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POŽARNO OPTEREĆENJE KROVNE I FASADNE ČELIČNE KONSTRUKCIJE – REKONSTRUKCIJA SAVA CENTRA

Rezime:

Rekonstrukcija Sava Centra u Beogradu, kulturnog dobra Republike Srbije, podrazumeva radove na objektu, koji moraju da obezbede da konstrukcija kongresnog centra ispunjava sve savremene zahteve protivpožarne zaštite. U radu su prikazni proračunski požari korišćeni za dokaz otpornosti na dejstvo požara čelične konstrukcije krova i fasade. Primenom analitičkih postupaka definisanih u Evrokodovima za konstrukcije i napredne CFD analize pokazano je da veći deo rožnjača u bloka A Sava Centra zadovoljava nosivost pri dejstvu požara u trajanju od 60 minuta. Sračunavanje požarnih opterećenja pri definisanju proračunskih požara takođe je prikazano u ovom radu.

Ključne reči: otpornost na požar, požarno opterećenje, napredni modeli požara

DESIGN FIRE LOAD OF THE ROOF AND FACADE STEEL STRUCTURE – RECONSTRUCTION OF THE SAVA CENTRE

Summary:

Reconstruction of the Sava Centre in Belgrade, a cultural good of the Republic of Serbia, includes works on the facility, ensuring that the congress centre's construction meets all modern requirements for fire protection. The paper presents the design fires used to conduct fire resistance design of the steel structure of the roof and facade. By applying analytical procedures defined in Eurocodes for structures and performing advanced CFD analysis, it has been shown that most of the purlins in Building A of the Sava Centre satisfy the required 60 minutes of fire resistance. This paper also presents the calculation of the fire loads applied in design fires.

Key words: fire resistance, advance fire models, fire load

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1. INTRODUCTION

The Sava Centre in Belgrade is the largest congress centre in Serbia. It was built in the period between 1976 and 1978 according to the design by the architect Stojan Maksimović and associates. The Sava Centre is one of the most famous structures in Serbia and the region. The Congress Centre is formed of two buildings: Building A - Conference and Commercial Centre and Building B - Congress and Concert Hall. Building A which is the subject of this analysis is parallel to Milentija Popovića Street. The complex was built as a combination of the reinforced concrete structure and steel structure, whereby glass was used as the main material for the facade cladding. The architecture of the building is based on contemporary, mostly sloped forms of glass green-blue facade planes, cascading terraces and gardens with horizontal brise-soleils, as well as concrete facades with small window perforations.

The development of the congress tourism and new regulations and standards in construction, innovative technologies and rapidly developing systems resulted in the need for a thorough reconstruction and rehabilitation of the building. The renovation and adaptation of Building A included: the reconstruction and renovation of the foundations, installation systems, parts of the first and second floors in the areas of new ceilings and parts of the ground floor in the area of new evacuation staircases and panoramic and service elevators.

Due to its characteristics and its importance to society, the Sava Centre was declared a monument of culture, which is why the reconstruction and rehabilitation of the building are very challenging and demanding for all participants in the project. The investor and designers encountered many complex tasks. One of the most complex tasks is the realisation of the structure fire protection. This paper presents the results of the fire resistance analysis study of the steel structure supporting the roof covering and facade cladding of Building A.

The adoption of the new Rulebook for Engineering Structures in the Republic of Serbia paved the way for proving the resistance of building structures to the effects of fire by applying the set of Eurocode standards. Article 5 of the mentioned rulebook defines the requirements that the structure must meet, among which is the requirement that the structure must be safe in case of fire. Article 6 of the rulebook for engineering structures defines the technical properties of structures. The technical properties of the structures must be such that the structure meets all the safety requirements defined by the code. When it comes to resistance to the effects of fire, the technical properties of the building structure must be such that in the event of a fire, the load-bearing capacity and stability of the building structure or its part are preserved during a certain period prescribed by a special regulation. Proof that the structure has the required technical properties is provided by the procedures defined in the standards listed in the Annex of the Code for building structures. Each chapter of the Eurocode in volume 2 of the first book contains a standard covering the issue of fire resistance of building structures (EN 1991-1-2, EN 1992-1-2, EN 1993-1-2, EN 1995-1-2, etc.).

This paper is focused on the fire resistance analysis of the steel structure supporting the roof and facade cladding of the Sava Centre Building A. The design fire loads implemented in order to prove the fire resistance of the structural elements are presented and elaborated. The conducted analyses include different approaches for defining fire load, such as the application of analytical procedures and modelling through advanced CFD simulations.

1.1 THE SUPPORT STRUCTURE FOR THE ROOF AND FACADE CLADDING

The main supporting structure of the Sava Centre is the reinforced concrete prefabricated structure. The roof structure and a part of the sloped facade are formed by reinforced concrete trusses and steel lattice purlins (Figure 1). The spacing between the roof lattice girders is 15 m which is also the span of the simply supported truss purlins. Purlins have been designed as space trusses with three chords. The same type of support has been used for the facade on the glazed surfaces of the sloped facade facing Milentija Popovića street.

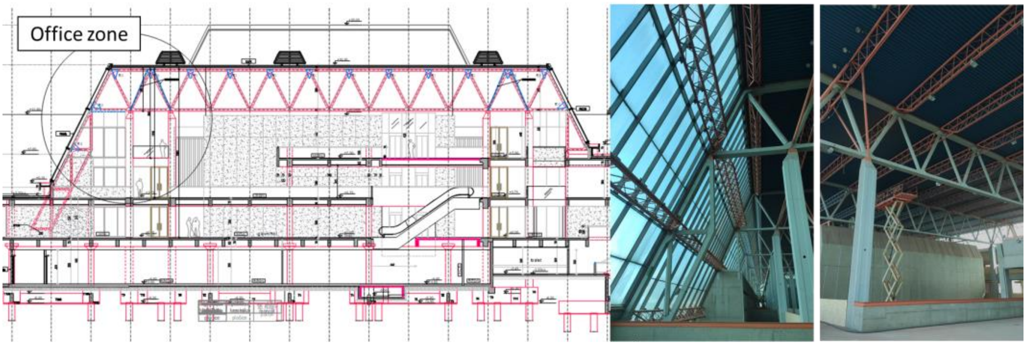


Figure 1 – Cross section: Sava Centre Building A

The compressed chords of the truss girder have been made of hollow tubular sections Ø108x4 mm, whereas the tensioned chord has been made of two tubular sections Ø60.3x6.3 mm. The main elements of the web have been made of solid sections of 30 mm in diameter, while the web for stabilisation of the top chord has been made of a circular cross-section of 18 mm in diameter.

2. FIRE LOAD

The first step in determining the fire load is defining the fire scenarios. It is necessary to define and analyse all possible scenarios of the occurrence of fire, select the critical ones, and for them provide proof of structure resistance to the effects of fire. The analysis of possible fire scenarios was carried out following the recommendations of the ISO 16733-1 Selection of design fire scenarios [1]. The standards EN 1991-1-2 [2] and ISO 16733-2 Design fires [3] were used to define the fire load. These two standards highly overlap and define the same fire load models. It should be noted that the latest revision of the ISO 16733-2 standard [3] is from 2021 and provides significant clarification of fire loads, introducing new types of loads that are not yet included in the Eurocode such as travelling fires.

Eurocode EN 1991-1-2 defines the following models of fire load:

- Standard temperature-time curve,
- Parametric temperature-time curves – Natural fire – Annex A,
- Thermal actions for external members – Simplified calculation method – Annex B,
- Localised fires – Annex C,
- Advanced fire models – Annex D,
- Fire load densities – Annex E.

The complex layout and variety of functions and spaces of the Sava Centre comprised the implementation of multiple different models of fire load. Figure 2 shows the longitudinal cross-section of the Sava Centre building. The walls and the ceiling structure of conference halls in

Building A are formed of reinforced concrete structural elements and they represent a separate fire sector. A fire in the conference hall cannot endanger the facade cladding and roof purlins. Zones of the building where the occurrence of fire may affect the bearing capacity and stability of the steel structure, purlins and facade beams are presented in Figure 2:

- GREEN colour between axes A and G, and axes K and M marks the corridors and hallways of the height of 8 or 12 m;
- YELLOW colour between axes M and P marks the banquet hall of a height of 16 m;
- RED colour between axes G and K, and axes P and R marks the technical room of a height of 4 m;
- BLUE colour between axes A and K marks the office area.

Analysing the areas of the Sava Centre, it was concluded that the application of the standard fire curve is not suitable for any of the mentioned areas. The applied fire loads for each of the zones are presented in the following.

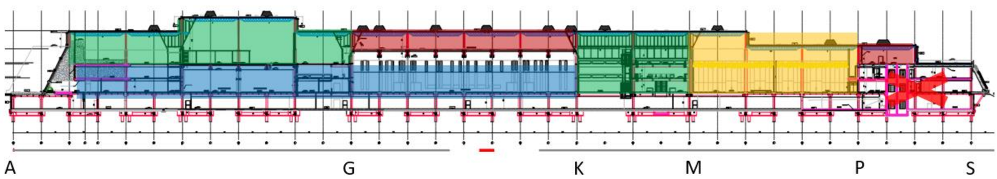


Figure 2 – Fire sectors: Sava Centre Building A

2.1 FIRE LOAD DENSITY

Fire load density is defined in Annex E of EN 1991-1-2 in the following way:

$$q_{\mathrm{f,d}} = q_{\mathrm{f,k}} \cdot m \cdot \delta_{\mathrm{q1}} \cdot \delta_{\mathrm{q2}} \cdot \prod_{1}^{10} \delta_{\mathrm{ni}}$$

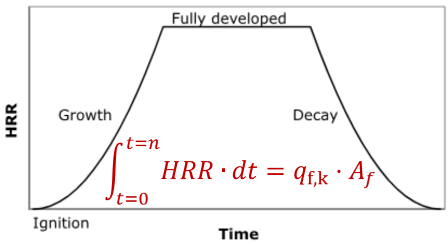
In the previous expression, the following labels are used: *m* - combustion factor, δ_{q1} – factor considering the danger of fire activation in relation to the area of the fire sector, δ_{q2} – factor considering the danger of fire activation in relation to the type of occupations, $\delta_{\mathrm{n1}} - \delta_{\mathrm{n10}}$ – factors dependent on active fire fighting measures.

According to the fire protection design, the installation of an automatic fire switchboard and its connection to the fire brigade is provided in the Sava Centre building. In case when there is direct communication of the switchboard with the fire brigade, the value of the coefficient $\delta_{\mathrm{n5}} = 0.87$ is disputed by the fire fighting authorities and it is required to use the value of $\delta_{\mathrm{n5}} = 1.0$. The authorities corroborated this with the practical issue that the brigade does not spring into action after receiving the signal over the day, but only during the night, between 22.00 and 6.00 o'clock. The other coefficient values were adopted in accordance with the Table E.2 of the standard EN 1991-1-2 [2]. The following value was obtained: $\prod_{1}^{10} \delta_{\mathrm{ni}} = 0.57$.

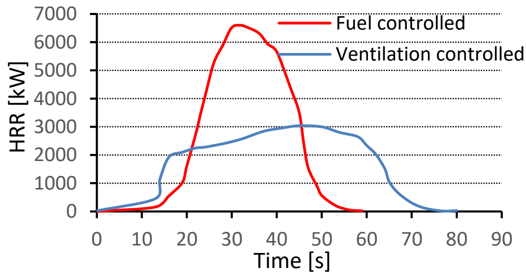
Fire load densities $q_{\mathrm{f,k}}$ [MJ/m²] were adopted depending on the area occupancy as defined in Eurocode 1 [2]:

- Corridors and hallways - transport (public space) 122 MJ/m²
- Banquet hall/classroom of a school 347 MJ/m² or theatre 365 MJ/m²
- Office 511 MJ/m²
- Technical room 200 MJ/m²

Fire propagation is defined by the HRR [kW] curve which represents the heat release rate HRR during the fire *t* [s] (Figure 3a). The integral of the HRR curve is equal to the product of the fire load density and fire sector surface area $[q_{\mathrm{f,k}} \cdot A_f]$. The shape of the HRR curve which defines the release of heat during the fire depends on the amount of combustible matter, as well as the ventilation conditions. Two HRR curves are presented in Figure 3b: one which is defined only by the amount of combustible material and the other which is defined by the conditions of ventilation of the fire sector. In case there is no supply of fresh air, the release of heat is longer, but of lower intensity depending on the maximum possible oxygen supply to the fire sector.



(a) general case



(b) fuel vs. ventilation controlled curve

Figure 3 – HRR-time design curves

2.2 CORRIDORS, HALLS AND BANQUET HALL

Due to the large volume of the connected space in the corridors and halls, the occurrence of a fully developed fire is not possible. The combustible material is not present in these areas except for localised pieces of furniture such as the info desk, bar or similar. Instead, according to ISO 16733-2, the development of a local fire or a travelling fire is possible in spaces with large areas and heights [3][4].

The Eurocode defines the fire load density and the algorithm for calculating the flame temperature. There are two possible design situations: the flame is lower than the floor height, and the flame reaches the ceiling and spreads below the surface of the ceiling. The minimum height from floor to ceiling in halls and corridors in the Sava Centre is 8 m. The ceiling height of the banquet hall varies from 12 m to 16 m. In areas of medium size and considerable height, it is possible to have a design situation in which two fire zones are formed; the lower one is colder and the upper one is warmer (two-zone model). However, the formation of two-fire zones in the banquet hall, corridors and halls is not possible due to the small amount of combustible matter compared to the height of the space.

The results of the temperature calculation at a certain height of the flame or above the flame are numerically very sensitive to the value of the diameter of the local fire, which is not defined in the Eurocode. The estimation of the diameter of the local fire was carried out according to the recommendations from Ref. [5]. Table 1 shows the local fire parameters according to Ref. [5]. When calculating the fire load in the banquet hall and the corridors, the parameters of the local fire for the “atrium in the office building” and “hotel reception hall” were adopted, respectively.

The maximum temperature at the height of 7 m in corridors and halls is lower than 250°C. The calculated temperature in the banquet hall at the height of 11 m is 257°C. The calculated temperatures are far below the critical temperatures for the truss purlin elements calculated for the accidental design situation (715°C).

Table 1 – Parameters of the localised fires

	A_{fi}	D	W_{fi}	HRR	q	t_{α}
	[m^2]	[m]	[m]	[KW/ m^2]	[MJ/m^2]	[s]
Atrium in the office building	9	3.4	12	250	200	300
Hotel reception hall	9	3.4	12	250	200	300
Exhibition hall	36	6.8	24	500	400	150
Church	20	5	18	250	300	150
Office large area	36	6.8	24	500	600	300
Sport hall	9	3.4	12	250	200	300
Supermarket	36	6.8	24	250	400	150
Restaurant room	20	5	18	250	300	150
A_{fi} – Fire area, D – Fire diameter, W_{fi} – Fire perimeter, t_{α} – Time needed to obtain HRR						

2.3 TECHNICAL ROOM

The fire load in the technical room according to the fire protection design is 200 MJ/m^2. The surface area of the room of 1320 m^2 is 2.5 times larger than the maximum surface area required for the implementation of the fire parametric curve. Considering this, the calculation of the fire load and steel temperature were determined using the software [6]. The machinery hall is the independent fire sector with only one door having dimensions of 1.0 m x 2.2 m. There are smoke domes with a diameter of 1.2 m. The obtained results of the air and steel temperature indicate the ventilation-controlled fire. It was adopted that the doors remain always open and the smoke escapes the area through the roof. The obtained steel temperature change over time is presented in Figure 4.

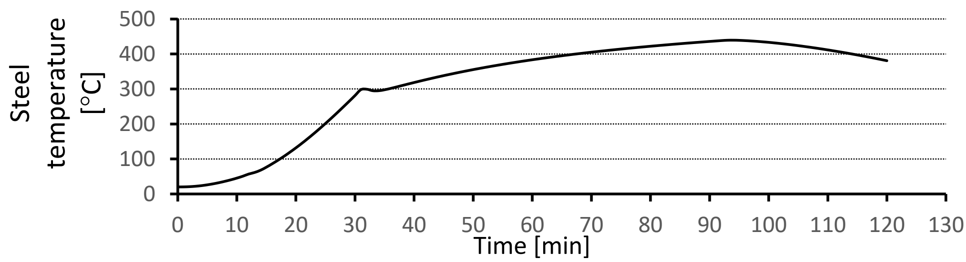


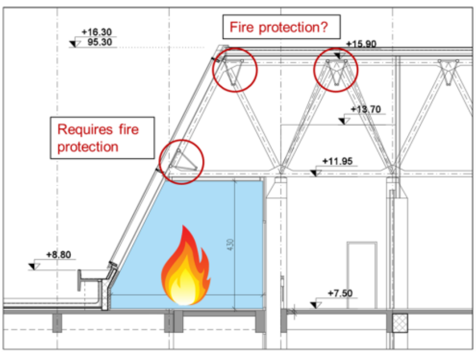
Figure 4 – Steel temperature-time curve

2.4 OFFICES

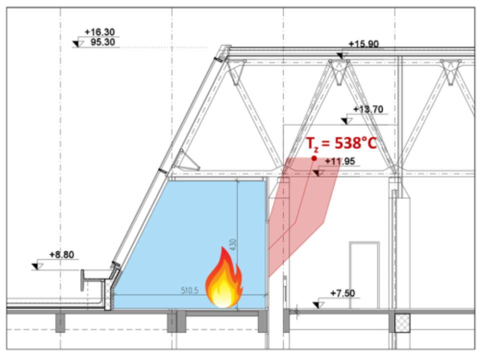
Office rooms are located along the two longitudinal building facades between axes A and K. The rooms are constructed as reinforced concrete structures with large glass areas, glazed facades and large windows in the wall towards the Sava Centre hall. The ceiling is lined with plasterboards. The investor opted for this combustible ceiling, accepting to fire protect the required number of purlins.

By analysing critical fire situations, it was concluded that the spread of fire from the offices is possible through the ceiling lining or the doors and windows towards the communication corridors in the Sava Centre. It was concluded that the first purlin/facade beam must be protected with fireproof coatings (Figure 5a). To determine if the same applies to the other purlins, the spread of fire outside the office space was analysed using the procedure for calculating the impact of fire on external elements. It was assumed that after a certain duration of the fire, the glass towards the communication corridors would break and the flames would penetrate the corridor of the Sava Centre. The breakage of the facade glass and the penetration of the flame into outer space are not relevant for the calculation of the fire resistance of the steel purlins. During a fire, the glass starts cracking when the temperature of the heated air exceeds 300°C. The probability of complete glass breakage as a function of temperature could be found in the literature. According to these data, it could be considered that at temperatures higher than 500°C, the glass will be completely broken in one opening. During the analysis, it was assumed that the glass broke on one window or door and that the flame spread into the corridor only through that opening (Figure 5b,c). This assumption is confirmed by the numerical analysis presented in the next section. The calculation was carried out for two typical offices with a smaller area of 75 m^2 and a larger surface area of around 150 m^2. A critical fire situation is one when the fire is in a larger office. In this case, the flame reaches the height of approximately 1.0 m under the lower edge of the purlin (Figure 5c). The flame temperature is 538°C which is lower in comparison to the critical temperature of 715°C determined by the bearing capacity of the purlin for the design fire situation. In the case of a smaller office, the flame is far away from the purlins and cannot affect purlins (Figure 5b).

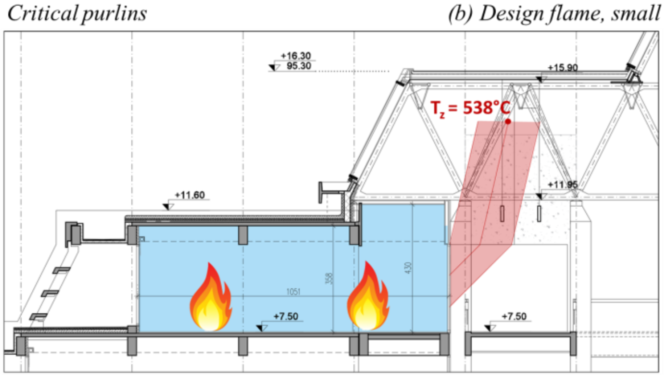
However, the design fire situations with the penetration of flame through the ceiling structure could not be verified using the algorithms provided in Eurocode. In this case, the recommendations provided in Annex D, EN 1991-1-2 [2] for the advanced fire models are used as described in the next section.



(a) Critical purlins



(b) Design flame, small office



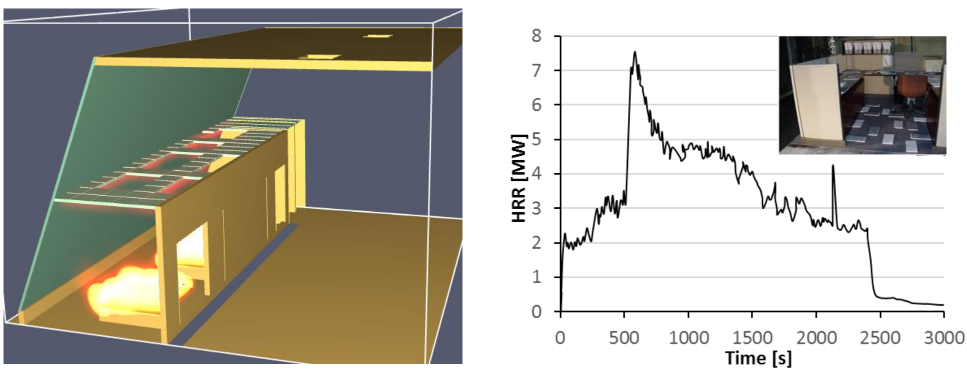
(c) Design flame, large office

Figure 5 – Fire in offices

3. CFD FIRE LOAD MODEL

Two different office spaces with four fire load models are analysed through CFD simulations. The two office spaces differ in total surface area and glass surface area (windows). Glass surfaces were modelled assuming cracking at a temperature of 500°C. In three models, the burner was set to the whole floor area, while the fourth model analyses the burn of the workstations. The ceiling was divided into 0.75 x 0.75 m cells to simulate plaster ceiling tiles. Two different approaches to the design of the plaster ceilings were considered. According to the first approach, the temperature was set to 412°C [8,9] at the beginning of combustion, while according to the second approach, the cells of the ceiling disappear without burning when the temperature of 700°C is reached in the thermocouple (a sensor that measures temperature). Thermocouples were also set under the roof, next to steel purlins, to measure the gas temperature required for further steel design.

The first load model represents the office space with a smaller surface area. Using the fire load density value of 511 MJ/m² according to Table E.4 in EN 1991-1-2:2002 [2], the value of heat release rate per area on the burner was calculated to be 250 kW/m^2. Figure 6a shows the first model with the plaster ceiling burning and eventually disappearing.



(a) CFD model *(b) HRR-time curve* [7]

Figure 6 – CFD simulations

The second fire load model has the same parameters as the first one, with the only difference in the approach implemented to the design of the ceiling. The ceiling was divided into 64 cells. A thermocouple was assigned to every cell. The thermocouples were programmed to induce the disappearance of every cell that reaches the temperature of 700°C.

The third fire load model is based on the HRR curves relevant to office workstations taken from previously published research [7]. This model represents a small office space with three workstations with a burning plaster ceiling. Each workstation is a burning surface with the applied HRR-time curve as shown in Figure 6b [7]. The dimensions of the workstations are 2.4 x 2.4 m and the height is 0.5 m.

The fourth fire load model represents the office space with a large surface area. The approach to the design of the fire load is the same as in the first model, with the only difference in the size of the burning surface. The design of the ceiling and the windows is the same as in the first model.

In all analysed models, the temperature of heated air varies in the range of ±15% of the mean value of the obtained results. The model with the combustible ceiling is adopted for further analysis in order to provide safe-sided results. This model is used to explore several fire situations. The first fire situation is the spread of fire through the door or window. The second design situation is the spread of the fire through the ceiling structure.

4. RESULTS OF CFD ANALYSIS

By varying the fire control parameters, several of them were recognised as key parameters affecting the calculation results: the moment of glass breakage, parameters that affect the burning of the ceiling, the opening of the door and the closing of the door. The temperature of flame and air in the first design situation in which the fire spreads through the opening towards the corridor are practically identical to the results obtained using Annex B [2]. At the moment when the glass breaks, the temperature in the room decreases significantly while the heated air leaks through the opening. Heated air continuously leaks, causing the temperature of the air in the room after glass break not reach values above 450°C.

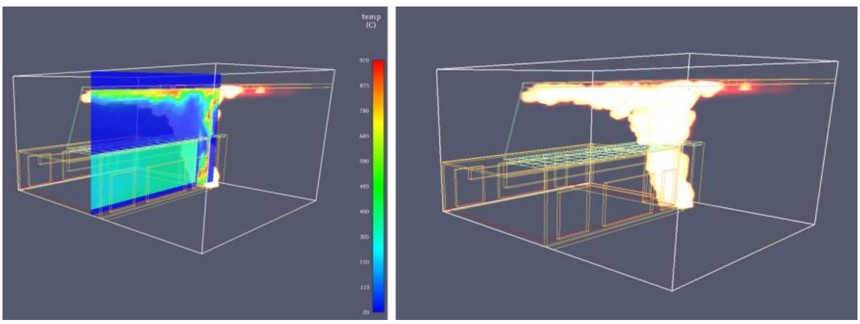


Figure 7 – CFD model visualisation of results

In the second design situation, the glass does not break, instead, a part of the suspended ceiling burns first. This situation is considered the relevant design situation. By opening a part of the ceiling, warm air leaks vertically towards the roof. In this case, a zone of hot air with a temperature of up to 700°C (thermocouple TC8) is formed directly above the office (Figures 7 and 8). At the place of the adjacent purlin next to the thermocouple TC7 (Figure 8), the maximum temperature is about 500°C. Finally, it was concluded that fireproof coatings should be applied to the first two roof purlins in the area next to large offices. Such a decision is on the side of safety because the critical temperature for the purlin is 715°C calculated for the accidental design situation.

5. CONCLUSIONS

The Sava Centre, with its spatial and structural specificities, is a building whose resistance to the effects of fire can be proven only by a comprehensive analysis that includes advanced calculation methods as well as CFD analysis. In the surrounding countries, CFD analysis is obligatory when proving the fire resistance for complex buildings such as congress halls, opera houses and theatres. The calculation of the resistance to fire effects of the structure of the Sava Centre did not include fire protection, but clearly indicated the critical elements of the structure that must be protected against fire.

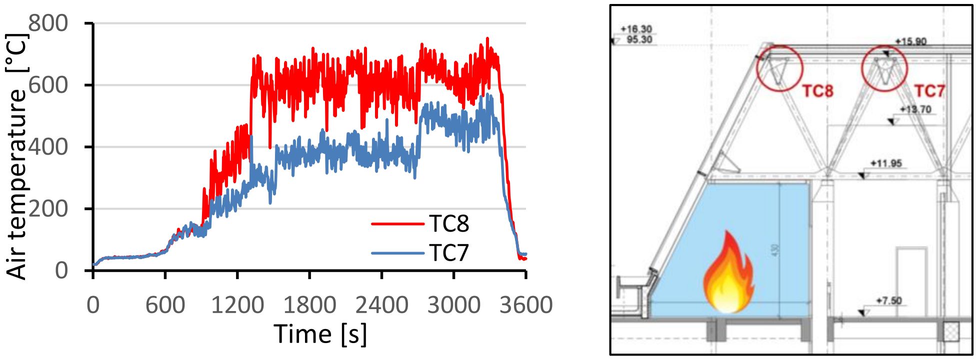


Figure 8 – CFD model results, the temperature of the air

With the adoption of the new Code of Building Structures, the conditions were created for implementing the new approach to solving the fire resistance of a structure. The responsibility is now on the designer of the structure to decide what measures should be implemented to achieve adequate resistance to the effects of fire. In the coming period, it is crucial that the authorities in charge of fire protection closely cooperate with civil engineers in order to create a detailed proving procedure for the safety of the structure against the effects of fire.

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