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FIRE LOAD FOR PERFORMANCE FIRE DESIGN OF CAR PARK STEEL STRUCTURE

Abstract

Three advanced fire models for structural design are defined in Eurocode: one-zone model, two-zone model and model based on Computational Fluid Dynamics (CFD). This paper describes the effects on structures exposed to fire, based on the CFD model. The advanced computational fluid dynamics model was used to define the thermal action and temperature of the structural steel elements on the analysed case study object, open multi-storey car park Obilićev Venac in Belgrade. The support structure of the car park is a typical composite floor structure with steel columns. Distance between the columns and the floor beams corresponds to the dimension of one parking slot. The maximum temperature values of steel structural elements that occur during a fire are investigated. Based on the results of the tests available in the literature, CFD fire load models were created. Two different fire loads are used in numerical simulations. The first one is the fire load model based on combustible materials, which simulate the typical modern small car weighing up to one tonne. In the second case, the fire loads model was described with the Heat Release Rate (HRR) curve. Two of the referenced HRR curves defined by the French CTICM and Netherlands TNO Institute are used in CFD models. The discussion in this paper is limited to fire cases with one burning car. The parametric study considered the dimensions and positions of the burner element in the model. The effects of the natural ventilation in the open car park during the fire were also investigated.

The presented results are from the Research project "Advanced structures design – fire safety guideline for V4" funded by the Višegrad fund. A joint effort of colleagues from Hungary, Czech Republic, Slovakia, Poland and Serbia, produced the project report, which described five different case studies.

Keywords

Fire load, fire resistance of steel structure, CFD model, car park

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1. INTRODUCTION

Fires as uncontrolled combustion endanger human lives and property. They are characterised by intense heat release and the appearance of flames. The intensity of heat release depends on the type of fuel, oxygen, and the heat source that initiates the fire. The task of fire protection is to reduce the risk to human life, i.e. to provide the safety of people and limit the spread of fire. The choice of a fire protection system implies the application of active or passive protection measures such as:

- automatic fire detection and alarm,
- automatic water extinguishing system,
- design of a steel structure for required fire resistance,
- division of a building to the smaller compartment floor area, and
- fire protection of a steel structure using approved insulation and coating materials.

Fire resistance of steel structures can be obtained using the specific European codes. Fire resistant design for some types of buildings is not fully defined in the current Eurocode structural fire design EN 1993-1-2 [1]. This paper describes two CFD models for fire load to prove the load-bearing capacity of the steel structure of an open multi-storey car park on the effect of fire.

As a case study, a calculation according to EN 1993-1-2 [1] has been conducted to see if the implementation of Eurocodes in the fire protection regulation in the Republic of Serbia would reduce construction costs and increase profits.

2. CASE STUDY

The multi-storey car park building Obilićev Venac in Belgrade, Republic of Serbia, was built in 1974. According to the original design, the building had five floors to which no fire protection was applied at the time of the construction (Figure 1a). The structure reconstruction was conducted in 2016 when two additional floors were built. Fire protection was applied to the whole structure of the total area of 19 000 m^2, according to the technical regulations in the Republic of Serbia SRPS U.J1.240 [2], which define building fire risk level IV for large closed car park buildings. According to the Standard SRPS U.J1.240 [2] for composite steel-concrete floor structures, fire protection is 60 minutes, whereas it is 90 minutes for columns. The cost of the fire protection is 24 €/m^2.

The influence of the fire was analysed on the ground floor level, where columns are the most loaded. It was assumed that the steel structural elements were unprotected. The temperature in the steel structure was quantified for one car fire scenario. The spread of fire in the car park is very rare. However, results of recent tests (TNO and CTICM tests) and some real fires have pointed out that a multiple car fire scenario may not be excluded [3].

This research deals with different models of fire loads that could be used in computational fluid dynamic analysis. The numerical model was developed in software PyroSim [4], including Fire Dynamics Simulator (FDS). The car park building was modelled, assigning the actual geometry and materials to all the structural elements (Figure 1b). The design case with the car near the column in the sidewall of the building using the different fire loads was discussed.

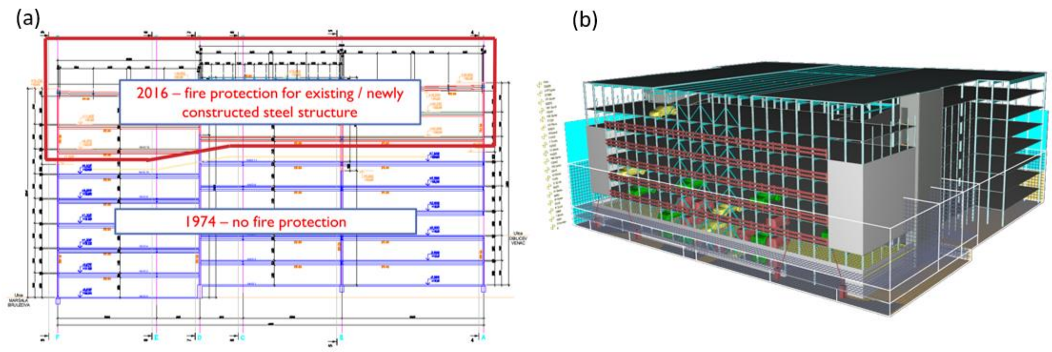

Figure 1: (a) Building cross-section, (b) Building model in PyroSim software

3. FIRE LOAD

The fire load of car park buildings is significantly different from the fire load of residential and commercial buildings. Localised fires which usually do not spread are characteristic of car parks. The combustion products in the fire are parts of the vehicle. The transmission of fire between two cars is possible if cars are at a short distance, less than 0.5 m. It takes 12 to 15 minutes to transfer the fire between vehicles. Additional 12 to 15 minutes are needed to transfer the fire to each subsequent vehicle. Spread of fire on the third and each following vehicle could be possible only if the firefighting does not start within 30 minutes. The practice has shown that the transmission of fires between vehicles is rare.

The fire load density used in calculations should be a design value, either based on measurements or, in special cases, based on fire resistance requirements given in national regulations.

For fire loads of multi-storey car parks, there are measured values of fire load that can be found in the literature. Most tests were done for closed car park buildings, and fire load was expressed via HRR as a function of fire duration. Figure 2a shows the fire loads from the tests implemented by the French CTICM [3]. The tests were conducted indoors, in a closed garage.

Similar fire tests with real fire in a closed car park, realised by referent laboratories in Sweden, the Netherlands, the United Kingdom, and New Zealand, can be found in the literature. The general conclusion of these research is that the fire load in the case of modern cars (2000 and newer) is higher due to the larger mass of plastic used for manufacturing different vehicle parts. Today, in modern cars, plastic parts are manufactured with new types of plastics that burn at higher temperatures, such as plastic for car dashboards. Tests with the latest generation (2015 and newer) of cars have not been realised and are not available. Based on the existing results, several reference curves have been proposed to be used in the fire resistant design of structures. Figure 2b shows two reference curves. The first one was suggested by CTICM and represents a statistically determined envelope of fire curves plotted in Figure 2a. The second curve is given in the standard NEN 6098:2010 of the Royal Netherlands Standardization Institute [6]. The second curve is more suitable for numerical calculations, providing a more stable numerical calculation. The CTICM curve can also be used in fire events with several cars, using the same curve more times, and delaying the subsequent fire's start for 8 minutes (see Figure 2b).

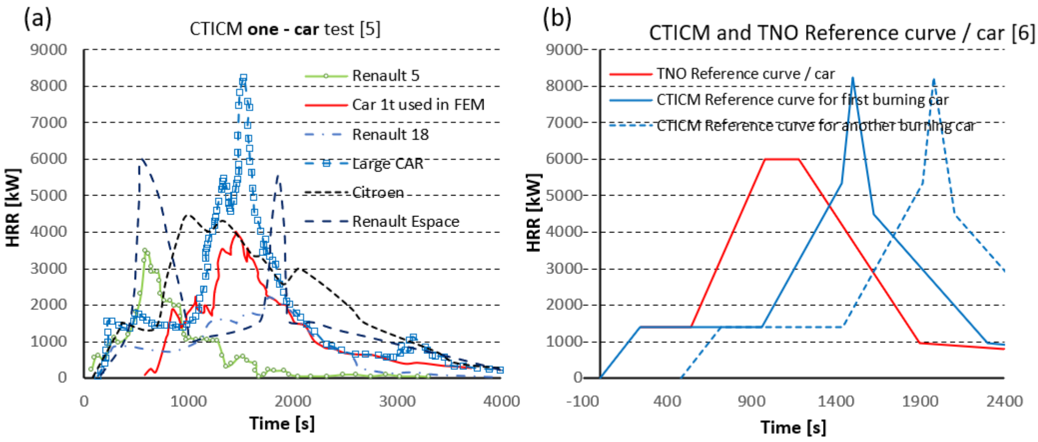

Figure 2: (a) HRR curves CTICM tests, (b) Reference HRR curve

3.1. CFD FIRE LOAD MODEL

Two models of fire loads were used in the CFD simulations. The first fire load model is based on material models of combustible materials from the existing software library were used, as well as materials generated with their thermal characteristics: density [kg/m^3], specific heat [kJ/(m^{2}K)], conductivity [W/(mK)] and heat of combustion [MJ/kg]. These properties define how much materials are heated and how they burn, which is essential for determining the ambient temperature around the combustion site. Table 1 shows certain types of plastic participation in a passenger car following data provided in [8]. All values are given for a small car weighing about 1.0 tonne, equivalent to the small car used in the CTICM experiment [4], see Figure 2a. As already mentioned, the share of plastic is higher in modern cars, so the amount of fuel in the model is greater compared to the cars used in the CTICM test.

Table 1: Plastic participation in a passenger car [9]

Material	Colour	Mass	Density	Specific heat	Conductivity	Heat of combustion
		kg	kg/m^3	kJ/(kgK)	W/(mK)	MJ/kg
Polypropylene		46.8	900	1.7	0.15	45.8
Polyurethane		57.4	40	1.0	0.05	25.0
Polyamide		10.5	1130	1.7	0.25	47.7
ABS		13.4	1070	1.7	0.40	40.0
PVC		5.1	1380	1.3	0.20	19.0
Polycarbonate		12.4	1200	1.2	0.20	31.3
Fuel		20.0	750	2.1	0.16	46.0
Rubber		70.0	1100	1.4	0.35	35.6

It is assumed that the fire is induced by petrol, a highly flammable material. The induced fire spreads further on the other parts of the burning car. The car was modelled accounting that it is formed from different materials which have dissimilar flammability. Elements forming a car were arranged across the model, assigning the proper mass, HRR, and ramp-up time.

The CFD model of the car is shown in Figure 3a. Different colours are used to present combustion materials following designation from Table 1. The model is generated in such a way that the position of the combustion material approximately corresponds to the position of the material in the real car. The obtained fire load from the CFD model fits well with the test HRR curve, see Figure 3b. The total fire load is higher by 7.5%, which can be described by the higher share of plastic in the model than the test vehicle in the CTICM experiment. The maximum HRR of 4600 kW is 15% higher than the measured value of 3900 kW in the CTICM test.

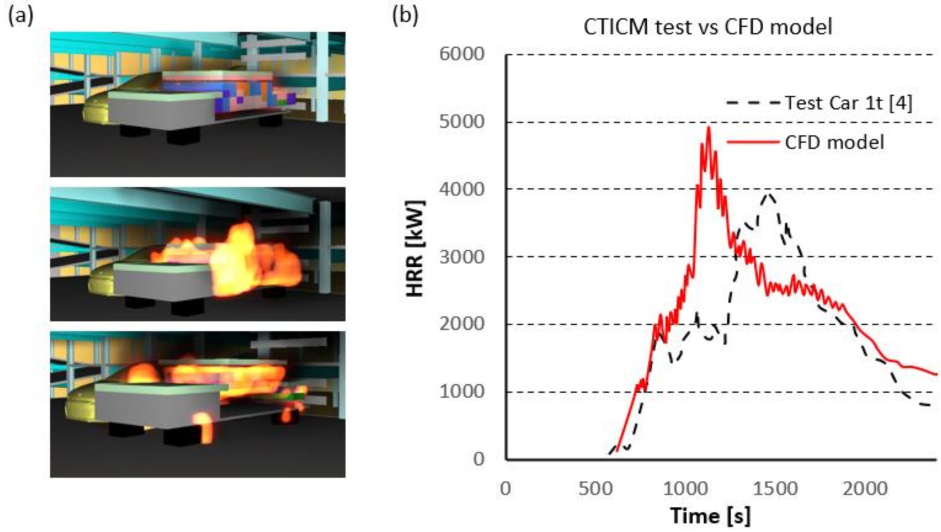

Figure 3: (a) PyroSim model and sequences of simulation, (b) HRR curves – Test vs CFD model

The second fire load model is based on the relevant HRR curves, following the recommendations given in the literature. In this case, the burner fire reaction was presented by reference HRR curve. The position of the burner in the model, the dimensions of the burner, and its height are the main parameters that have the leading influence on the value of the obtained ambient temperature. Cases with burners 1.7 x 4.2 m, as well as with a burner 1.7 x 2.2 m, were analysed. It was assumed that a height of 1.0 m above the floor level for the burner position leads to impact assessment with results on the safe side. According to the layout of parking slots of the car park Obilićev Venac, the position of the parking slot in CFD model is right between columns and beams. This car position is not on the safe side; the car may take an arbitrary position on the floor. The position of the car right below the beam is critical. The fact that Obilićev Venac is an open car park building, the natural ventilation of air cannot be ignored. The air flow of 1.0 m/s during combustion was adopted in the model. Within the parametric analysis, the calculation of the ambient temperature without the air flow was also performed.

4. RESULTS AND DISCUSSION

Through time, the temperature change was measured at five points around the burning car, as shown in Figure 4. The results show a good match with the data given in the relevant literature, as shown in Table 2. For further calculation according to Eurocode, the gas temperature recorded in the software should be transformed into the adiabatic surface temperature [7]. The obtained adiabatic temperature-time curves are given and compared to the ISO 834 curve in Figures 5 to 7. It is noticed that the adiabatic temperature of the structure reaches the temperature values defined by the ISO fire curve. However, the fire caused by the vehicle progresses slower, and after a few minutes after getting the flared phase, the extinguishing begins. This results in the lower temperature value of steel structure elements are exposed to fire. The relation between steel temperature and the air temperature was calculated according to Eurocode. Results from the CFD model compared against the experimental results [3] are presented in Table 2. The CFD model represents the fire load in the open car park building Obilićev Venac. According to the CFD model, the difference in temperature of steel elements in the open car park building compared with the closed one is between 15% and 45%.

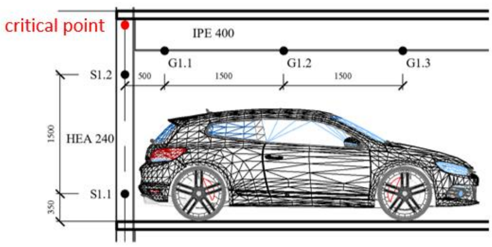

Figure 4: Marked points for measuring temperature

Table 2: CFD model vs CTICM test results [3]

Results	Ambient temperature	Steel beam lower flange	Steel beam upper flange	Column inside flange	Column outside flange
	[°C]	G1.2 [°C]	G1.2 [°C]	S1.2 [°C]	S1.2 [°C]
Small car CFD model	890	464	464	215	215
CTICM test	1080	660	590	250	340

By analysing the obtained results in Figures 5 to 7, it can be observed that the adiabatic temperature is considerably different along the steel element. The critical point for the column is the joint of the column and the beam immediately below the RC slab. The highest temperature of the steel structure is obtained on the beam above the burning vehicle. The façade cladding has a considerable impact on the temperature of the ambient around the column. The existence of a small parapet below the RC slab has a considerable impact on the air flow, so in case there is a parapet, the air temperature during fires is up to 140°C higher. A proper assessment of the position and dimensions of the burner in the model is important for the analysis results. Figure 6 shows the calculation results when a burner having dimensions 1,7 x 4,2 m is used, which corresponds to the vehicle's surface area.

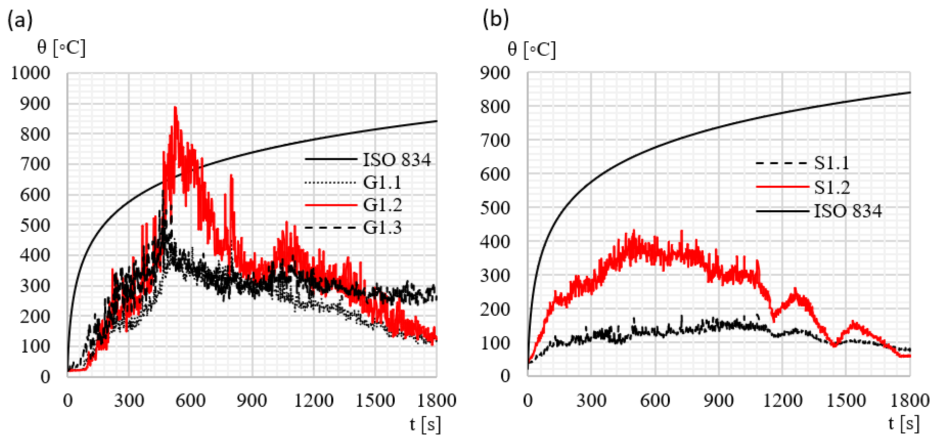

Figure 5: Adiabatic temperature-time for small car model (a) beam (b) column

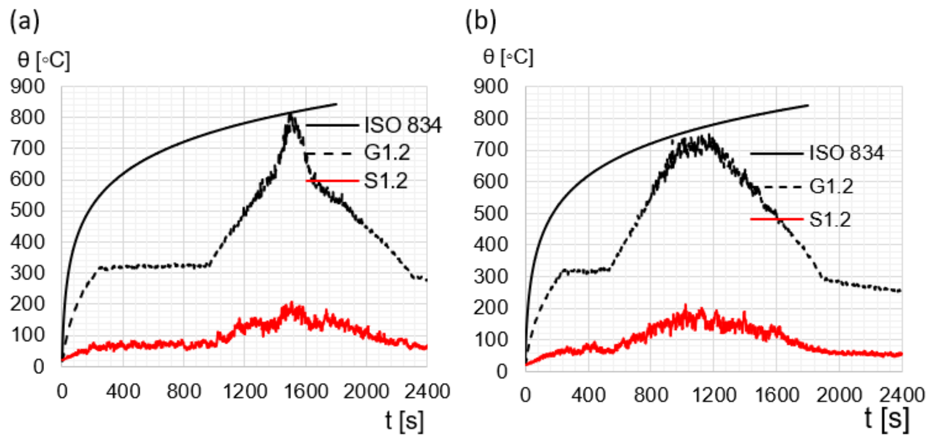

Figure 6: Adiabatic temperature-time, burner 1,7 x 4,2 m (a) CTICM, (b) TNO

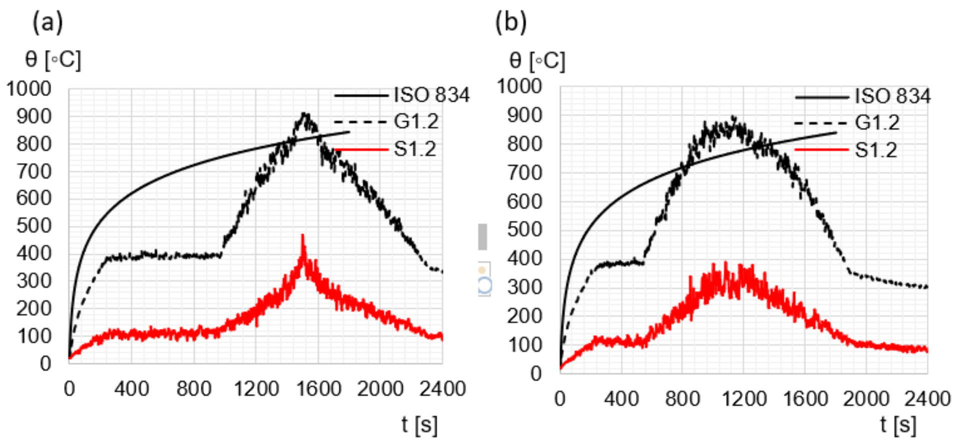

Figure 7:Adiabatic temperature-time, burner 1,7 x 2,2 m (a) CTICM, (b) TNO

In the second case, in Figure 7, are presented results obtained with a burner of dimensions 1,7 m x 2,2 m which corresponds to the surface area of the car passenger cabin. By further reducing the burner surface area, considerably overestimated values of steel elements temperature were obtained compared to the experimental values. The position of the burner in the layout affects the values of results up to around 10%. The elevation of the burner in the model has a considerable impact on the values of the adiabatic temperature. In this case, a height of 1.0 m was adopted, which is the height above the most combustible components of the car. There is always the impact of air flow in the open garages. The existence of the minimum ventilation of 1 m/s reduces the ambient temperature up to 150 °C.
The highest temperature from CFD analysis needs to be used for the further fire resistant design of the steel structure. Advanced CFD analyses could be an adequate option for very challenging steel structures for which fire resistant design is not under the scope of Eurocode simplified calculations.

5. CONCLUSIONS AND FURTHER DISCUSSION

The case study presented in this paper shows that it is possible to use the CFD advanced fire model for the fire resistant design of steel structures. However, numerous crucial parameters for analysis are not fully defined in referent literature.

Eurocode offers new possibilities for the design and calculation of steel structure fire resistance. Suppose that, using the more sophisticated method for obtaining the gas temperature, including numerical modelling and Fire Dynamics Simulator, could reduce firefight costs.

In all V4 countries, Poland, Hungary, and the Czech Republic, CFD analysis is prescribed in national annexes for use in advanced fire modelling. The minimal local fire is also defined in some V4 countries as Hungary and the Czech Republic. In Serbia and the region, we need to prepare national regulations with detailed instructions on using the advanced fire models for the fire resistant design of steel structures.

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