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THERMAL EFFECT OF A LOCALIZED FIRE IN THE STEEL STRUCTURE OF AN OPEN CAR PARK

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ABSTRACT

Due to the recent fire events in open car parks and in order to increase the fire safety in this type of the building structures, simple calculation methods should be developed to estimate the thermal effects of a localized fire. This investigation deals with a parametric analysis, using different fire events (different vehicle classes), fire scenarios (relative position of the car with respect to the main element of the structure and dimensions of the compartment) and section factor of the main supporting element of the structure (dimensions of the beam cross section). The temperature was calculated for each fire scenario, around the beam (gas temperature) and also in the steel beam. The thermal effect on part of the structure was calculated by a mixed formulation, taking into consideration the Hasemi and Heskestad methods to evaluate the temperature of the gas and also the lumped thermal model for the calculation of the steel temperature. These results will be compared with the results obtained using the software Elefir-EN and CFD simulation by Ansys FLUENT.

Keywords: open car parks, localised fire, gas temperature, steel temperature.

INTRODUCTION

Fire events in car parks have been a major problem for buildings, vehicles and humans, since this kind of buildings starts to become more popular. This type of fire events is very dangerous, because vehicles have combustible materials that are the main cause for fire propagation. The estimate time for fire propagation has been experimentally determined to be 12 minutes (D. Joyeux *et al*., 2002) or 15 minutes between vehicles, according to the recommendation of European Convention for Constructional Steelwork (ECCS, 1993).

Few events in open car parks have been reported. On October 1st of 2007, in Rotterdam, 7 cars were parked but only 6 were involved in this accident. The building structure was made of prefabricated hollow concrete slabs supported by RHS steel beams and L type beams. The steel beams were protected with fire resistance boards, justifying the limited temperatures achieved and the inexistence of large deformation in the bottom steel flanges. More recently, on January 1st of 2018, at Liverpool Echo Arena, 1400 cars were destroyed due to a big fire event. The fire is reported to have reached temperatures of 1000 ºC and the building presents a huge damage level on slabs and other structural elements. This fire began due to a problem that happened in the engine of an old Land Rover that was parked there.

Statistics results from a research project (D. Joyeux et al, 2002) say that, approximately 98% of the fires were restricted to less than 4 cars, 4 cars were burning in only 2 cases, while 1 fire involved 5 cars and 2 fires involved 7 cars. A New Zealand study (Li Yuguang *et al*., 2007) revealed that approximately in 97% of the fires only 1 burning car was involved. The Building Research Establishment (BRE, 2010) developed a project to gather information on the nature of fires involving the current design of car parks and future safety strategies for car park buildings. The study reported 3096 fire events developed during 12 years, where 51% started with the ignition of a car, but in most cases, no fire spread to other cars was identified.

EXPERIMENTAL TESTS FROM LITERATURE

Butcher in 1968 (E. G. Butcher *et al.*, 1968) made 3 car fire tests in a specially built steel structure with an insulated ceiling, approximately 2.1m above the floor. Nine cars were used in a 3x3 array with parallel spacing's ranging from 0.75 to 1.2m. The central car was ignited, but the fire did not spread to any of the adjacent cars. The maximum measured temperature was 840ºC in the air, 360ºC in the steel column, 275 ºC in the steel beam. A single parked vehicle fire was unlikely to cause uncontrollable fire spread within a car park. The damage to the car park building was not critical in that time.

In 1973, a full-scale car fire test was developed in the multi-storey open car park with unprotected steel frames and concrete decks (Gewain, 1973). Three cars were used, and the central one was ignited. The maximum temperature of the air was 432ºC (above windscreen, after 11 minutes). The air temperatures for most parts in the building was smaller than 204°C and the maximum temperature of the steel was 226ºC. The deflection and elongation of elements was null after cooling. The fire did not spread to any of the adjacent cars during the 50 minutes of test. In that time there was a low fire hazard in an open car parking structure and the steel provided stable fire resistance of the structure.

In 1995, ten car fire tests were realized at CTICM (*Centre Technique Industriel de la Construction Métallique*) laboratory using calorimetric hood. These tests showed that the classification of cars in classes is relevant according to the energy of cars released in a car fire (Schleich *et al.*, 2002). The most important test of these was the number 7, that resulted in the safety curve of a class-3 car burning, as we can see in Figure 1. This test number 7 was used a class-3 car (Laguna) that represents very well the energy released by any class 3 burning vehicle.

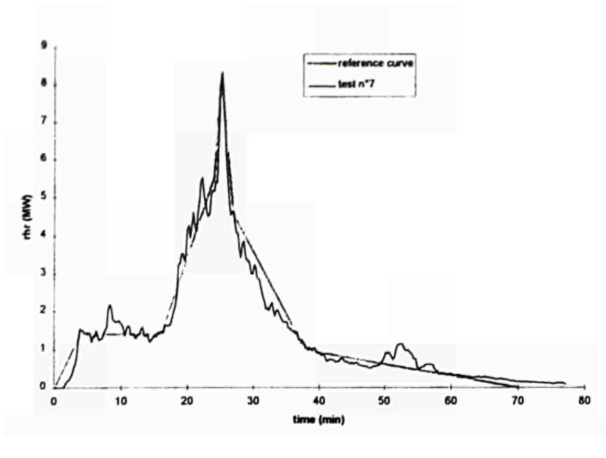


Fig. 1 - Reference curve and real values obtained in the test number 7 made by CTICM (Schleich *et al.*, 2002).

Considering the reference curve showed in Figure 1, one can observe that this curve is formed by seven lines. These lines are formed by six reference values that represent the time instants 4, 16, 24, 25, 27 and 38. The reference values used to make the reference curve are presented in Table 1. Relating the energy released by the class-3 vehicle with the theoretical energy of other car classes, it is possible to find the reference curve for all classes of vehicles, see Table 2.

Table 1 - Reference values of the heat release rate to the class-3 car (D. Joyeux *et al*., 2002).

Time [min]	HRR [MW]
0	0
4	1,4
16	1,4
24	5,5
25	8,3
27	4,5
38	1
70	0

Table 2 - Theoretical energy to all car class

Car Class	Theoretical Energy [MJ]
1	6000
2	7500
3	9500
4	12000
5	12000

Other experiments follow the research, such as in 1985 in Australia (I.D. BENNETTS *et al*., 1987) and more recently in Japan 2000 (T. Hirashima *et al*., 2003). The most recent tests demonstrate an increase in the temperature level of the structural elements, due to a mix of new materials used in the construction of vehicles that present more combustible materials, causing a hotter flame.

MATERIALS AND METHODS

The gas temperature near a principal structural element of an open car park structure and the steel temperature in the beam need to be calculated. The simple calculation method (Heskestad and Hasemi methods) is used to find the gas temperature and is also compared with the results found in Elefir-EN and CFD simulation.

Five section factors for the main element of the structure were selected, two fire compartments and 6 relative positions of the vehicle with respect to the main element of the structure (beam) were considered. All these fire scenarios were used to compare the maximum temperature in the gas and in the steel, resulting in a comparison of the efficiency of each method.

The fire compartment was assumed to be made of a composite structure, using a steel frame and a concrete slab. The main dimension are: width equal to 10m and height equal to 3 and 5 m. The fire source is considered equal to a circle with 2m of diameter, located 0.3m above the ground. The fire scenario is represented in Figure 2, where H is equal to 3m for the compartment of fire 1 and 5m for the compartment of fire 2.

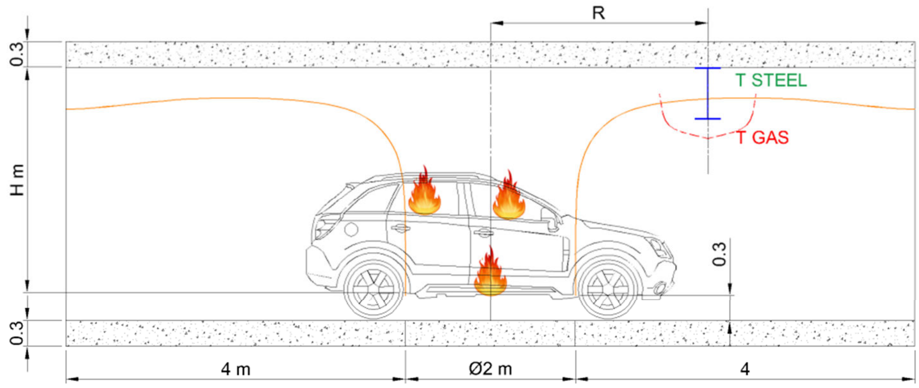


Fig. 2 - Fire model and compartment.

Considering the simple calculation method, it is worth mentioning that the area of the fire increases during the fire event, reaching is maximum value for time equal to 25 min. After that time, the area was kept constant until the end of the fire. Figure 3 represents the variation of the diameter of the fire source, during all the fire events under consideration.

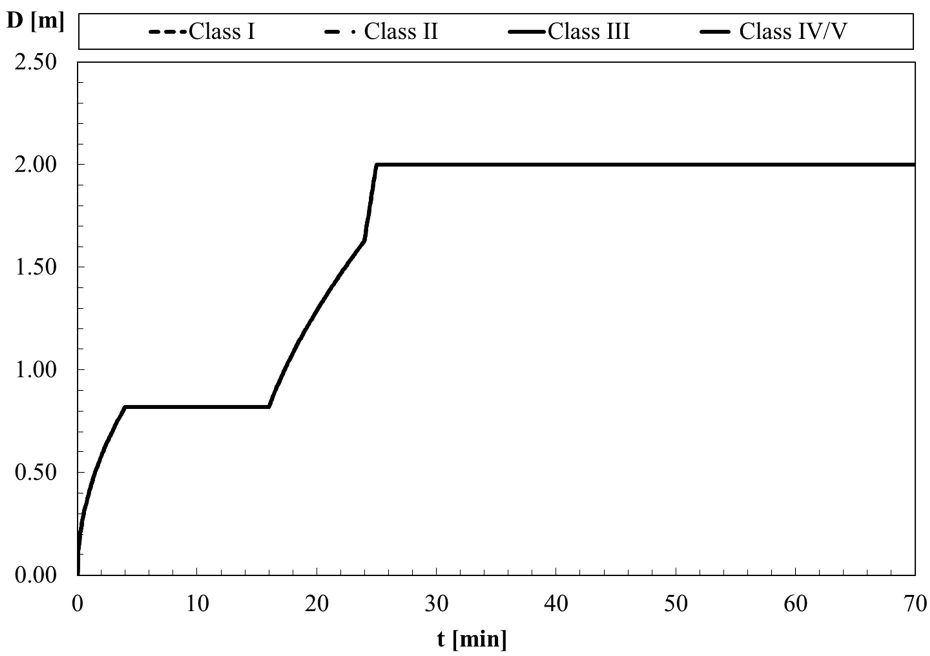


Fig. 3 - Diameter of fire varying with the time of fire.

The simple calculation method mixes the formulae of two methods, Heskestad and Hasemi. The difference between these methods is: Heskestad method is used when the flame is not impacting the ceiling, see Figure 4, and Hasemi method is used when the flame touches the ceiling, see Figure 5. The Heskestad method enables the calculation of the flame temperature, while the Hasemi method enables the calculation of the heat flux received by the surface of the structural member due to the fire source, being only valid when the diameter of the fire source, D, is not longer than 10m and the heat release rate, Q, is not higher than 50MW.

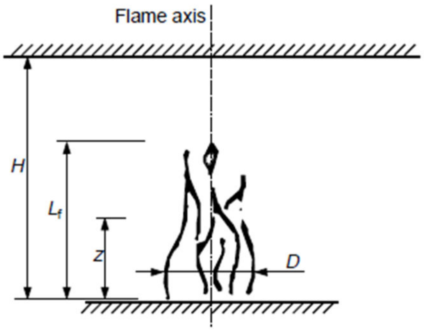


Fig. 4 - Model of a localized fire with the flames does not touching the ceiling (CEN, 2002).

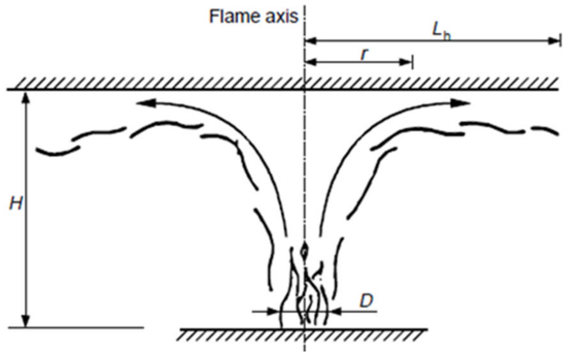


Fig. 5 - Model of a localized fire with the flames touching the ceiling (CEN, 2002).

The length of the flames, L_f can be evaluated according to Eq. 1, where D is the diameter of fire and Q is the HRR of cars. Figure 6 shows the length of the flames when the source is on the ground. Depending on the fire event, the fire source can be located above the ground, and in that case the height, H, has to be considered as the vertical distance from the fire source to the ceiling.

$$L_f = -1{,}02 * D + 0{,}0148 * Q^{\frac{2}{5}} \qquad \text{(Eq. 1)}$$

Figure 6 represents the length of the flame for all the fire events and scenarios (H=2.7m and H=4.7m) during time. This plot allows to identify when the method of analysis requires to be changed, from Heskestad to Hasemi and back again to Heskestad.

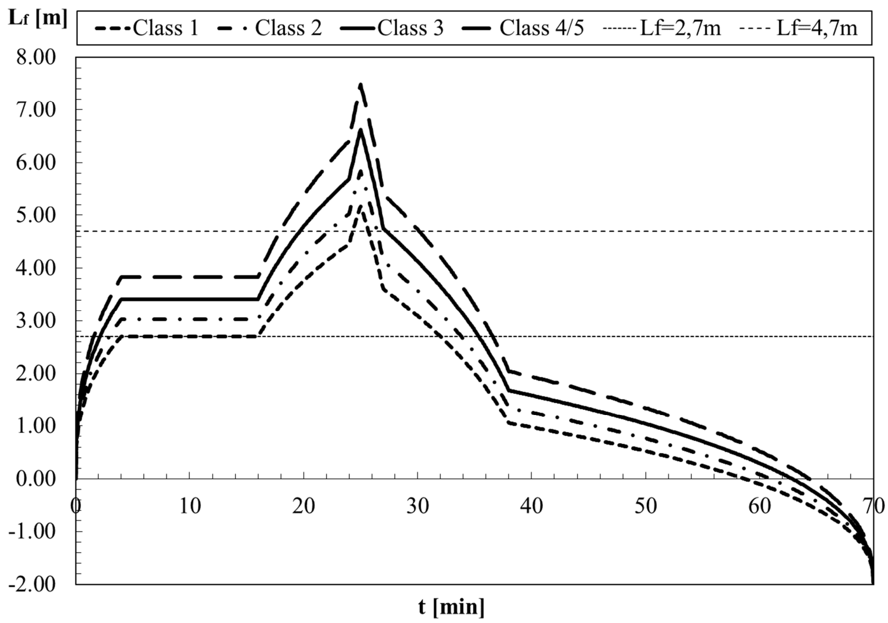


Fig. 6 - Length of the flame for all car classes.

Table and Table present the time domain where each method should be applied.

Table 3 - Time domain for each fire event and fire scenario 1.

Vehicles classes	Methods (time in minutes)		
	Heskestad	Hasemi	Heskestad
Class 1	0,00 ≤ t < 4,00	4,00 ≤ t ≤ 32,00	32,00 < t ≤ 70,00
Class 2	0,00 ≤ t < 3,00	3,00 ≤ t ≤ 33,83	33,83 < t ≤ 70,00
Class 3	0,00 ≤ t < 2,17	2,17 ≤ t ≤ 35,33	35,33 < t ≤ 70,00
Class 4/5	0,00 ≤ t < 1,67	1,67 ≤ t ≤ 36,50	36,50 < t ≤ 70,00

Table 4 - Time domain for each fire event and fire scenario 2.

Vehicles classes	Methods (time in minutes)		
	Heskestad	Hasemi	Heskestad
Class 1	0,00 ≤ t < 24,33	24,33 ≤ t ≤ 25,67	25,67 < t ≤ 70,00
Class 2	0,00 ≤ t < 22,25	22,25 ≤ t ≤ 26,42	26,42 < t ≤ 70,00
Class 3	0,00 ≤ t < 19,75	19,75 ≤ t ≤ 27,17	27,17 < t ≤ 70,00
Class 4/5	0,00 ≤ t < 18,00	18,00 ≤ t ≤ 30,08	30,08 < t ≤ 70,00

The temperature of the gas can be calculated in the proximity of the main structural element (beam), using the formulae of Annex C in Eurocode 1 (CEN, 2002). The temperature of the steel element can be found, using the lumped thermal model presented in Eurocode 3 (CEN, 2005), for an equivalent uniform temperature distribution in the cross-section.

The gas temperature near the main structural steel element (beam), when using the Heskestad's method, is calculated by Eq. 2, being Q_c equal to the convective part of the HRR of the vehicle, that was assumed as being 80% of the HRR. The temperature of the flame depends on the length of the flame, z, and also on the virtual origin of the fire z_0, calculated using the Eq. 3.

$$T(z) = 20 + 0,25 * {Q_c}^{2/3} * (z - z_0)^{-5/3} \leq 900 \qquad \text{(Eq. 2)}$$

$$z_0 = -1,02 * D + 0,00524 * Q^{2/5} \qquad \text{(Eq. 3)}$$

The gas temperature near the main structural steel element (beam), when using the Hasemi method is calculated by an iterative procedure, using the Newton Raphson method. This iterative procedure is required because the net heat flux has to be equal to zero, according to Eq. 4. This equation shows that when the impinging heat flux is constant, after long period, the temperature of the member tends to an equilibrium temperature with the gas temperature, and the net heat flux vanish.

$$\dot{h}_{net} = \dot{h} - \alpha_c * (T_m - 20) - \phi * \varepsilon_m * \varepsilon_f * \sigma * [(T_m + 273)^4 - 293^4] = 0 \qquad \text{(Eq. 4)}$$

The simple and the advanced calculation method used nonlinear properties for both, solid and fluid materials, as represented in Figure 7 and Figure 8.

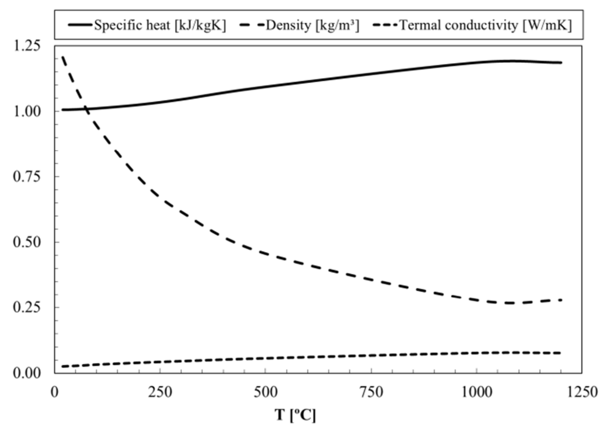


Fig. 7 - Properties of the air.

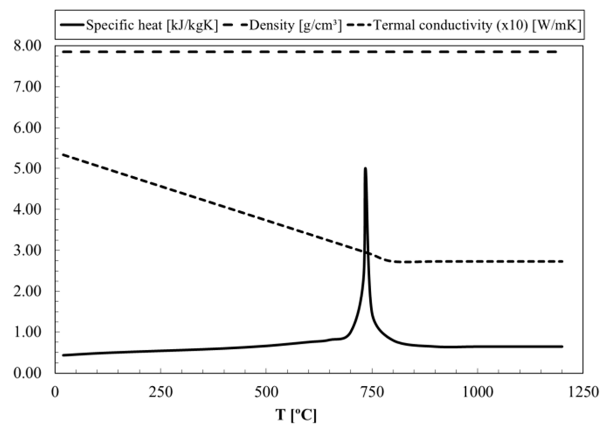


Fig. 8 - Properties of the steel.

The software Ansys was used to carry out the CFD simulation, running the application Workbench, using FLUENT. The model was defined for both parts (solid and fluid), as represented in Figure 9. The mesh uses a grid with 5.1mm in the edges and 50mm in the faces, see Figure 10. The boundary conditions are represented in Figure 11, assuming the inlet velocity type applied to the fire source, taking into account the momentum (velocity of the gas) and thermal conditions of the inlet (temperature of the gas). The other boundary conditions are: the pressure outlet type, where the pressure is specified and the temperature is also specified (300 K); the wall type applied to the concrete region, where the adiabatic thermal condition is applied and finally the stationary type applied to the fluid region bellow the fire source. The initial temperature of 300K was applied to all the regions.

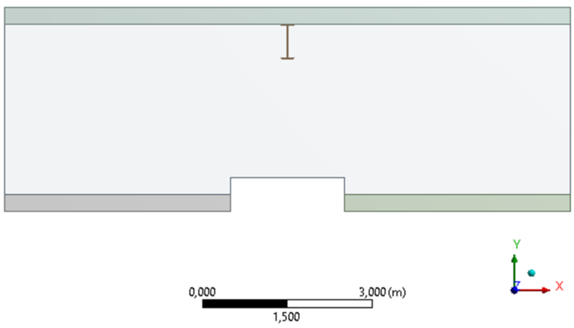


Fig. 9 - The geometry used in the CFD simulation corresponding for compartment of fire 1.

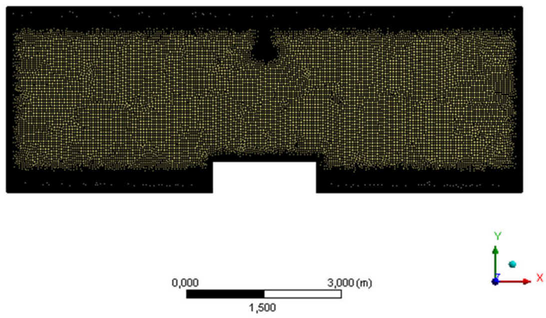


Fig. 10 - The mesh used in the CFD simulation corresponding for compartment of fire 1.

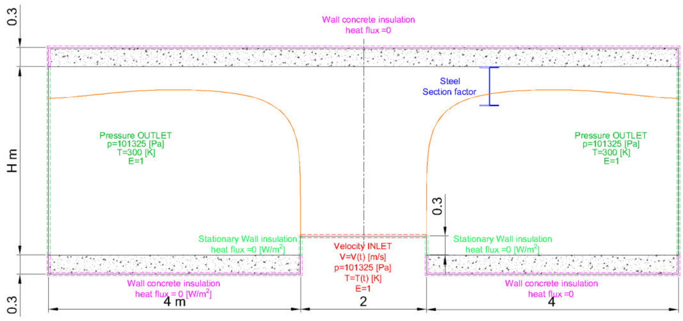


Fig. 11 - Boundary conditions used for CFD simulation.

The software Elefir-EN was also used to find the maximum temperature in the air and in the steel beam. This software evaluates the fire resistance of carbon and stainless-steel members, according to EN1991-1-2 (CEN, 2002) and EN1993-1-2 (CEN, 2005). According to the fire scenario, the calculations were developed in time domain, using the section factors for each beam type, see Table 5, considering the option with three sides of the beam exposed to the fire with no protection. The heating curve followed the HRR for each fire event, using the maximum diameter of the fire equal to 2m. This method considers the use of the Hasemi method, during all the fire duration, whenever the flame is expected to reach the ceiling.

RESULTS AND DISCUSSIONS

The maximum gas temperature was calculated around the structural element. This maximum value corresponds to the time when the maximum HRR is released (time=25 minutes). The results were determined for the each Compartment (C1 and C2), for the all fire events (all car classes) and for the fire scenario of R=0, see Figure 12. The maximum temperature seems to increase with the fire load (car class). The maximum gas temperature is higher for the compartment 1, which reveals the effect of the height of the compartment. A CFD simulation was also developed for both compartments and for all the cross section under evaluation, but for only one fire event (fire of class 3) and for the fire scenario (R=0). This temperature was determined from the nodal temperatures around the main structural elements, just beneath the lower flange of the beam. This temperature is the average result obtained from all shape sections used to represent the main structural element.

The maximum temperature of the steel beam was also determined using the same simple solution methods for R=0. This maximum value is reached after the reference time of 25 minutes. This value is depicted in Figure 13 for a specific steel section (IPE600 with section factor of 115 m^{-1}) and for all car classes. The results for both simple calculation methods agree well for the fire scenario in compartment 1, but seems to be diverge for the fire scenario of compartment 2 (higher ceiling position). In any case, the maximum temperature of the steel element increases with the fire load.

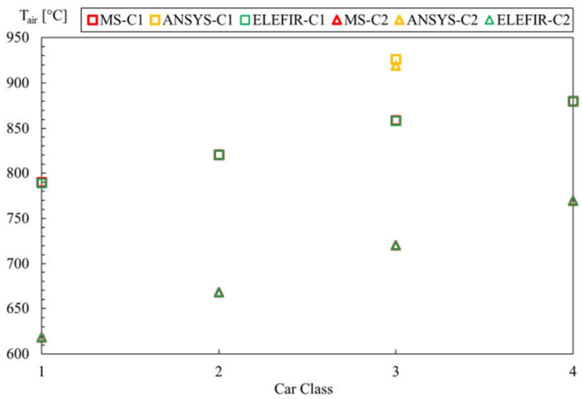


Fig. 12 - Maximum gas temperature: simple simple calculation method (MS), ANSYS and Elefir-EN for both compartments C1and C2.

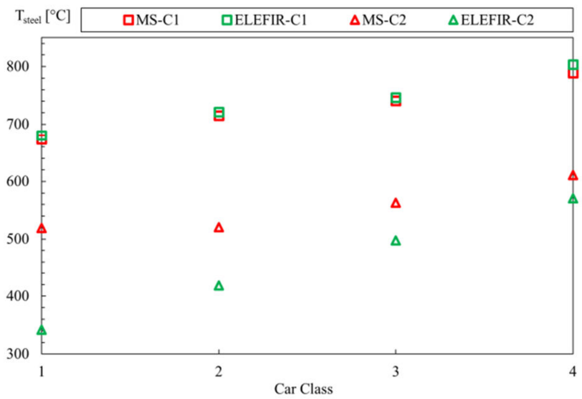


Fig. 13 - Maximum steel temperature: Simple calculation method (MS) and Elefir-EN for both compartments C1, C2.

Figure 14 represents the maximum temperature of the gas for both compartments and for different radial positions. These maximum temperatures are reached for time equal to 25 minutes. The maximum temperature of the gas decreases with the distance from the centre line of the flame. Two simple methods were compared (Elefir-EN and the simple calculation method developed herein using mixed formulation). The results agree very well between both methods. The maximum temperature of the gas decreases with the radial distance to the centre line of the plume.

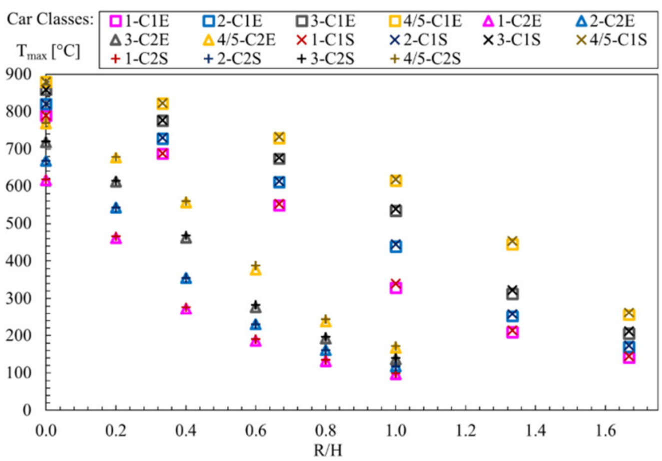


Fig. 14 - Maximum temperature of the gas, according to the car class and relative position of the beam, for both compartments C1 and C2: S - simple calculation method; E - Elefir-EN.

Figure 15 presents the maximum temperature of the steel IPE600 beam (section factor $115\ m^{-1}$), for all different fire events (car classes) and discrete relative position of the car with respect to the main element of the structure, considering both compartments, C1 and C2. The results were obtained by the simple calculation method and by Elefir-EN. The results agree well for the smallest compartment C1 and diverge for the highest fire compartment. This difference may be explained by the fact of using mixed formulation. The compartment C2 requires the use of Heskestad formulation during most of the time of the fire event, while Elefir-EN use Hasemi method from the beginning of the fire until the end.

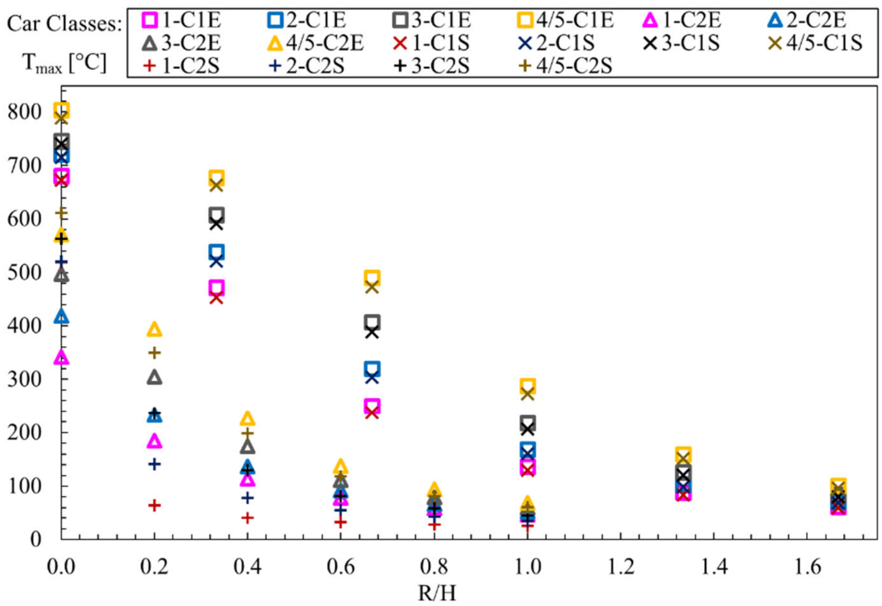


Fig. 15 - Maximum temperatures of the steel, according the car class and relative position of the beam for both compartments of fire C1 and C2: S - simple calculation method; E - Elefir-EN.

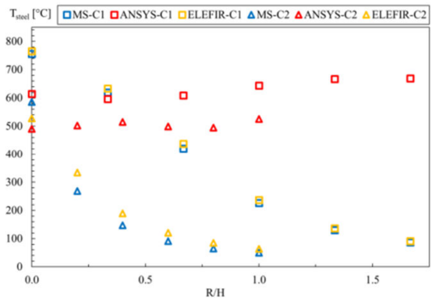
The main characteristics of the steel beam are presented in Table 5. The section factors were determined for the case of three exposed sides, assuming the protection of the upper flange that is in contact with the concrete slab.

Figure 16 below presents the results for the maximum temperature of the steel beam, when considering the fire event of class 3 and different fire scenarios. The finite volume method was also used to determine the average temperature of the steel beam, using seven point distributed over the flanges and web. The maximum average temperature of the steel beam (ANSYS) agrees well with the results obtained by the simple calculation methods when the beam is next to the fire plume. When the relative distance between the fire plume and the steel beam increases, the maximum average temperature tends to increase, due to the confinement of the heat flow by the beam geometry. The maximum average temperature of the beam also decreases with the height of the compartment, as expected.

The results for the maximum temperature of the steel agree very well for the compartment C1, but the difference between both methods increases with the dimension of the height of the compartment C2. Both simple calculation methods (herein developed and Elefir-EN) assume the existence of unconfined ceiling, which is not exactly the case when dealing with such types of geometries.

Table 5 - Shape of sections used and their principal dimensions.

Bean	A_m/V [m^{-1}]	$[A_m/V]_b$ [m^{-1}]	h [mm]	b [mm]	t_f [mm]	t_w [mm]
IPE 450	143	110	450	190	14.6	9.4
IPE 500	134	104	500	200	16	10.2
IPE 600	115	91	600	220	19	12
HE 600 A	89	65	590	300	25	13
HE 650 A	87	65	640	300	26	13.5



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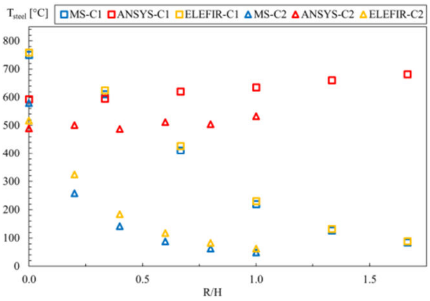

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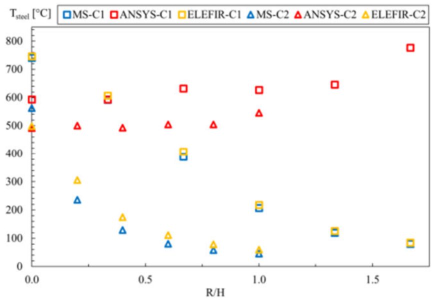

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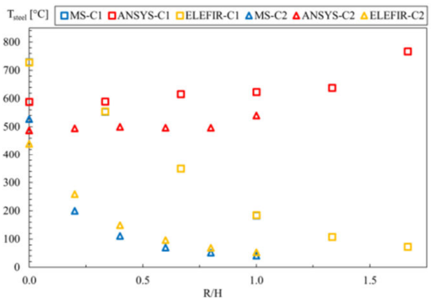

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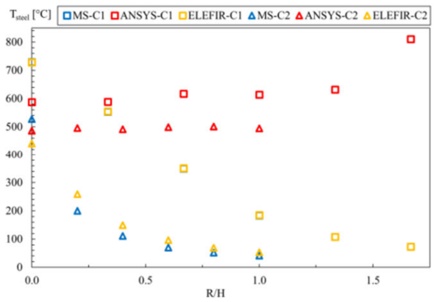
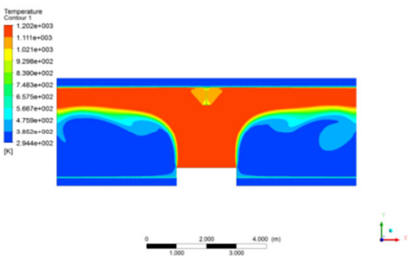
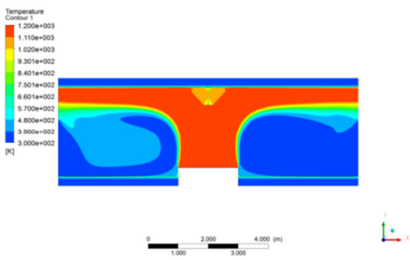
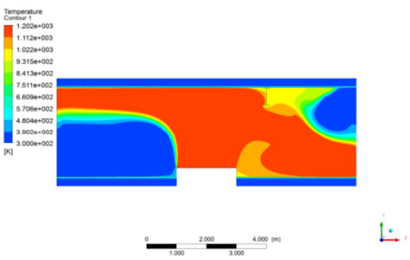


SF = 87

Fig. 16 - Maximum temperatures in the steel beam, considering the fire event (class 3) in both compartments C1 and C2. Solution methods: - simple calc. methods (MS and Elefir-EN), advanced calc. method (ANSYS).


R = 0, t = 25 minutes.


R = 0, t = 38 minutes.


R = 2, t = 25 minutes.

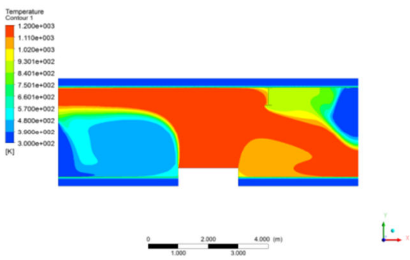
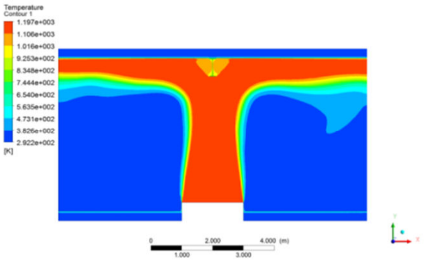

R = 2, t = 38 minutes.

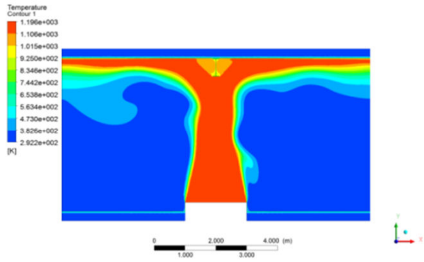
Fig. 17 - Contour of the global temperature for the compartment C1 considering the steel beam IPE600 for two relative positions of a class 3 fire event.

The confinement of the hot layer near the steel element justifies the increase of the temperature of the steel element. This fact can be observed in Figure 17 for the case of IPE600 steel beam in the compartment C1. This effect was identified for all the cross section types. The temperature field is depicted for two different times (25 and 38 minutes) during the fire event of a class 3 vehicle and for a fire scenario with R=0 and R=2m distance between the fire source and the beam element.

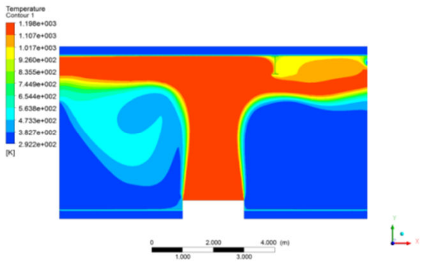
Figure 18 represents the fire effect of a class 3 vehicle in the compartment C2, for two different fire scenarios (R=0 and R=2 m). The temperature field is affected by the confinement to the heat flow from the steel beam. The temperature field is almost symmetric for the case of R=0, but asymmetric for any other relative position. This fact justifies the higher temperature level for all different relative position (R=1, 2, 3, 4 and 5).



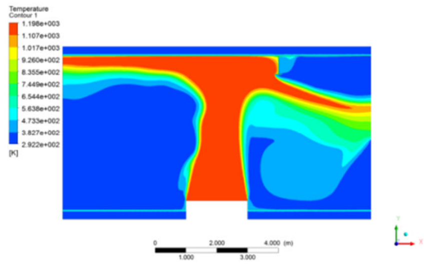
R = 0, t = 25 minutes.



R = 0, t = 38 minutes.



R = 2, t = 25 minutes.



R = 2, t = 38 minutes.

Fig. 18 - Contour of the global temperature for the compartment C2 considering the steel beam IPE600 for two relative positions of a class 3 fire event.

CONCLUSIONS

Sixty different fire CFD simulations were developed to analyse the effect of the car fire into the gas temperature and into the temperature of the main structural element of the structure, using one fire event (class 3). Two hundred and forty different scenarios were study by the simple calculation methods. Depending on the method used to find the maximum temperature of the steel and maximum temperature of the gas, different results are expected. The simple calculation method does not take into consideration the confinement of the heat flow. This confinement will affect the maximum temperature of the steel element, as demonstrated by the results of the advanced calculation method.

The simple calculation method presented herein uses a mixed formulation between the Heskestad and Hasemi formulae. The Elefir-EN uses only one formulae, depending on the fact if the length of the flame is impacting the ceiling during the fire event. Both simple calculation methods agree for compartments with small height. When the height of the compartment increases, the results do not agree due to the fact that mixed formulation should be used.

The simple calculation method will provide good approximation to real fire scenarios, whenever the relative distance between the fire source and the steel element is zero. For the other relative positions (fire scenarios with R=1, 2, 3, 4 and 5) the temperature of the steel element can be under predicted.

REFERENCES

[1] BRE, "Fire Spread in Car Parks”. Building Research Establishment, Eland House Bressenden Place London, United Kingdom, 2010.

[2] CEN. EN 1991-1-2 - Eurocode 1: Actions on structures - Part 1-2: General actions - Actions on structures exposed to fire. Brussels: CEN - European Committee for Standardization, pp. 59. 2002.

[3] CEN. EN 1993-1-2 - Eurocode 3: Design of steel structures - Part 1-2: General rules - Structural fire design. Brussels: CEN - European Committee for Standardization, pp. 78. 2005.

[4] I.D. Bennetts, D.J. Proe, R.R. Lewine and I.R. Thomas: Fire and Unprotected Steel in Closed Car Parks. BHP Melbourne Research Laboratories Report Number MRL/PS98/87/001, August 1987.

[5] D. Joyeux, J. Kruppa, L.-G. Cajot, J.-B. Schleich, P. van de Leur, L. Twilt, “Demonstration of real fire tests in car parks and high buildings”, EU publications, technical steel research, ISBN 92-894-4234-4, Luxembourg, 2002, p. 170.

[6] E. G. Butcher, G. J. Langdon-Thomas, G. K. Bedford, “Fire and Car-Park Buildings”, London, H.M.S.O, Joint Fire Research Organization. Fire note; no. 10, 1968, p. 24.

[7] ECCS, “Fire Safety in Open Car Parks”, Modern Fire Engineering, Technical Committee 3, nº75, European Convention for Constructional Steelwork: Brussels, Belgium, 1993, p. 90.

[8] Schleich, Jean-Baptiste; Cajot, Louis-Guy; Pierre, M.; Brasseur, Marc; Franssen, Jean-Marc; kruppa, Joël; Joyeux, Daniel; Twilt, Leen; Van Oerle, J.; Aurtenetxe, Gartze; “Development of Design Rules for Steel Structures Subjected to Natural Fires in Closed Car Parks”, Technical Steel Research, EUR 18867, European Commission: Brussels, Belgium, 2002, p. 154.

[9] Feijter and Breunese, “Investigation of the fire at the car park Lloydstraat, Rotterdam”, EFECTIS Nederlan Report - EFECTIS-R0894 (E), December, pp. 50, 2007.

[10] Franssen, J.-M. and Vila Real, P. (2016) The Computer Program "ELEFIR-EN", in Fire Design of Steel Structures: Eurocode 1-1-2: General Actions - Actions on Structures Exposed to Fire / Eurocode 3: Design of Steel Structures, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany. doi: 10.1002/9783433607008.

[12] Gewain, R. G., “Fire experience and fire tests in automobile parking structures”, Fire Journal, pp. 50-54, July 1973.

[13] Li Yuguang, Spearpoint M J. Analysis of vehicle fire statistics in New Zealand parking buildings. Fire Technology, Vol. 43, No. 2, 2007, pp.93-106.

[14] T. Hirashima, Y. Wang, H. Uesugi, T. Kitano, T. Ave, Large Scale Fire Tests of A 4-story Type Car Park Part 2 Analysis Of The Thermal Stresses And Deflections. Fire Safety Science 7- proceedings of the 7th international symposium - IAFSS, ISBN 0-9545348-0-8, doi:10.3801/IAFSS.FSS.7-655, pp. 655-666, 2003.