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STRUCTURAL FIRE RESISTANCE DESIGN OF THE FOOTBALL STADIUM ROOF STEEL STRUCTURE

Abstract

When analysing the fire resistance of the steel structure of the stadium roof in the event of a fire, the specific features of the stadium building must be taken into consideration. The stadium stands are open units of the building that are directly connected to the surrounding area. The clear height between the stadium roof and the stands is commonly large. However, the clear height between relatively small parts of the roof, directly above the top of the stands, could be smaller, potentially making this part of the roof the most vulnerable. On the stands of the stadium, it is prohibited to bring items that contain combustible material. In addition, the structure of the stadium, benches or chairs must be made of non-combustible material. Therefore, a fire that could compromise the steel structure of the stadium roof can only come from the stadium premises on the stands or under the stands. The fire scenarios on the stadium roof are not described in detail in the literature compared to indoor (covered) sports arenas. To assess the fire resistance of the roof structure, it is necessary to check all possible and potentially dangerous scenarios. The subject of the analysis presented in this paper is the roof steel structure of the stadium in Loznica, Serbia, which was built in the period 2021–2023. The study considers the following fire scenarios and their effects on the roof steel structure: (i) a local fire on the stands, and (ii) a fire in the stadium premises affecting the external members. The fire in stadium premises was analysed using the analytical expressions provided in Annex B of EN 1991-1-2 and EN 1993-1-2, as well as through CFD (Computational Fluid Dynamics) analysis of fire propagation. The calculation was performed for the domains of temperature, time and resistance, depending on the applied fire load analysis. Results showed that the steel structure of the stadium roof in Loznica meets the load-bearing codified criteria for the fire effects, with the exception of only one main roof truss. To address this issue, it was decided to install fire-resistant glass in the TV studio on the building's third floor to separate this area from the stands and prevent fire effects on the critical main roof truss.

Keywords

Fire load, fire resistance, external fire, steel roof structure, CFD analysis.

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1. INTRODUCTION

The "Lagator" stadium in Loznica is located in the northern part of the town. The old stadium contained the western and eastern stands with a total capacity of 5,000 visitors, as well as the main field and auxiliary fields. On the west side of the stands, there was an office space for stadium facilities: locker rooms, offices and spectator rooms for journalists. A cantilevered roof that covered the central part of the western stand was above the office space. The new football stadium facility stretches in the north-south direction. Its content corresponds to category 4 sports facilities prescribed by UEFA through the Rulebook on Standard Infrastructure. The capacity of the stadium is 8066 visitors with 75 wheelchair spaces for the disabled. The main facilities of the stadium are located on the northwest side of the stadium. Conference and media rooms, as well as a television studio, are on the first floor. The second floor is equipped with offices and necessary meeting rooms for employees. The third floor of the business area of the stadium is the top level of the west stand, where is provided a VIP bar with a cold kitchen, a television studio and a control room. The business area of the building is separated from the roof structure of the stands by a non-combustible inter-floor structure, fire resistant for 120 minutes. The connection between the stands and the business area of the building is accomplished by a glass panel between the stands and the VIP bar, and the stands and the TV studio. The cold kitchen is separated from the grandstand area by a fire-resistant wall.

1.1 DESCRIPTION OF THE STEEL ROOF STRUCTURE

The structure of the stadium is formed of a reinforced concrete structure of the stands and business areas, while the roof structure is designed as a steel lattice multiplanar system. The structure of the roof is formed from purlins and main space truss beams. RHS steel profiles were adopted for the purlins spanning 9.0 m. The main roof trusses, 56 in total, are placed radially around the perimeter of the stadium stands. The static system of the main roof trusses is a double-sided console, as presented in Fig. 1. The span of a roof truss is dependent on its position at the base of the stands. The static height of the roof trusses varies along the span, with a height of 3300 mm at the supports at the point of fixation on the RC capitals, and a height of 500 mm at the free end of the overhang.

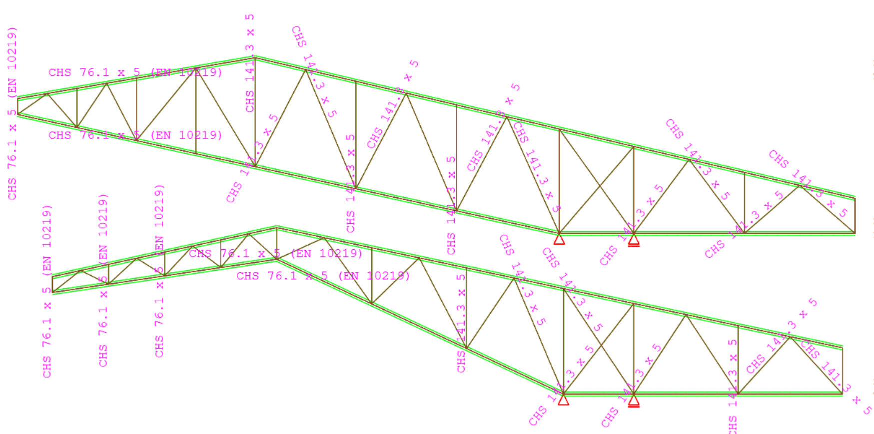


Figure 1. Roof structure

The brace elements of the main roof trusses are formed from vertical and diagonal members. The out-of-plane spatial stability of the chord is achieved by stiffeners in the form of crossed diagonal ties at the level of the top and bottom chord. The stability of the primary support is realised by stiffeners in the form of crossed diagonals. A circular cross-section CHS 168.3/6 mm was adopted for the truss chord members. Circular tubular profiles were adopted for the cross-sections of the truss brace members, CHS 141.3/5, CHS 88.9/5 and CHS 76.1/5. The global stability of the roof structure is accomplished by horizontal roof bracing.

2. DESIGN OF FIRE RESISTANCE

When analysing fire resistance, the following fire scenarios were considered:

- Local fire on the stands – a fire scenario that is possible in all the stands. This fire occurs in an open area and can only be a local fire. The design situation with the fire effect that engulfed the entire surface of the stands is not possible, as there is no sufficient combustible material.

- Fire inside the area of the third floor on the west stand. The ceiling structure of the third floor is made of non-combustible materials, with a fire resistance of 120 minutes. A fire in the area of the third floor cannot endanger the roof structure of the stands by the transmission of fire through the ceiling structure. However, fire from the third-floor area can compromise the roof of the stands with flames that can escape through the large glass surfaces between the stands and the third-floor area.

2.1. FIRE LOAD

The fire load was estimated (adopted) in accordance with the Fire protection design. The required fire resistance of the stadium roof is 60 minutes. To assess the fire load on the main roof structure, two stadium zones were analysed: stadium stands, NORTH, SOUTH and EAST, and the third floor of the business section of the building on the WEST stand. The values of fire load from the platform “EUROALARM” [1] were compared to the values from the standard EN 1991-1-2 [2]. According to the EUROALARM data, in the west stand area with VIP bar, studio, cold kitchen and control room, the fire load is in the range of 251–335 MJ/m^2. Eurocode does not precisely define this load. After analysing the data provided in EN 1991-1-2 [2] which defines the fire loads for office space – 511 MJ/m^2, classrooms – 347 MJ/m^2, cinema halls – 365 MJ/m^2, and transport areas, platforms and airport buildings – 122 MJ/m^2, it was decided to use the following fire loads for the proof of load resistance:

- 511 MJ/m^2 for the fire in the area of the third floor of the western stand,
- 365 or 122 MJ/m^2 on the stands as a local fire.

A higher value of the fire load on the stands was adopted locally in the zones of the stands planned for the TV crew platforms. TV platforms have dimensions of 3x3 m or 3x4 m.

Following the adopted firefighting measures, the fire load factors for the stands were defined according to Annex E of EN 1991-1-2: δ_{q1} = 2.1 (fire risk depending on the space purpose – adopted for offices, hotels, paper industry), δ_{q2} = 1.0 (there is no sprinkler system on the stands), δ_{n1} = δ_{n2} = 1.0 (there is no automatic fire alarm on the stands), δ_{n3} = δ_{n4} = 1.0 (there is no automatic alert to the fire brigade), δ_{n6} = δ_{n5} = 1.0 (there is a competent off-site fire brigade), δ_{n7} = 0.78 (there are access roads), δ_{n8} = 1.0 (there are no fire extinguishers on the stands), δ_{n9} = 1.5 (there is a smoke escape system, open area).

For adopting the dimensions of a local fire, recommendations provided by Franssen et al. were used [3]. The recommended local fire area is 9 m^2 for sports halls and 20 m^2 for multi-functional spaces. The maximum size of a local fire is limited to 36 m^2. For analysing the fire on the stands, the dimensions of the fire area were adopted on the safety side:

1. Fire on the TV platform, total area of 12 m^2 (365 MJ/m^2),

2. The maximum local fire on the stands, on the area of 36 m^2 (122 MJ/m^2).

Possible scenarios of a fire on a TV platform are shown in Fig. 2. The fire on the east stand was chosen as the relevant design situation due to the smaller clear height between the roof structure and the top platform of the stands. Due to the geometry of the supporting capital, a local fire in the top platform of the stands affects the roof steel structure at the main support. The calculation showed that the case when a local fire is directly under the roof truss on lower parts of stands is irrelevant due to the larger clear height between stands and the roof truss members.

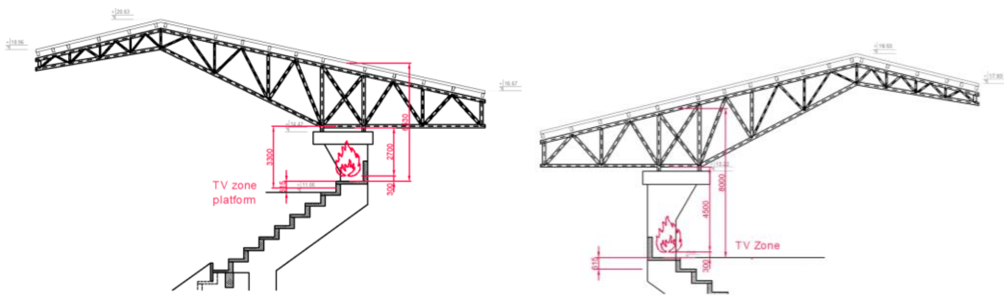


Figure 2. a) East stand, b) North and south stand

The size of the first platform under the bottom chord of the main truss does not allow the development of a large local fire. The relatively small fire load and the limited surface area of the localized fire result in a flame height that does not compromise the resistance of the steel structure. Namely, the temperature of the direct flame at the bottom chord of the truss is 565°C, which is less than the temperature defined by the external fire curve of 680°C.

The second design situation of fire effects that could compromise the roof truss is the fire in the area of the third floor. The structural design of the ceiling includes a balcony above the exit to the stands, 2.25 m wide, as presented in Fig. 3. The balcony structure is planned along the VIP lodge and commentator seats. The calculation of the flame height and temperature was conducted according to Annex B of the standards EN 1991-1-2 [2] and EN 1993-1-2 [4]. The flame is schematically presented in Fig. 3. The calculation of flame height and temperature proved that the fire in the VIP lodge area could not compromise the main beam in any of the analysed cases. The obtained fire temperatures on the level of the bottom chord of the main truss are lower than 300°C. However, a design situation with the flame spreading through the TV studio window showed that, due to the absence of the balcony, the length of the flame and temperature could potentially compromise the fire resistance of the steel structure. In this case, the temperature of the flame at the bottom chord of the main truss is 704°C.

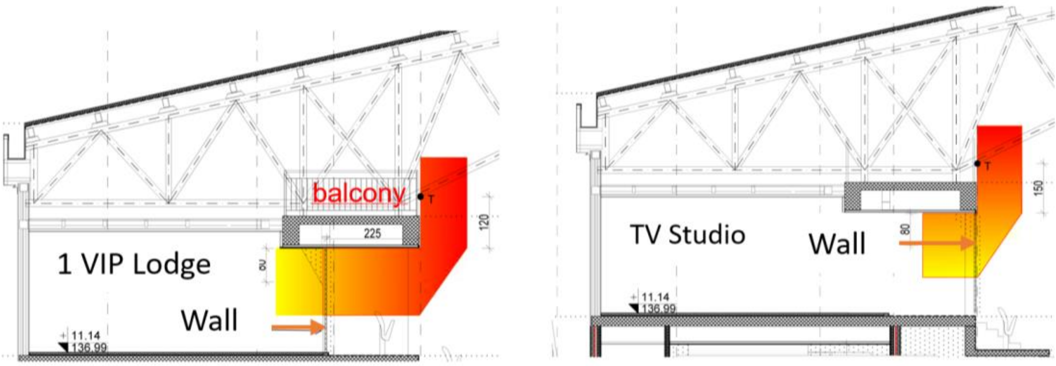
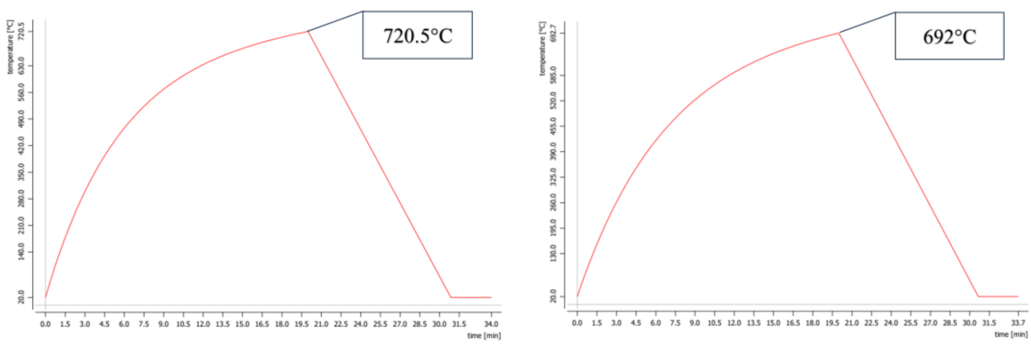


Figure 3. a) VIP lodge, b) TV studio

Parametric curves of real fires defined in Annex A of EN 1991-1-2 [2] were used for the assessment of fire duration and maximum temperature on the third floor. Fire curves for the VIP lodge and TV studio were created for the defined fire load. For the fire load of 511 MJ/m^2, the air temperature in the VIP lodge is 720°C after 22 minutes of fire duration. In the case of the TV studio, for the fire load of 511 MJ/m^2, the calculated air temperature is 692°C after 20 minutes of fire duration. In both cases, the total fire duration is 31.5 minutes, as presented in Fig. 4.



a) VIP lodge *b) TV studio*

Figure 4. Parametric fire curve Time [min] – Temperature [℃]

2.2. CFD ANALYSIS

The importance of the building required the additional check of the obtained temperature values in the fire. A CFD (Computational Fluid Dynamics) analysis of the fire effect on the steel structure was performed. A numerical model of the roof of the west stand with the third-floor area, shown in Fig. 5, was developed to verify the effect of fire at the third floor on the roof truss bottom chord. Fig. 5 shows the numerical model and the fire propagation curve in the TV studio, i.e. HRR curve. The maximum fire load is $1.1 \cdot 10^7$ W, which is reached 15 minutes after the start of the fire. An important parameter in the analysis of the fire effect is the moment of opening of the glass surfaces (glass breakage) on the facade wall.

The opening on the facade is one of the parameters that significantly affect the results. Namely, the dimensions of the opening affect the development of the fire and define the opening through which the flame exits into the stands. A smaller opening on the facade implies lower air temperature in the room, simultaneously producing a longer length of the flame and a higher temperature along the flame. The design situation with larger dimensions of openings on the facade results in higher air temperatures in the space, reduced lengths of the flame and lower temperatures along the flame axis [5].

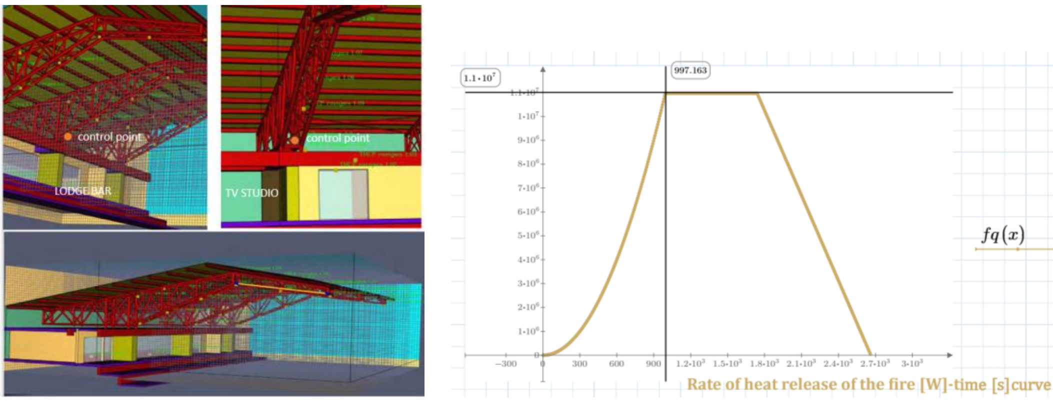


Figure 5. CFD model, HRR curve

In the area of the third floor, door-sized openings for access to the stands were used in the CFD simulation. In the case of the TV studio, the glass breakage and flame penetration into the stands were analysed. The effect of the window position was investigated through the CFD analysis. The window on the TV studio is located between the two roof trusses so that the flame does not act directly on the roof beams. The results obtained in the CFD model confirmed the drawn conclusions and the results of the implemented analytical calculation models, as shown in Table 1.

The obtained calculation results from CFD models are presented in Fig. 6. During the fire simulation, three gas temperature situations were monitored: in the room, at the exit from the room, and at the bottom chord of the roof truss. The obtained results are compared with the results from analytical models in Table 1. It is emphasized that the CFD analysis accounted for the exact position of the opening in relation to the roof support, whereas the analytical expressions assumed that the axis of the flame and the axis of the roof support are in one vertical plane.

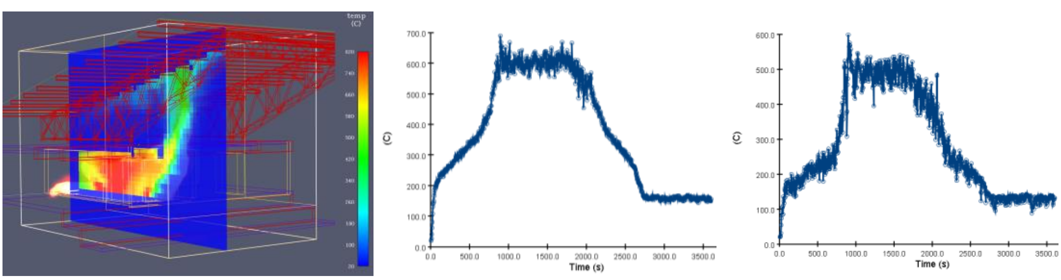


Figure 6. CFD results: visualisation, room air temperature, air temperature at the bottom chord

Table 1. Maximal air temperature [°C]

	CFD	Annex A and B, EN 1991-1-2 [2]
Room	650	720
Bottom chord	520	704

3. STEEL STRUCTURE FIRE RESISTANCE

The fire resistance of the steel structure is determined in the temperature domain. For all the steel structure elements that may be compromised by fire, illustrated in Fig. 7, the critical temperature was calculated using Eq. (1).

$$\theta_{\mathrm{a,cr}} = \left(39.19 \cdot \ln\left(\frac{1}{0.9674 \cdot {\mu_0}^{3.833}} - 1\right) + 482\right) \tag{1}$$

The critical temperature of a steel structure element is the function of the degree of utilization of an element $\mu_0 = N_{\mathrm{fiEd}}/N_{\mathrm{fi\theta Rd}}$. To calculate the resistance of an element at an elevated temperature $N_{\mathrm{fi\theta Rd}}$, it is necessary to calculate the steel element temperature based on the temperature of the gas in fire, considering the cross-section factor. The design force in the element N_{fiEd} is calculated for the accidental design situation for the combination of the dead and wind load. The design of the steel structure at room temperature demonstrated that the serviceability limit state requirements are relevant for the design of main roof trusses. Therefore, structural members of the main truss had considerable capacity reserves for fire design.

For the analysed elements of the steel structure, exposed to fire, the following critical temperatures were obtained:

- The bottom chord of the truss $\theta_{\mathrm{a,cr}} = 734°\mathrm{C}$,
- Truss web elements $\theta_{\mathrm{a,cr}} > 677°\mathrm{C}$.

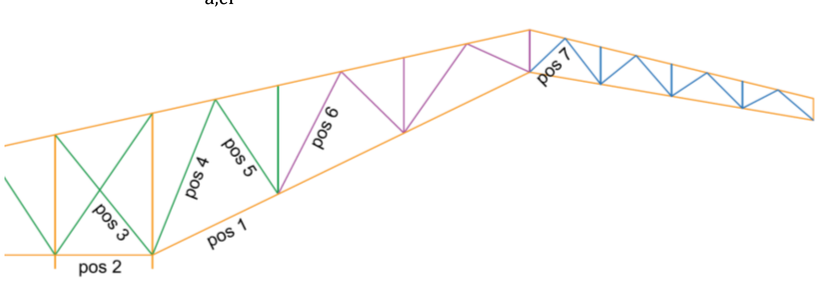


Figure 7. Critical roof truss members

By comparing the temperature of the flame, i.e. the temperature of the steel, and the calculated critical temperature of the key elements of the steel structure, it was concluded that the main roof truss at the location of the TV studio does not have the required fire resistance in the event of a fire. Three possible measures to increase the fire resistance of the steel structure were considered:

- Adoption of larger cross-sections to increase the fire resistance of the steel structure,
- Application of fire-resistant coating on the critical part of the main roof truss,

- Installation of fire-resistant glass on the TV studio, with a fire resistance longer than 60 minutes, to prevent the fire effects on the main roof truss.

After consulting the designer of fire protection design and observing the requirements of the regulatory bodies, it was decided to install fire-resistant glass in the TV studio.

4. CONCLUSION

This paper presents an example of the fire resistance calculation of the stadium roof steel structure. Although it is an outdoor building, it was concluded that a fire in some parts of the building could compromise the steel structure resistance.

Only one roof truss of the stadium structure had a lower fire resistance than the required one (60 min). The problem of the fire resistance of the critical roof structural members was solved at the critical area by separating the TV studio on the third floor in which a fire can develop from the area of the stands. The separation of the third-floor area from the area of the stands was carried out by the adoption of a fire-resistant glass partition, which aims to prevent the effect of fire from the roof truss.

Based on the presented case and the experience of the authors, the following conclusions can be drawn:

- When conducting fire design of a stadium structure, it is necessary to analyse all the potential fire scenarios, including fire on the stands, but also fire in the business areas around and below the stands.
- Partitioning of the building to fire sectors determines the fire scenario which needs to be analysed.
- It is crucial to precisely define the fire load in cooperation with the fire protection designer.
- The roof structure directly above the top platforms of the stands is the most vulnerable zone of the structure to the effects of fire.
- Higher sectors of the roof structure, including purlins and the main truss top chord, cannot be compromised by fire.

The recommendations of some football associations define a critical height of 6 m for which it is not necessary to control the fire resistance in case of fire. Parts of the roof lower than 6 m must be checked for potential fire scenarios.

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