PARAMETRIC ANALYSES OF FIRE RESISTANCE OF STEEL COLUMNS SUBJECTED TO CAR PARK FIRE SCENARIOS

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ABSTRACT

Performance-based approaches are more and more widely-used for assessment of open car parks behaviour in case of fire. The Annex C of the current EN 1991-1-2 already includes formulae to evaluate the temperatures in the plume along the vertical flame axis of a localised fire when the flame does not impact the ceiling. It also allows evaluating the heat flux at the ceiling level as a function of the horizontal distance from the fire, if the flame impacts the ceiling. More recently, a new calculation method has been developed in order to assess the thermal impact of a localised fire on a vertical element situated outside the fire. This method has been implemented into SAFIR software and allows analyzing the global behaviour of structures subjected to localised fires. This present paper describes a parametric study performed with SAFIR software on the bearing capacity of steel columns under recommended fire scenarios.

1   INTRODUCTION

The objective of this research is to provide tabulated data for the design of steel columns under localised fires, which may arise from burning cars in car parks. In such type of application, using the commonly used prescriptive approach to evaluate the thermal effect is unrealistic. Indeed, a flashover is unlikely to happen and considering uniformly distributed temperatures would thus not properly represent the event. In such case, the effect of localised fires on the car park columns should be analyzed. Such research work was initiated in [1]. At the time being, two localised fires models are described in Annex C of EN 1991-1-2 [2]. Hasemi's model [3] allows assessing fluxes impinging horizontal elements at the ceiling level and is applicable when the flame impacts the ceiling, while Heskestad's model [4] focuses on the gas temperature evolution along the vertical axis of the flame and is applicable when the flame does not reach the ceiling. However Eurocode is lacking in defining methods to analyse the thermal effect of a localised fire on a column situated near a fire, not engulfed into the flame but sufficiently closed to be affected by the radiation. Tests performed by Byström et al. [5] highlighted that the method described in EN1991-1-2 for

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calculating plume temperatures and heat transfer to columns gives conservative results for both gas and steel temperatures, when compared to experiment results.

In the frame of the LOCAFI RFCS project [6], holistic investigations have been undertaken in order to develop an analytical method based on the existing Heskestad and Hasemi models and on the concept of virtual solid flame. It allows obtaining the thermal effect on vertical elements situated outside the fire source and on horizontal elements situated at the ceiling when the flame does not impact the ceiling [7].Two different series of pool fire tests have been performed in order to determine the heat fluxes received by vertical members engulfed in the fire or situated outside the fire source [8]. This experimental campaign has provided a wide amount of data for the calibration of CFD models [9] and of the analytical method. Flame tilting and other flame characteristics were considered during experimental tests and CFD simulations, and are then implicitly dealt with in the analytical method. After validation, this method was implemented in an user-friendly tool (OZone) and FEM softwares (SAFIR and ANSYS).

This article presents how this method is applied to commonly used car park columns in order to obtain their load bearing capacity when subjected to car park fires. The evaluation of the fire resistance is performed using numerical simulations with SAFIR software [10]. Thermal analyses are performed by means of 2D simulations at each vertical level (neglecting the longitudinal transfers) and mechanical analyses are run using 3D beam elements. The research work considers different cross sections: first category resumes R90 to R110 hot rolled round steel bars and the second category resumes 90x90 to 160x160 square bars, of ArcelorMittal sales programme with a S355 steel grade. In addition, several wide flange hot rolled profiles (HD) in S460 were analyzed. The present paper focuses on square sections. The other results will be available on ArcelorMittal Sections and Merchant bars website[4].

2   VIRTUAL SOLID FLAME METHOD

This analytical method has been developed within the frame of the LOCAFI project, with two levels of refinement: i) a model based on numerical integration for implementation into advanced models like the Finite Elements software SAFIR and ii) a model based on analytical formulae for handmade use. This paper presents the application of the Virtual Solid Flame method by use of SAFIR software, and will consequently focus on the first model.

In the case of a structural element not engulfed into the flames, the fire mainly affects it through radiation heat flux, which is strongly influenced by the relative position between the flame and the structural element. The evaluation of radiation heat fluxes is performed by representing the localised fire as a virtual solid flame, cylindrical or conical, that radiates in all directions. It has been demonstrated [6] that cylindrical shape leads to significant overestimations of the radiative heat fluxes while conical shape gives good correlations or slight and acceptable safe-sided discrepancies. It has to be noted that the convective heat flux is negligible if the structural element is not engulfed into the fire, but it has to be taken into account if the element intersects the ceiling jet layer, which appears if the flame impacts the ceiling. The equations from EN 1991-1-2 are applied for members situated in this layer or engulfed into the fire, for which convective fluxes play a role. To evaluate the radiative heat flux received, the vertical member is divided into finite faces and the heat flux is determined for each surface of the boundary. The radiative heat flux received by one specific face is evaluated by discretizing the virtual solid flame into finite bands, as depicted on

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[4] Other results are part of an ongoing internal project and will be available on http://sections.arcelormittal.com

Fig. 1, for which radiative properties are uniform. A configuration factor is used to evaluate the fraction of the heat flux leaving a radiating band z_j received by *Face$_i$* (*Fig. 1*).
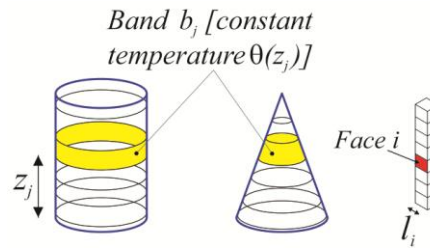

Fig. 1. Radiative exchange between the solid flame and the member [6].

The total radiative heat flux received by a face is the sum of all the contributions:

$$flux_{flame \rightarrow face_i} = \sum_{b_j} \sigma . \varepsilon . \theta_{f,j}{}^4 . F_{b_j \rightarrow face_i} \tag{1}$$

where is σ the Stephan-Boltzmann constant [W/m^{2}K^4], ε is the member emissivity, $\theta_{f,j}$ is the temperature of band b_j [K], and $F_{b_j \rightarrow face_i}$ is the configuration factor between band b_j and the face *face$_i$*. Finally the total heat flux φ_{tot} received by a section is the sum of the previously calculated radiative heat flux and convective heat flux. Then, the temperature of a section is given by a thermal balance considering incident and emitted heat fluxes, in agreement with Equation C.9 from EN1991-1-2 and with Equation 4.25 from EN1993-1-2 [11]. It is important to note that as the fire intensity – the heat release rate – varies with time, the total heat flux will also vary with time. If a scenario with several fire sources is encountered, the principle of additionality applies, assuming an upper limit of 100 [kWm^{-2}]. This physical limitation is recommended in EN1991-1-2 Annex C.

3 GEOMETRY OF THE MODEL

3.1 Boundary conditions
Numerical simulations were performed with several column lengths: 2.5[m], 3.36[m], 3.6[m] and 4[m]. The boundary conditions depicted below are used in SAFIR software, the axis z being the column axis. This corresponds to the upper level of a braced car park steel structure and can be considered as a worst case scenario considering the buckling length given in EN1993-1-2.

Table 1. Boundary conditions in SAFIR

Node	Displacement in x	Displacement in y	Displacement in z	Rotation around x	Rotation around y	Rotation around z	Warping
Column base	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Free
Column head	Blocked	Blocked	Free	Free	Free	Blocked	Free

3.2 Initial imperfection and load eccentricity
The EN1993-1-2 states that for the analysis of isolated vertical members a sinusoidal initial imperfection with amplitude of H/1000 should be used, when not specified by relevant product standards (H being the height of the column). The standard 10059 for squares shapes [12] gives a straightness imperfection of H/400 for a square side greater than 80 [mm]. But according to the Note 1 of clause C.5(2) from EN1993-1-5 Annex C [informative] [13] – when using Finite Element Methods, 80 % of the geometric fabrication tolerances is recommended. Consequently, a sinusoidal initial imperfection is taken equal to H/500 and is applied in the positive Y-direction (global system

coordinate). No residual stresses have been considered in the analysis since their effect is negligible in case of fire [14].

The load cases are considered depending on the application point. Let the length d represent the side length of a square section. An eccentricity is applied in the negative Y-direction (global system coordinate) to represent to worst case scenario (since the initial imperfection is applied in the positive Y-direction). For those cross sections, a zero load eccentricity and an eccentricity of $d/5$ are considered.

4   THERMAL EFFECT IN THE MODEL

4.1 Car park fire scenarios
Four scenarios are considered to represent car park fires.
  I.   An internal column surrounded by 3 cars and 1 van.
  II.   An internal column surrounded by 4 cars.
  III.   An external column surrounded by 1 car and 1 van.
  IV.   An external column surrounded by 2 cars.
These scenarios and the relative Rate of Heat Released curves emanate from the Guidebook for the verification of car parks subjected to fire from CTICM [15]. The cars RHR curves were obtained from experimental campaigns and more details can be found in [16], while RHR curve for the van is an estimation resulting from a risk analysis which was not validated by tests and which is considered as overly conservative [15]. The presence of a van in the fire scenarios is considered in French regulations. The scenario I and the Rate of Heat Released curves of the four vehicles are depicted in *Fig. 2*. In the scenarios involving a van, the latter is placed at the parking place n°2. In scenario IV, the two cars involved are placed at parking places n°1 and n°2. Concerning the fire ignition, it is assumed that it takes 12 minutes to propagate the fire to the surrounding vehicles [16]. The vehicles coordinates in meters are, for parking places 1, 2, 3, 4 respectively:
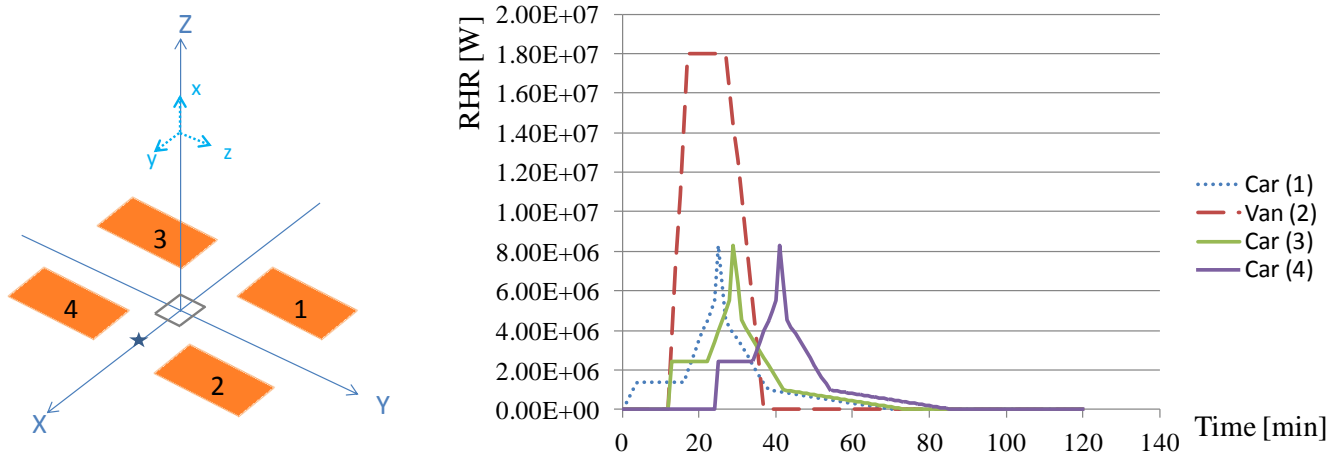*(-1.25 ; 2.5)   (1.25 ; 2.5)   (-1.25 ; -2.5)   (1.25 ; -2.5).*

Fig. 2. a) Geometry of scenario I; b) RHR curves for scenario I.

4.2 Fire model
According to EN 1991-1-2, the flame length of a localised fire L_f [m] is given by

$$L_f = -1.02\,D + 0.0148\,Q^{2/5} \tag{2}$$

where D is the flame diameter [m] and Q is the rate of heat released [W].

When the flame impacts the ceiling, the Hasemi's model can be considered: the length of the flame underneath the ceiling L_H [m] and the Hasemi flux $Q_H{}^*$ [W] are calculated using the EN1991-1-2 Annex C formulae:

$$Q_H{}^* = Q/(1.11 \times 10^6 H^{2.5}) \tag{3}$$

$$L_H = (2.9 \times H \times (Q_H{}^*)^{0.33}) - H \tag{4}$$

Where H is the source to ceiling distance [m].

In SAFIR, a virtual conical shape has been chosen to represent the fire. Considering that the general dimensions of a parking space are 2.5[m]x5[m], the cone base representing the fire has an equivalent diameter of 4 meters (depicted in *Fig. 3.a*). With the geometry depicted in *Fig. 2.a* and the maximum RHR of a car and of the van, *Eq.(2).* results in a flame length higher than the ceiling level. The virtual cone is then truncated and the scenario depicted in *Fig. 3.b* is encountered: the column is out of the virtual solid flame but intersects the ceiling jet. For finite elements engulfed into this ceiling jet, thermal effect is influenced by both radiation and convection heat fluxes and thus the equations from EN 1991-1-2 must be applied. For all columns considered in this project, it is assumed that the top portion of the column engulfed into the ceiling jet is 0.5[m] long.

Fig. 3. a) Distance between column and fire; b) Truncated virtual cone.

5   RESULTS

5.1 Temperature distribution

Considering a 3.36[m] column with 130[mm]x130[mm] square cross section in fire scenario I, the steel temperature across the section at 33 minutes for two different levels are represented in *Fig. 4*. The timing corresponds to two minutes after the maximum RHR plateau of the van. On the left, the temperatures at a level of 0.94[m] are depicted – thus corresponding to the Virtual Solid Flame model, while on the right the temperatures at a height of 3.1[m] are depicted – thus corresponding to Hasemi's model. The first distribution is asymmetric and the higher temperatures are encountered on the van side while the second distribution is symmetric. Indeed, Hasemi's fluxes are equal all over the section. The temperature distribution along this column at 33 minutes for Node 1068 (highlighted in *Fig. 4*) is represented on *Fig. 5*.a. On the graph, it appears that steel temperature is much higher in the ceiling jet than in the zone subjected to radiation. Considering the same column length but with a 160[mm]x160[mm] section and with the same timing, the profile of temperature is represented on *Fig. 6.a*. The coordinates of the section centre being equal to (0[m],0[m]), the reference point is in this case Node 1067, situated at (0.064[m],0.064[m]).

5.2 Structural response

Two types of failure may occur for the columns considered in this research. A plasticity failure is more likely to happen for less massive columns subjected to high temperatures while a buckling failure tends to occur for other columns. The displaced shape at failure (with a scale factor equal to 1) of a 3.36[m] column with 130[mm]x130[mm] square cross section, considering fire scenario I and with no load eccentricity is depicted on *Fig. 5.b*. In this situation: a plasticity failure occurs in the beam elements situated inside the ceiling jet, due to the high temperatures. The load bearing

capacity obtained with FEM is 3300[kN]. On *Fig. 6.b*, is depicted the displaced shape at failure of the same column, but with a 160[mm]x160[mm] cross section. In this situation: a failure by buckling occurs for 6060[kN].
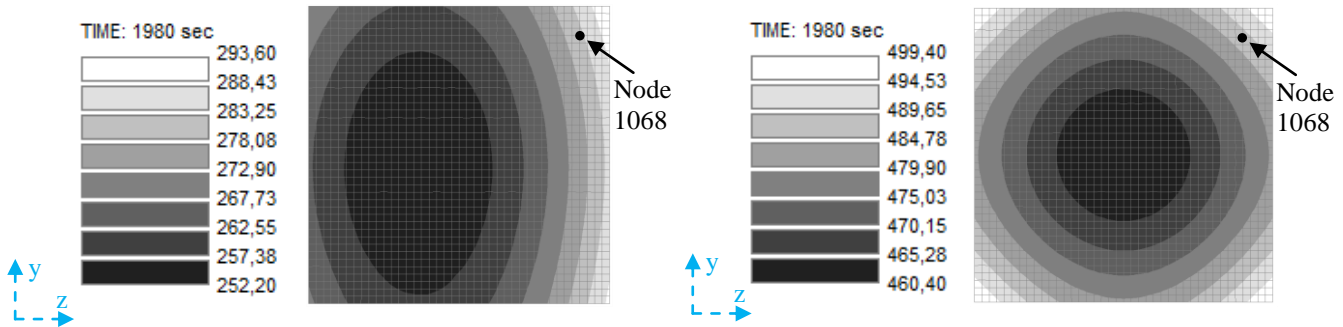

Fig. 4. Temperature distribution [°C] at 33 minutes for a 3.36 [m] column with a 130[mm]x130[mm] square cross section in fire scenario I at a) a height of 0.94[m] ; b) a height of 3.1[m].
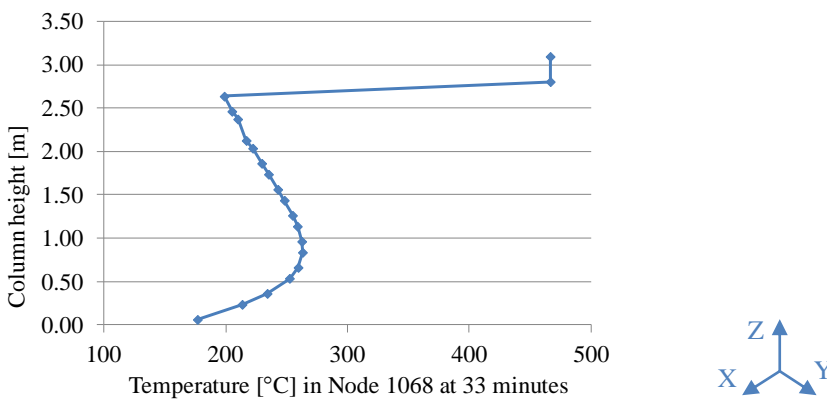

Fig. 5. a) Temperature distribution at Node 1068 at 33 minutes along a 3.36 [m] column with a 130[mm]x130[mm] square cross section in fire scenario I ; b) Displacement shape in failure (scale factor 1) of a 3.36[m] column with a 130[mm]x130[mm] square cross section in fire scenario I.
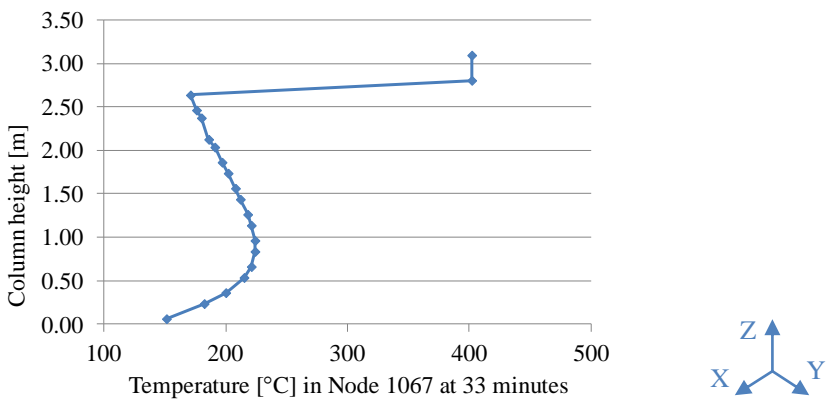

Fig. 6. a) Temperature distribution at Node 1067 at 33 minutes along a 3.36 [m] column with a 160[mm]x160[mm] square cross section in fire scenario I ; b) Displacement shape in failure (scale factor 1) of a 3.36[m] column with a 160[mm]x160[mm] square cross section in fire scenario I.

5.3 Tabulated data

This research results in tabulated data containing the load bearing capacity of steel columns under standard ISO fire (R60, R90 and R120) or under localised fires, obtained with Finite Elements numerical analysis using SAFIR software. Several cross sections have been investigated but this paper only presents the results for a 3.36[m] column with 130[mm]x130[mm] square section in

S355 (see *Table 1*). As an example, a 3 storeys car park of 30[m]x40[m] with a column every 10[m] and with a composite slab of 0.12[m] is considered. The following assumptions are made:

− *Permanent load G = 2.5 [kN/m²] and Variable load on slab Q = 2 [kN/m²]*

− *Fire load combination = 1G + 0.7Q*

The applied load on a 1ˢᵗ level central column is thus about 1200 [kN] (excluding the self-weight of the columns) in fire load combination. In *Table 1*, a "Status" column indicates if the column may resist the fire. Cold results are also given in the table but were obtained using different boundary conditions (pinned-pinned), and the Ultimate Limit States load combination *1.35G + 1.5Q* is used to obtain a design load about 1900 [kN]. Considering the eccentric loading, the cold load combination is governing the design. Although the results of one cross section and one column length are shown, the same tendency is observed for the other steel columns analyzed in the frame of this project. The load bearing capacity of the column is significantly greater when considering the action of localised fires than then when using prescriptive approach based on ISO fire curve. This is consistent with the results obtained in the research work done by Zhang et al. [17]. Using the Virtual Solid Flame method (VSFM), along with further research about localised fires, may consequently increase the cost-efficiency of steel solutions for car parks.

Table 1. Results for 130x130 square section – column length 3.36 [m]

L=3,36 [m]

Fire model	Load eccentricity	FEM load bearing capacity [kN] for 130x130	Status
Cold	0	3139	✓
ISO R60		289	✗
ISO R90		148.5	✗
ISO R120		115.5	✗
VSFM scenario I		3300	✓
VSFM scenario II		3800	✓
VSFM scenario III		3600	✓
VSFM scenario IV		4200	✓
Cold	d/5	1915	✓
ISO R60		221.7	✗
ISO R90		114.5	✗
ISO R120		83.3	✗
VSFM scenario I		2300	✓
VSFM scenario II		2700	✓
VSFM scenario III		2600	✓
VSFM scenario IV		3100	✓

6 CONCLUSIONS

In case of steel columns under localised fires arising from burning cars, using the commonly used prescriptive approach to evaluate the thermal effect is unrealistic. In the frame of the RFCS project LOCAFI, an analytical method based on the existing Heskestad and Hasemi methods and on the concept of virtual solid flame has been developed to allow obtaining the thermal effect on vertical elements situated outside the fire source and on horizontal elements situated at the ceiling when the flame does not impact the ceiling. In the frame of the research presented in this paper, Virtual Solid Flame method is applied to commonly used car park columns. The evaluation of their load bearing

capacity is performed using numerical simulations with SAFIR software. Thermal analyses are performed by means of 2D simulations at each vertical level and mechanical analyses are run using 3D beam elements. The following conclusions can be drawn.

- Higher load bearing capacities are obtained using Virtual Solid Flame method than using prescriptive approach based on ISO fire curve.
- The use of Virtual Solid Flame method, along with further research concerning localised fires, could consequently increase the cost-efficiency of steel solutions for car parks.

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