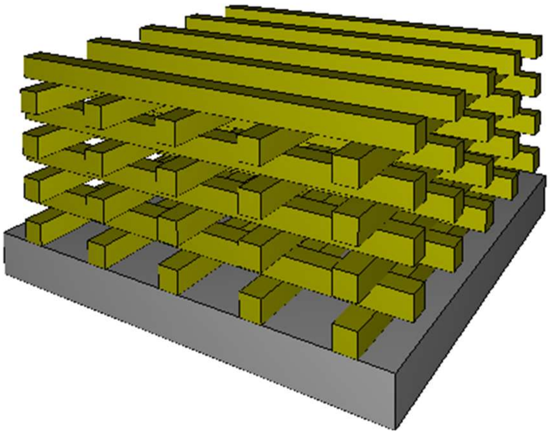
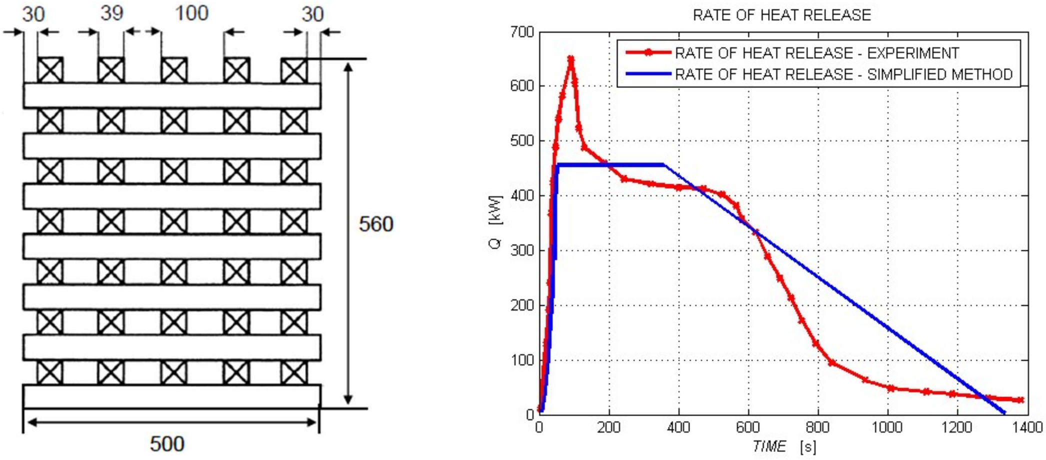


Fig.4: Wooden crib, created in FDS software

For detection of the heat release rate of the wooden crib, it is possible to use a simplified method which is described in detail e. g. in *SFPE Handbook of Fire Protection Engineering, 3rd edition*. This method is based on the calculation of: the control surface of the fuel which is dependent on the distance of individual wooden members; the total weight of the wooden crib; the rate of combustion; the porosity of the wooden members which is dependent on the total height of the crib; the width of the wooden members; the ventilation which is dependent on the area and the height of the openings; the location of the ignition source.

In comparison with the simplified method, it was used the experiment from [7], Fig. 5 (a). The results are shown below.



(a) (b)

Fig.5: Wooden crib: (a) wooden crib from the experiment [7], (b) comparison of the simplified method and the experiment.

3.2 Flammable liquids

Every flammable liquid, as well as every flammable material, behave differently during a fire. It mainly depends if the liquid is in a pure state or in a mixture. A simplified or an advanced method for determination of the flammable liquids heat release rate is available to use.

The simplified method is based on the following equation [5]:

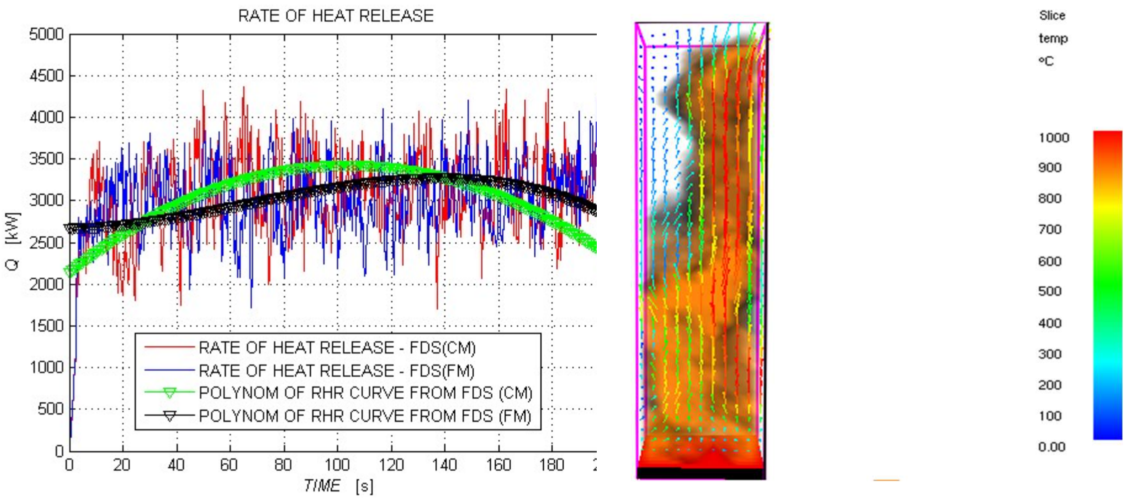
$$Q_c = \dot{m} \cdot \chi \cdot \Delta H_c^{\,2} \qquad (1)$$

- where ΔH_c is an effective heat of combustion, χ is a factor of the combustion efficiency and $\dot{m}$ is a burning or mass loss rate.

For a more precise solution, it is also possible to use the Computational Fluid Dynamics methods. By the simplified method, the maximum heat release rate value for the heptane is $Q_{heptan,0,7} = 2248 kW$ (70 % combustion efficiency), $Q_{heptan,1,0} = 3211 kW$ (100 % combustion efficiency). For the calculation, 100 litres of the heptane were assumed.

The Fire Dynamics Simulator (FDS) was used for a comparison with the simplified calculation. The FDS is a large-eddy simulation (LES) code for low-speed flows, with an emphasis on smoke and heat transport from fires. SmokeView (SMV) is a visualization program used to display the output of FDS simulations.

In the FDS software, two simulations of the flammable liquid were created, (1) with coarse computational mesh – CM, (2) with fine computational mesh - FM. The results were padded by the polynomial of the third grade for a better comparison, see Fig. 6.



(a) (b)

Fig.6: Flammable liquid: (a) results of the heat release rate, (b) mathematical simulation of the fire from the FDS software.

4. Results

4.1 Wooden Crib

As can be seen in Fig. 5, the heat release rate curves have a good match in the shape of the curves but the maximum values are different in their peaks (approx. 30 % = 200 kW). It is necessary to consider that the simplified method takes into account only general principles of combustion and reaction. But the experiments describe the real burning in specific conditions. For further validation, it is necessary to do a sensitivity analysis and comparison with more experiments.

4.2 Flammable Liquid

The results for the flammable liquid have a good match between the simplified method and the CFD simulation. If 100 % combustion efficiency was set up (ideal conditions for burning), the maximum values were nearly identical.

5. Conclusion

These calculations confirm that the heat release rate curves of the wooden crib have a good match in the shape of the curves but the maximum values are different in their peaks. The results for the flammable liquid have a good match between the simplified method and the CFD simulation but are dependent on the combustion efficiency.

For a better comparison, it is recommended to provide a sensitivity analysis with more samples. The simplified method advantages are the simplicity and speed compared to experiments or CFD simulations. The disadvantage is their inaccuracy. For the flammable liquid, it was proved that fine computational mesh is more precise.

Based on that, it could be recommended that simplified methods are better for preliminary calculations. In order to gain a higher quality of results, it is more convenient to use data from experiments or mathematical simulations.

Acknowledgements

The work has been supported by the Grant Agency of the Czech Technical University, project No. SGS15/032/OHK1/1T/11. The support is gratefully acknowledged.

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6.11.6 Paper 12

Reprint of the paper

- Fire Resistance Analysis of Concrete Members with the use of Simplified and Advanced Models of Fire (*in Czech*)
- in Czech, translated to English

Contribution of the author of this thesis to the paper

- M. Benýšek is the author of the text of the paper (that was written under the supervision of J. Procházka and R. Štefan).
- The author’s contribution is 100 %.

FIRE RESISTANCE ANALYSIS OF CONCRETE MEMBERS WITH THE USE OF SIMPLIFIED AND ADVANCED MODELS OF FIRE

Benýšek Martin

Abstract:

This paper focuses on the comparison of simplified and advanced fire models, with subsequent use for assessment of fire resistance of concrete structures. Fire models and examples of modelling in Fire Dynamics Simulator (FDS) software are introduced herein. Simplified and advanced models of fire were applied for one hotel room and one restaurant. Specifically, the fire resistance of reinforced concrete structures is assessed.

Keywords: concrete structures ● fire resistance ● temperature-time curves ● CFD models ● software FDS ● fire models ● heat transfer

1. Introduction

Fire is a dangerous element, which threatens people and their property. The occurrence of a fire incident leads to smoke emissions, which are toxic, and temperature increase, which has a negative effect on constructions since it may cause the collapse of the building. Simplified fire models are often described by time-temperature curves, which tend to be conservative. Thus, they inaccurately describe the fire process. When dealing with complex situations or structures, advanced fire models are more convenient since a greater number of factors affecting the fire event is considered. Advanced fire models include zone and CFD models. In this paper the software Fire Dynamics Simulator (FDS), as a representant of the CFD, was used.

As a process, fire can have many different forms and all forms release chemical reactions between the material and oxygen in the air. Fire can be a benefit if it is used correctly. However, uncontrolled fire can cause material damages and human suffering. It depends on the form of the fuel and if the fuel is solid, liquid or gaseous. For example, wood splinters are ignited differently than wood beams. Combustion products, fire spread, influence on structures, etc. are related to the type of the combustion material [1].

Basic requirements for fire models are determined in EN 1992-1-2, Eurocode 1 or e.g. international standard ISO/TR 13387-3 and ASTM E 1355-90.

It is necessary to arrange sufficient amount of fire experiments (small scale and full scale) to get knowledge about this phenomenon.

2. Models of Fire

Basic types of fire models are nominal temperature-time curves. These curves describe the phase of fully developed fires after the flashover effect with a rapid increase of temperatures (in general, flashover normally occurs if the temperature range is 500-600 °C or if the heat flux on a floor is approx. 20 kW/m^2). These models of fire, nominal temperature-time curves, are usually used for assessment of the fire resistance of structures or in experiments in fire testing laboratories. It is the simplest type of model which should be conservative [2]. The fire resistance according to other kinds of fire scenarios has to be re-calculated via the fire performance to the performance according to the standard temperature-time curve.

Localised fires and parametric temperature-time curves are simplified fire models. One-zone, two-zone and Computational Fluid Dynamics (CFD) models are advanced fire models.

Zone models express the ideal type of fire in an enclosed space. It is based on the physical phenomena observed in real fires.

In the beginning, the model describes the fire in a room before the flashover, which assumes the creation of two separated layers or zones – a so-called two-zone model [3]. After the flashover effect, the two-zone model is transferred due to the flashover effect to the one-zone model (the whole space is full of smoke).

The FDS, software based on CFD method, solves numerically the Navier-Stokes equations and it is a large-eddy simulation code for low-speed flows, with an emphasis on smoke and heat transport from fires [4].

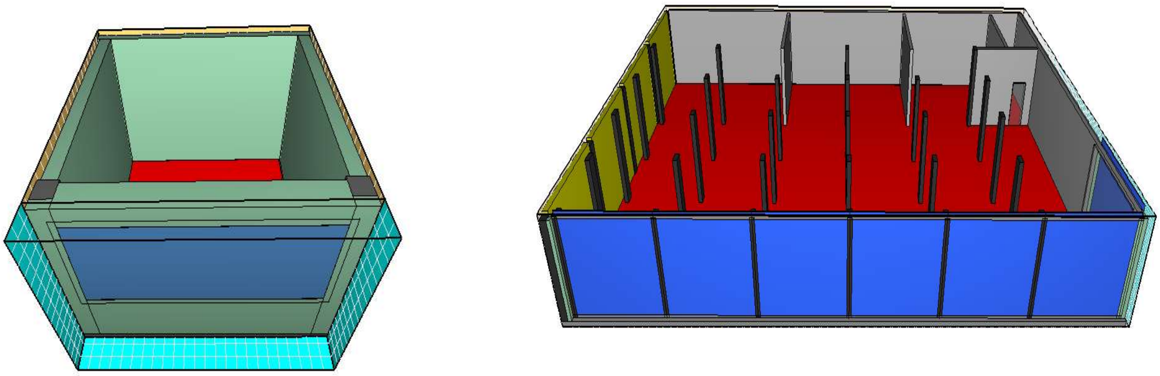
3. Input Parameters

A hotel building with five floors was selected for the comparison of a simplified and advanced fire model. The hotel room has the dimensions 3.6 m x 3.7 m x 2.8 m (w x l x h) and the restaurant 16.3 m x 24.8 m x 3.5 m. The main load-bearing structures of the monolithic system are columns and slabs, and the infill masonry. Windows were assumed with common filling – in the FDS the glass will disappear due to the temperature difference of 80 °C.

Structures were created in the FDS software with the assistance of the OBST function, windows and fire load with VENT function. The T-squared curve according to EN 1991-1-2 was used as a fire load. This curve was applied to the whole floor area. T-squared fire describes the flashover effect as the time-temperature curves.

The hotel room was simulated in the FDS with coarse mesh (0,2 m x 0,2 m x 0,2 m) and fine mesh (0,1 m x 0,1 m x 0,1 m). Considering to the structural design at normal temperatures, the restaurant was made with many columns in a space and alternatively with only two columns.

For comparison with the CFD model, represented by the FDS software, the following temperature-time curves were used: a) standard temperature-time curve – ISO 834 [5], b) BFD curve [6], c) parametric temperature-time curve [5].



(a) (b)

Fig.1: FDS software – visualization of (a) hotel room, (b) restaurant [7].

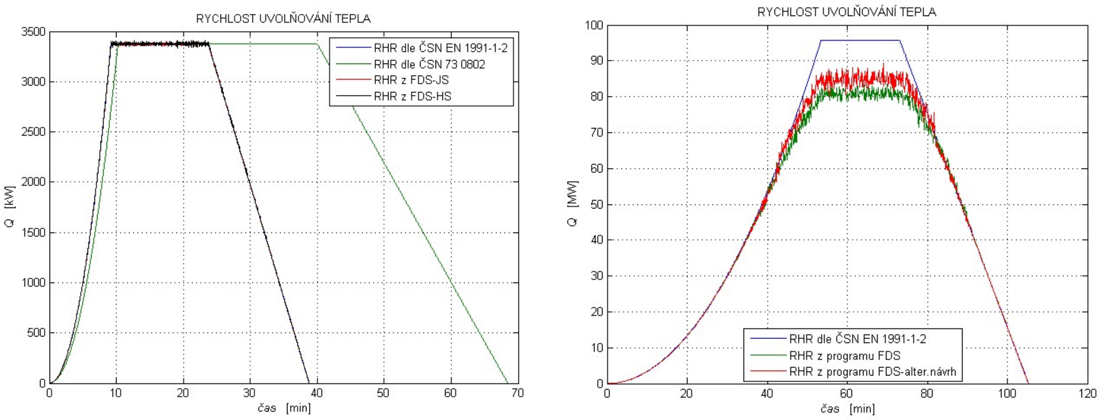
4. Results and Discussion

A basic verification of the model was made by comparing the HRR (or RHR) curve from both models, i.e. EC (EN 1991-1-2) and the FDS software.

As shown in Fig.2, identical results (input EN 1991-1-2 curve, output curve from FDS based on ČSN 73 0802, output curve from FDS based on EN 1991-1-2 coarse mesh “HS”, output curve from FDS based on EN 1991-1-2 fine mesh “JS”) were found for the hotel room.

The same trend was not exhibited for the restaurant, mostly because of the disposition influence, which caused fire asphyxia (input EN 1991-1-2 curve, output curve from FDS based on EN 1991-1-2, output curve from FDS based on EN 1991-1-2 – alternative design with only two columns in a space).

It is likely that the occurrence of fire asphyxia was the reason why lower temperatures were observed in the fire compartment, i.e. the restaurant room. For the restaurant, three HRR curves are shown – input EN 1991-1-2 curve, output curve from FDS based on EN 1991-1-2, output curve from FDS based on ČSN 73 0802 (Czech standard). In addition, as a complementary verification, the average time-temperature curves obtained from the simulations were compared to the BFD curve and the parametric temperature-time curve from EN 1991-1-2.



(a) (b)

Fig.2: Heat Release Rates for the (a) hotel room, (b) restaurant [11].

The layout solution with only two columns (marked as alternative design) had a better conformity with the FDS model based on EN 1991-1-2. But the results did not have such a good conformity as in the case of the hotel room. Non-ideal air ventilation was verified according to ten supporting models which are not described herein.

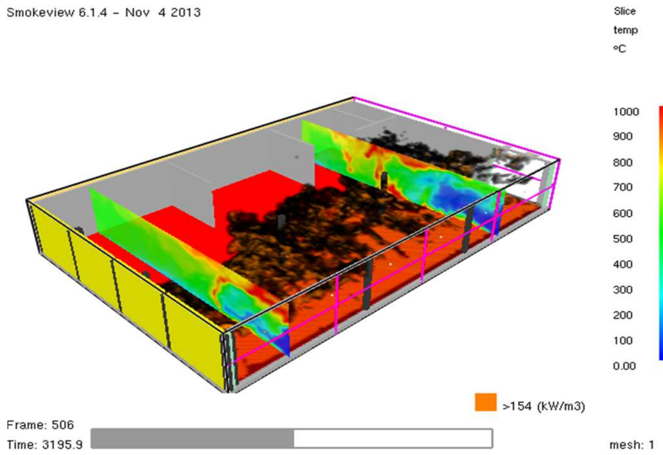
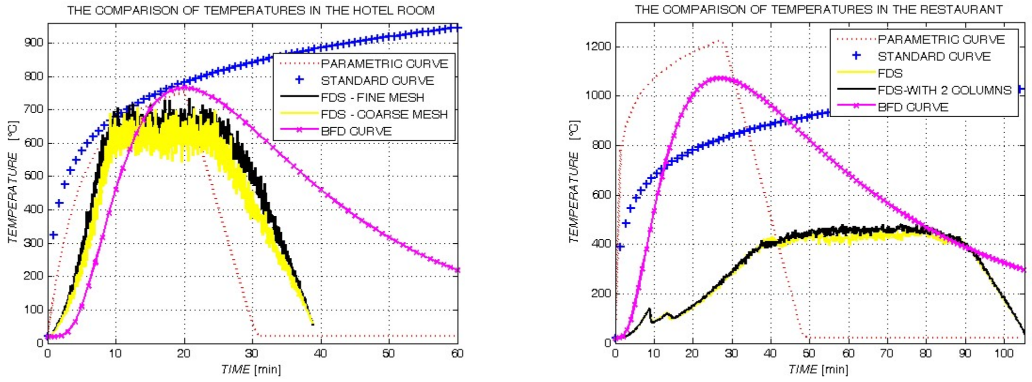


Fig. 3: Fire in the restaurant – FDS software [8].

For the resulting comparison, average temperatures from the thermocouples reached from the FDS software were used, see Fig. 4.



(a) (b)

Fig. 4: Resulting temperature-time curves for the: (a) hotel room, (b) restaurant [11].

The load-bearing structures were subsequently assessed for the fire resistance. The results of this assessment are shown in Tab. 1. The standard temperature-time curve is conservative. The resulting fire resistance is higher in a case of parametric temperature-time curve or FDS simulation which can lead to the more economic design. For a fire resistance calculation, the RCC$_{fi}$ software was used [9].

Tab. 1 Comparison of fire resistance.

Comparison of fire resistance for a column, required fire resistance is 15 min (given by Czech code)	
Types of models	**Maximum fire resistance**
Standard curve	R_{SC} 60
Parametric curve	R_{PC} 240
T^2 fire	R_{T2} 240
Direct calculation (EN 1992-1-2)	R_{DC} 35

Temperatures profiles are shown in Fig 5. There are three profiles according to the three fire scenarios which were used for the fire resistance assessment of a slab, linear and non-linear heat transfer is shown herein (TPn is non-linear, TPl is linear, see Fig. 5). The slab was subsequently assessed by the Isotherm 500 °C method according to EN 1992-1-2. The non-linear heat transfer curves were obtained by the TempAnalysis software [10], the linear heat transfer curves were created by my own code in MATLAB [2], [11].

The linear heat transfer is very conservative, the difference between these curves is approx. 1000 °C.

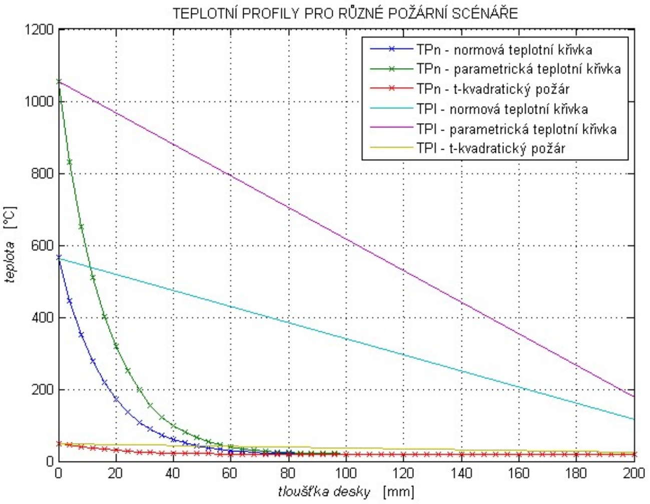


Fig. 5: Comparison of the temperature profiles [11].

Types of the fire models and calculated fire resistances for the slab are shown below, see Tab. .

Tab. 2 Comparison of fire resistance.

Comparison of fire resistance for the slab, required fire resistance is 15 min (given by Czech code)	
Types of models	**Maximum fire resistance**
Standard temperature-time curve ISO 834	R_{SC} 60
Parametric temperature-time curve	R_{PC} 240
T^2 fire	R_{T2} 240

5. Conclusion

The fine mesh of the CFD model yielded higher temperatures and provided a better agreement with time-temperature curves. For the restaurant, different values of RHR were observed in EC and FDS curves. This difference of the maximum RHR values was 12.5% (11 933 kW). The EC curve is likely conservative since it describes openings as permanently open and neglects air convection, whereas the FDS ones are more realistic. Thus, different fire scenarios were found when comparing these models. The way temperature evolves is the key for assessing the fire resistance of structural members.

The results from this work prove that the EC curves are not the most suitable for evaluating complex fire compartments, while CFD models offer better possibilities, with the drawback of being computationally expensive. Alternatively, zone models could be used. The findings from this work indicate that questions about fire resistance analysis remain unanswered; hence, further research on fire models and their optimization for fire engineering is necessary.

Acknowledgements

These results were obtained working on the diploma thesis.

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