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Methodology and application to compartment fires

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Abstract

Purpose – This paper aims to present the assumptions and the issues that arise when developing an integrated modelling methodology between a computational fluid dynamics (CFD) software applied to compartment fires and a finite element (FE) software applied to structural systems.

Design/methodology/approach – Particular emphasis is given to the weak coupling approach developed between the CFD code fire dynamics simulator (FDS) and the FE software SAFIR. Then, to show the potential benefits of such a methodology, a multi-storey steel-concrete composite open car park was considered.

Findings – Results show that the FDS–SAFIR coupling allows overcoming shortcomings of simplified models by performing the thermal analysis in the structural elements based on a more advanced modelling of the fire development, whereas it appears that the Hasemi model is more conservative in terms of thermal action.

Originality/value – A typical design approach using the Hasemi model is compared with a more advanced analysis that relies on the proposed FDS–SAFIR coupling.

Keywords Steel structures, CFD-FE coupling, Weak coupling, Open car parks, Fire behaviour

Paper type Research paper

1. Introduction

To obtain the thermo-mechanical response of structures exposed to fire, integrated modelling methodologies applied to compartment fires would represent a powerful tool to widen the application field of structural fire safety engineering by overcoming limitations associated with simplified procedures. For instance, the simplified Hasemi localised fire model (Pchelintsev *et al.*, 1997) and incorporated in EN1991-1-2 (2004) is

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suitable for analysing the fire performance of open car parks. It provides the heat flux at the ceiling level, thus being appropriate for beams and slab. However, simplified models that provide information about the thermal action along the height of a column owing to localised fires are not yet available, and cautionary assumptions are usually taken. As a result, this may lead to a conservative fire design. To overcome this issue, computational fluid dynamics (CFD)-advanced fire models that are capable of an accurate modelling, both in time and in space, of the fire development represent a tempting alternative. The exploitation of integrated modelling strategies based on the coupling between CFD and finite element (FE) programmes are already used in medicine, e.g. for modelling the blood flow in arteries (Zhao *et al.*, 1998). However, in the fire engineering field, very few applications are available, and the ones that have been developed are often limited to specific software pairs (Fellinger *et al.*, 2004). The Research Fund of Coal and Steel (RFCS) project called FIRESTRUCT (Welch *et al.*, 2008) dealt with this issue by studying different coupling approaches and using different software. In this paper, the weak coupling approach developed between the CFD software fire dynamics simulator (FDS) and the FE software SAFIR is described, but it has to be underlined that the methodology could be used with any CFD and any FE software. The work is finally enriched by reporting on the comparison between the fire performance of a steel-concrete composite open car park analysed by applying first the simplified Hasemi model and then the FDS–SAFIR integrated methodology.

2. Overview on integrated computational fluid dynamics–finite element methodology

2.1 Compartment fires: problem definition

Three problems have to be solved when modelling the behaviour of a structure subjected to a compartment fire, each of them being governed by a different physical phenomenon and, hence, by different equations:

(1) the temperature development in the compartment;

(2) the thermal response of the structure; and

(3) the mechanical response of the structure.

The fire development analysis yields the temperatures of gases and the radiative and mass flows in the compartment. By means of the thermal analysis, the temperatures in the structural elements are obtained. The mechanical response provides the behaviour of the structural system, i.e. stresses, deflections, etc. Several differences distinguish these three processes. First, the spatial scale of the thermal analysis in the structure is an order of magnitude smaller than the spatial scale used for the development of the compartment temperature and the mechanical response. Second, the time scale may be different to solve the problem within CFD and FE analysis. Third, as regards to the temperature development in the compartment and the mechanical response, a three-dimensional (3D) analysis is generally required, whereas for the thermal analysis, a two-dimensional (2D) analysis is usually sufficient. Thus, some issues arise when an integrated modelling methodology CFD-FE is to be used to tackle the whole problem. It is natural to assign the task of performing the analysis of the compartment fire development to the CFD model and the mechanical response to the FE model, but it is not so straightforward to decide where to carry out the thermal analysis in the structural elements. Both software may be exploited to fulfil the task. The advantages to perform the thermal analysis in the CFD model are, first, to get direct information about the temperature development in the compartment and, second, to take into account the energy absorbed by the structure. On the other hand, if the thermal analysis in the structure is carried out in the FE model, all necessary data are directly available by the FE code to determine the mechanical response. Moreover, the choice also depends on how the CFD and the FE codes can accurately solve the heat conduction equation with respect to the particular problem under study. Whatever the choice, the difficulties arise when data have to be exchanged between the two software because of different scales in space and time. Moreover, if the thermal analysis is performed in the CFD software, the compartment model must include the structure as well. The latter aspect is not desirable, as described later on.

2.2 Levels of coupling

From the description of the problem, it is clear that coupling CFD to FE is far from straightforward and that the selected level of coupling influences the complexity of the model. In reality, all three problems are mutually coupled – full coupling or two-way coupling – as shown in Figure 1. Table I reports on the main phenomena involved in a compartment fire along with their mutual interactions, and it intends to highlight the large amount of interactions that are extremely difficult to deal comprehensively with (Welch *et al.*, 2008).

The implementation of full coupling allows taking into account all phenomena, and it guarantees a general field of application as well as a solution that tends to be exact. An example of full coupling is the interface developed between VESTA, a CFD software, and DIANA, an FE software developed by TNO in The Netherlands (Welch *et al.*, 2008). However, an integrated methodology that relies on full coupling is very complex to achieve. The first reason lies in various uncertainties that question the so-called exactness of the method. For instance, heat leakage through cracks in concrete (3 to 1 and 3 to 2) or gypsum plaster board enclosures are still very difficult to quantify because they do not follow deterministic rules. Moreover, from a programming point of view, the code of the selected CFD software and the code of the FE programme have to be modified so that they can communicate for the exchange of data, but it means that in most cases, the integrated methodology will not work if another CFD or another FE software is used. This is a clear drawback in terms of versatility and flexibility. Furthermore, for each simulation, a CFD specialist as well as an FE specialist are required, as the two models cannot be run independently. Other typical issues that may occur in the design practice are related to possible modifications that the structure undergoes during the construction process as well as modifications of the structure that have to be applied because of an unsatisfactory behaviour in terms of fire safety requirements. As the structural elements must be included in the CFD model, any changes in the structural

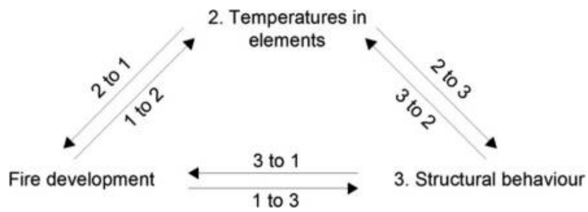


Figure 1. Full coupling between the main phenomena involved in a compartment fire

Phenomenon	Coupling 1-2	2-3	3-1	1-3	3-2	2-1
Fire						
Convection and radiation to structural elements	x					
Velocity of gases						
Convection factors	x					
Dynamic pressure on walls and windows				x		
Pressure						
Static pressure on walls and windows				x		
Temperature in materials						
Thermal elongation of elements		x				
Degradation of mechanical properties		x				
Absorption of energy from the compartment						x
Plasticity and cracking in elements						
Generation of heat or heat leakage			x		x	
Modification of material thermal properties					x	
Displacements in elements						
Modification of the gas flow			x			
Modification of the element thermal exposure					x	

Table I. Mutual interactions between main phenomena involved in a compartment fire

system imply that the whole analysis must be re-run, entailing large time-consuming analyses.

From these considerations, a simplified approach, the so-called weak coupling, is proposed to overcome the major aforementioned issues with the aim to be applicable to a wide number of likely-to-occur scenarios in compartment fires.

3. Proposed weak coupling methodology

3.1 Assumptions and general remarks

In the proposed weak coupling (or one-way) approach, the mutual interactions are discarded, as illustrated in Figure 2. For weak coupling, we mean that the degree of interdependence, from a computer programming point of view, between the CFD software and the FE software is low, and the multi physics problem is treated through sequential analyses, i.e. the fire development analysis is performed first, then the thermal analysis in the structural elements and finally the mechanical analysis of the structure that does not consequently influence the temperature field in the structural elements. As a result, the CFD software models the fire development, while the FE

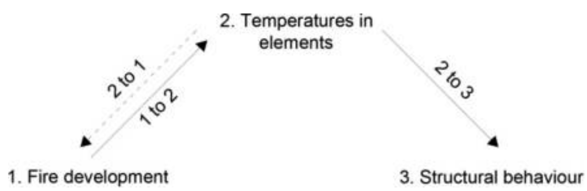


Figure 2. Weak coupling between the main phenomena involved in a compartment fire

programme performs the thermal and the mechanical analyses. The fire development is calculated independently of the thermal response in the linear elements of the structure such as steel columns, beams or truss girders. If part of the structure is made of planar elements that also constitute boundaries of the compartment such as concrete walls or slabs, they must be modelled, perhaps with some degrees of approximation (Cooper and Franssen, 1999), in the fire development analysis. The FE software will nevertheless compute the detailed temperature field in these structural elements subsequently. Therefore, if p variations of the structure must be evaluated under q fire scenarios, only q CFD analyses have to be performed, compared to $p \cdot q$ coupled analyses in a full coupling approach.

In this strategy, the thermal response of the structure represents the input of the mechanical analysis. Hence, it can be performed first, over the whole time domain, and then the resulting data are transferred at the beginning of the mechanical analysis, which is performed subsequently.

Nonetheless, these simplifications imply some limitations:

- the dimensions of the structural elements and their displacements perpendicular to their longitudinal axis shall be small compared to the dimensions of the compartment to not significantly influence the temperatures and the air flow around the elements. According to this assumption, a series of 2D thermal analyses rather than a unique 3D thermal analysis is made on the structural elements because the transverse dimension of the section of the elements is small with respect to the longitudinal dimensions. For instance, a 1×1 m concrete columns in a 100 m^2 compartment should clearly be considered in the CFD model. Very flexible structures that are sensitive to air pressure variation are also not suitable for such an integrated modelling methodology because the effects of air pressure variation on the displacements of the structure cannot be neglected. Floor systems designed according to the tensile membrane action also exhibit very large displacements during the fire and may not comply with this requirement if the floor-to-ceiling distance is small compared to the displacement.
- It is possible, for each 2D thermal analysis, to consider the boundary conditions at the surface of the section at the same point, namely, the point of the section located on the node line of the beam element, for example, the centre of gravity of the section. The influence of the distance from the node line of the section to the border of the section is neglected. This is consistent with the fact that the structure is not present in the CFD analysis because the size of the section perpendicular to the longitudinal axis is negligible with respect to the size of the compartment; the distance from the centre of the section to the border (approximately [half] of the size of the section) is then also negligible.
- Generally, in the CFD model, the dimensions of a rectangular compartment correspond to the clear distances between opposite walls. However, in the FE model, a slab is generally modelled in correspondence to its centreline as illustrated in Figure 3. Thus, the slab would fall outside the CFD domain, and assumptions have to be made to determine thermal information at the slab centreline.
- As the structure is not included in the CFD model, the effect of shielding from any structural elements on others cannot be detected. For example, if a series of closely

spaced columns one behind the other is impinged by a radiant flux with direction parallel to the column series, the magnitude of the flux received by each column will only depend on the distance of each single column from the fire source, and no effects of shielding will be taken into account on the columns behind the first one.

- Irrigated structures in which water is circulating to keep the temperature of the structure within acceptable limits cannot be neglected because they may contribute in evacuating important amount of energy from the compartment.

This procedure is thus particularly well adapted for metallic structures made of relatively thin members (frame, truss girders) and located in large compartments (railway or airport entrance halls, exhibition halls) where a localised fire is developing, and simplified thermal models, such as those proposed in EN1991-1-2 (2004), cannot be used because the geometry of the compartment is too complex or the position of the structure in the compartment with respect to the position of the fire is not within the field of application of a simplified model.

3.2 How it works

In this section, the practical issues that have to be solved when implementing such an approach are presented. The programmes used in this paper to illustrate the proposed integrated methodology are FDS (McGrattan *et al.*, 2007) and SAFIR (Franssen, 2005). The main steps needed to couple CFD and FE models are as follows:

(1) At the end of the CFD analysis, a transfer file containing all information regarding the state in the compartment, i.e. temperature of gas and radiant intensities from various directions, is produced. These quantities can be provided at each grid point of the CFD model (the grid that was required to allow a precise determination of the solution) or instead at grid points representing only the part of the compartment where the structure to be analysed is located. Convection factors are also transferred, but a uniform value introduced by the user before performing the thermal analysis is instead used; typically, a value of 35 W/m^2K as suggested in EN1991-1-2 (2004). The format of the transfer file should be as standardised as possible so that in a future perspective, it could be used for any choice of CFD and FE software. Hence, type of file (e.g. ASCII),

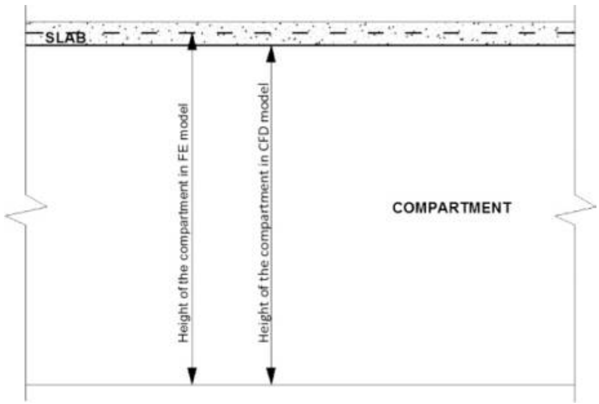


Figure 3.
Different compartment dimensions for the CFD and the FE model

syntax, type of reference system, type and format of numbers, presence of blank lines, etc., have to be clearly stated. Such a format has been proposed within the FIRESTRUCT project and can be obtained from the authors. Radiant intensities from different directions are preferred to impinging radiant fluxes on predefined surfaces because the structural elements are not included in the CFD model, and thus no information is available at that stage about the shape of the cross-sections. The fluxes at the surface of the structural elements will be computed within the FE software by integrating the radiant intensities, which allow taking into account possible shadow effects in concave sections.

(2) A 3D Cartesian spatial interpolation is needed because the points of the structure where the information is needed (called here "the structural points") generally do not coincide with the points of the CFD grid where the information is provided. If any structural points fall outside the CFD domain for the reason described in Section 3.1, they are moved to the closest boundary of the CFD domain where the Cartesian interpolation can be made, namely, the boundary corresponding to the centre of the outermost cells because FDS provides the information at the centre of cells (Figure 4). A trilinear interpolation algorithm was successfully implemented in SAFIR to fulfill the 3D Cartesian interpolation.

(3) An interpolation in the time domain is also necessary because the time steps of the CFD analysis and the time steps of the thermal analysis may not be the same. In this case, a simple linear interpolation was exploited.

(4) To get the impinging fluxes q on the surface of the structural elements, a spherical numerical integration of radiant intensities I has to be performed. A numerical integration can be performed according to equation:

$$q = \sum_{i=1}^{n} I_i \cos\theta_i \omega_i$$

where n is the number of intensities considered for the integration, ω_{i} is the solid angle associated to the direction i, θ_i is the angle between the direction of the radiant intensity i and the normal to the surface, while I_i is the radiant intensity associated with the i-direction.

The directions of the intensities which are required to perform the spherical integration are generally not the directions in which the intensities are given by the CFD analysis. This is particularly the case if the structural elements are not parallel to the axes of the system of coordinates used in the CFD analysis (e.g. for diagonals in a truss girder). A spherical interpolation is thus performed to obtain the radiant intensities in the directions required by the numerical integration. Rotations of local axes are required

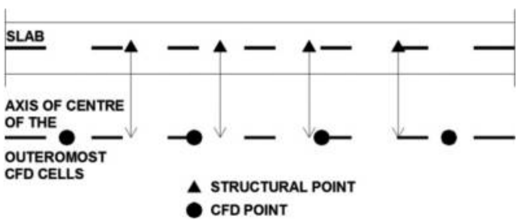


Figure 4.
Case of structural points outside the CFD domain

to find the surface system of coordinates taking into account the direction of the longitudinal axis and the shape of the cross-section.

It is essential that the type of mesh and type of system of coordinates used in the CFD analysis (Step 1) be clearly defined and taken into account in Steps 2 and 4. The format of the transfer file is based on the assumption of a structured rectangular mesh in a dextrorsum Cartesian system of coordinates. The position of the origin of the system of coordinates and the directions of the X, Y and Z axes, as well as the direction of gravity, shall be common in the CFD and in the FE analyses.

4. Application of the proposed methodology to a structural system

To show the potential benefits of such a methodology, the fire performance analysis of a multi-storey steel-concrete composite open car park designed according to the Eurocodes for which simplified localised fire models are in their range of applicability is presented. Thus, a typical design approach that uses the Hasemi model is compared with a more advanced analysis that relies on the proposed FDS–SAFIR coupling.

4.1 Description of the open car park

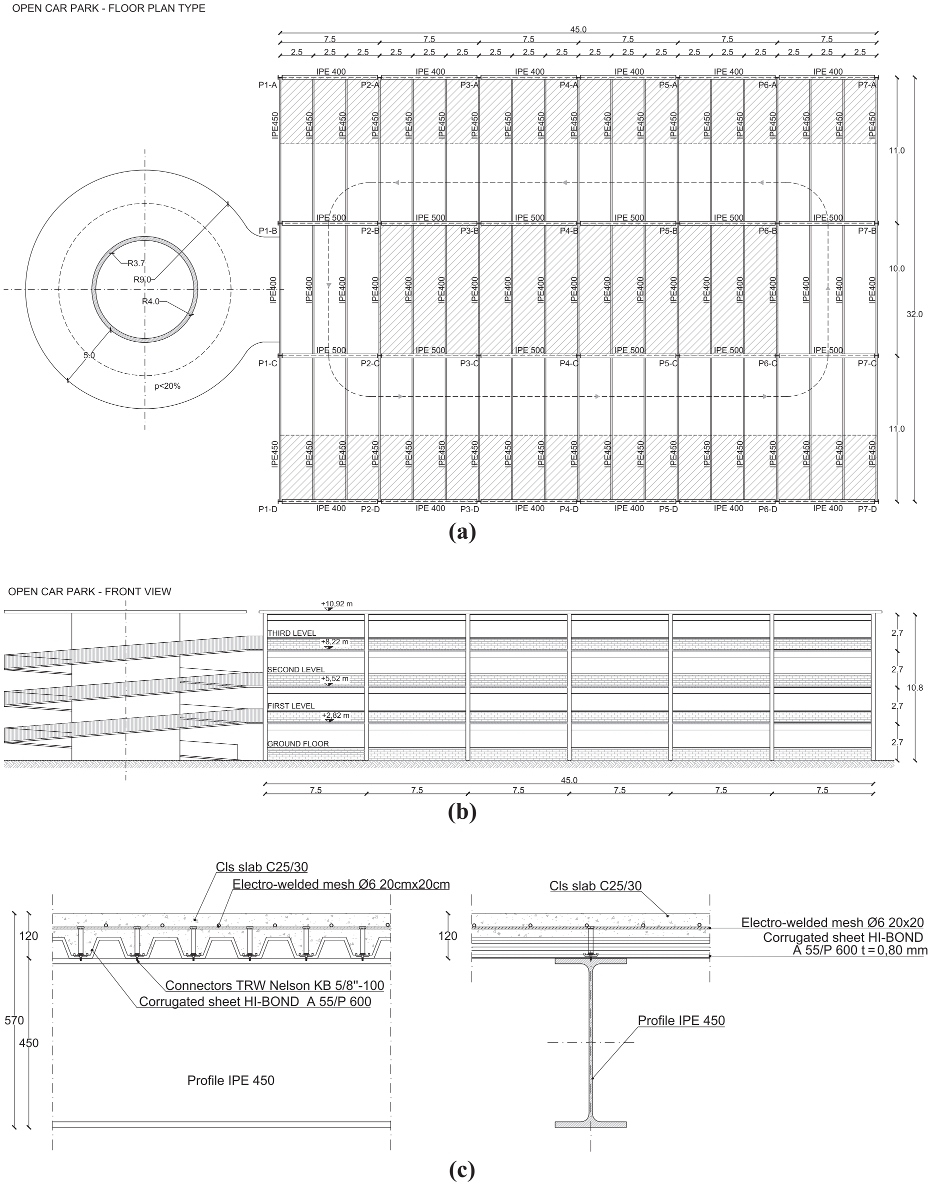
The structure is a four-storey steel-concrete composite open car park. The elevation and plan layouts are illustrated in Figures 5(a) and (b). The steel-framed structure was designed according to the Eurocodes and was made of steel grade S275, of a composite slab of concrete class C25/30 and profiled steel sheets [Figure 5(c)], of secondary beams IPE400 and IPE450, of primary beams IPE500 and IPE400 and of steel columns HEB200, HEB220 and HEB240. Moreover, the structure was assumed braced. An adequate degree of openings along the perimeter was allowed for the car park to be classified as open. Both primary and secondary beams were considered as simply supported, whereas columns were continuous along their entire height. No fire protection was applied to the structure.

4.2 Definition of fire scenarios

Different fire scenarios with a variable number of vehicles by assuming rate of heat release (RHR) curves representative of burning cars of Class 3 were considered (INERIS, 2001). By taking into account the car park layout, the analysed fire scenarios are shown in Figure 6. When multiple cars were involved into a fire, a time shift ignition between nearby cars was envisaged as observed in real car fires. As a result, the ignition of cars just next to the first that ignites the fire was delayed by 12 min. Moreover, it is worth pointing out that the worst fire scenario for the column, i.e. four burning cars around it, was not considered because of the car park layout. In fact, the likelihood of occurrence of this scenario is very low owing to the absence of face-to-face parking spots around the column [Figure 5(a)]. Then, based on the definition of the fire scenarios, the two approaches, i.e. Hasemi model and FDS–SAFIR coupling, were used.

4.3 A three-dimensional finite element model

To evaluate the fire performance of the open car park, a 3D FE model was developed in SAFIR (Franssen, 2005). As the deterministic fire scenarios for car parks, as provided in INERIS (2001), are localised fires, only a small part of the car park is significantly influenced by each fire scenario. Thus, half of it was actually modelled, and boundary conditions that guaranteed slab continuity were applied. Moreover, it is very unlikely that a fire could spread to all floors; consequently, only fire scenarios acting at one level of the car park were modelled by relying on a good compartmentalisation of the slab.



Notes: (a) Plan view, dimension in m; (b) elevation view, dimension in m; (c) detail of the composite slab, dimension in mm

Figure 5.
Geometric layout of the open car park

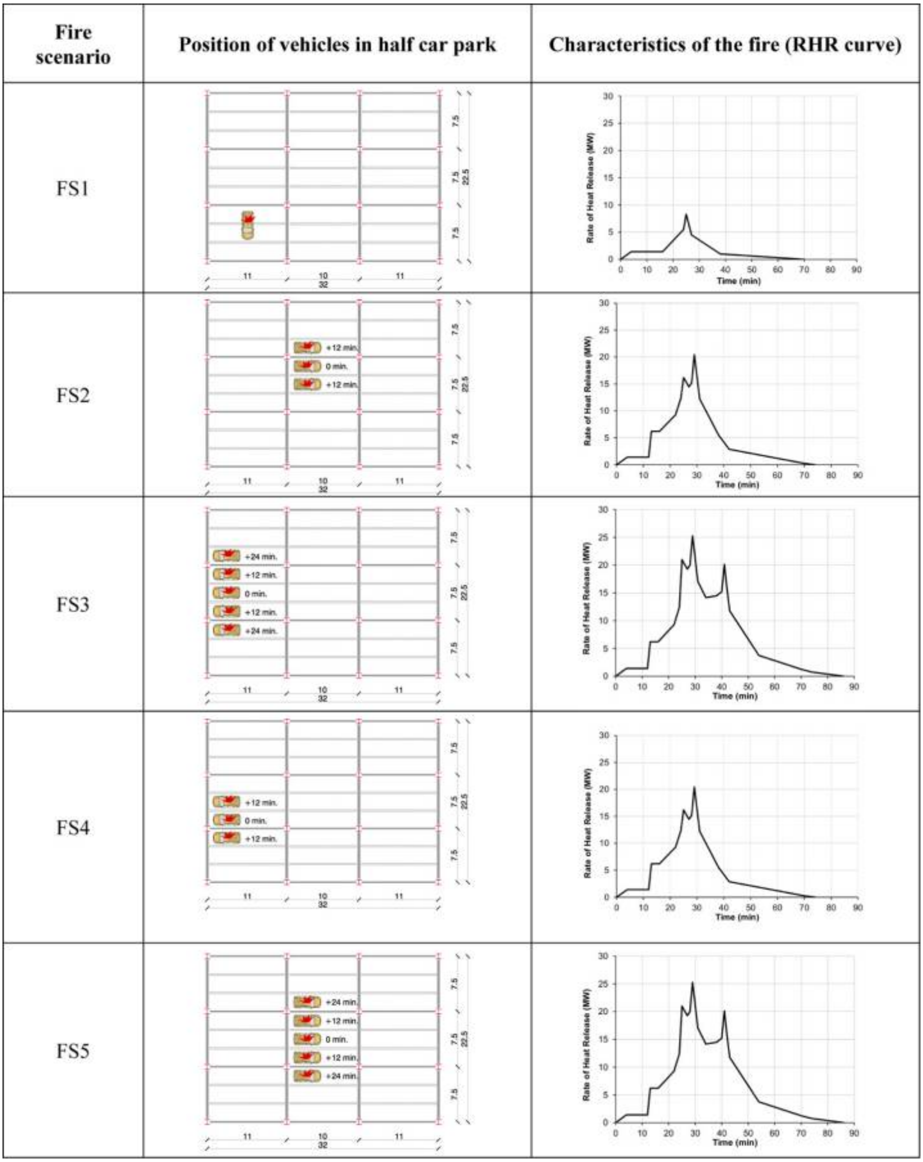


Figure 6.
Fire scenarios

The slab was modelled by means of shell elements, whereas beams were modelled with Bernoulli beam elements. To take into account the column continuity, the columns of the floor above were also included into the model, as illustrated in Figure 7, and they were kept at ambient temperature. Relevant vertical loads in the fire situation (EN 1990, 2002) were applied to the structure, and they comprised dead load, self-weight and live load;

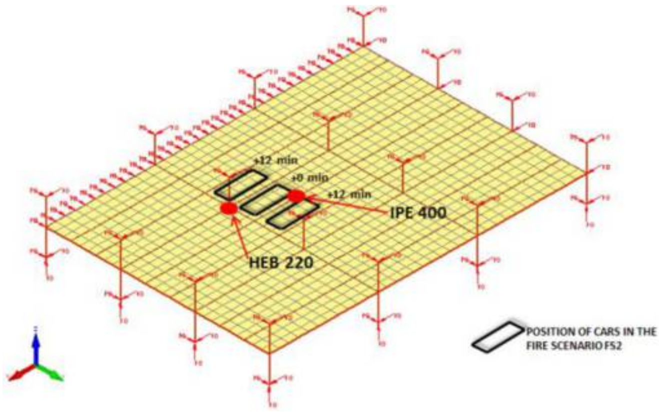


Figure 7.
3D FE model of half car park and positions of the cars in FS2

the latter equal to 2.5 kN/m^2 (DM 14 January, 2008). In Figure 7, two critical sections are highlighted:

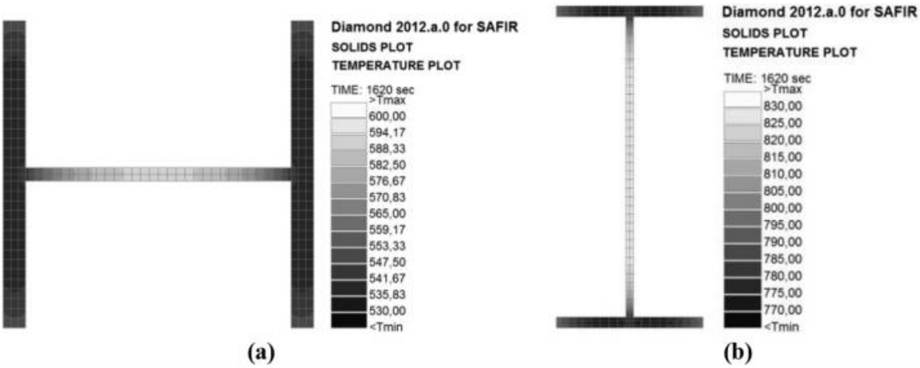
(1) the top section of the nearest column to the fire (point HEB220); and
(2) the section of the secondary beam that under the critical fire scenario experiences the largest vertical displacement (point IPE400) In the remainder of the article, comparisons were made at such points.

4.4 Fire analysis of the car park with the Hasemi model

The study of the fire performance of the car park was initially carried out by analysing it under all fire scenarios shown in Figure 6 by means of the Hasemi model. This allowed the identification of the most critical one that was then analysed through the application of the FDS–SAFIR-integrated strategy. This way of proceeding was pursued because the FDS–SAFIR coupling is more computationally demanding and time-consuming. Furthermore, SAFIR already implements the Hasemi model; thus, it is quite handy to perform such an analysis.

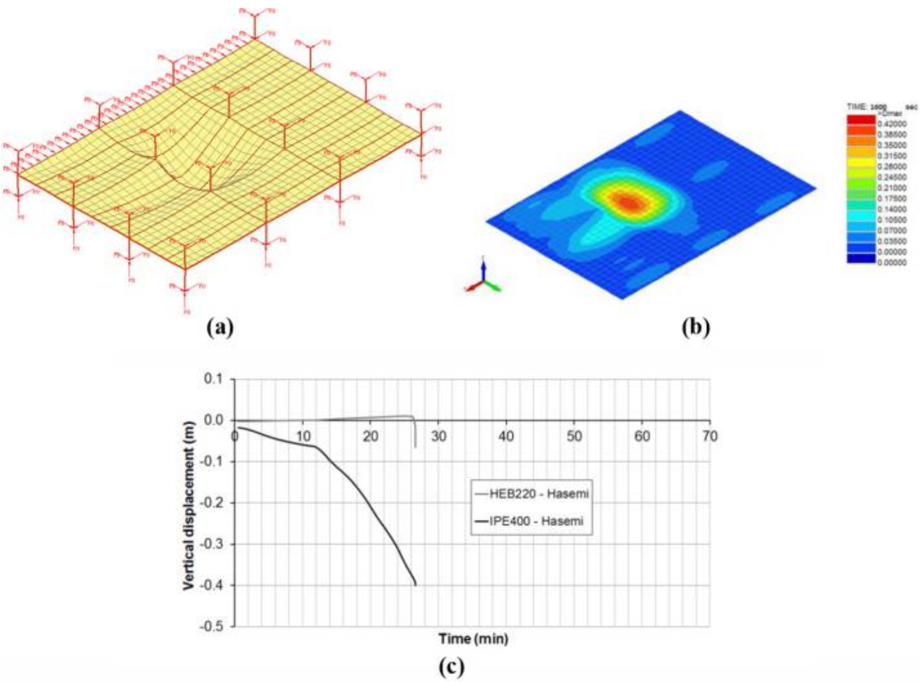
4.4.1 Thermal analysis. Thermal analyses were conducted on each structural element: slab, columns and beams. Primary beams were considered exposed on three sides with the slab on top of them, whereas secondary beams were exposed on four sides, as more than 15 per cent of the top flange was not covered by the steel sheet of the slab (EN 1994-1-2, 2005). The slab on the top of the primary beams was used in thermal analyses for reproducing the non-uniform temperature distribution in the section. However, in the mechanical analyses it was not effective because the slab was already modelled by means of shell elements. In the absence of a simplified model, a cautious thermal action was applied along the entire height of the column and equal to the heat flux determined at its summit with the Hasemi model. As a result, the temperature distribution in °C at failure in the HEB220 column top section and in the critical section of the IPE400 secondary beam owing to FS2, as depicted in Figure 7, is shown in Figure 8.

4.4.2 Mechanical analysis. From the results of the mechanical analyses performed for each fire scenario, it was found out that FS2 was the most critical one as entailed the collapse of the HEB220 column directly located next to the burning cars after 27 min of fire exposure. FS3 also caused structural failure, but later on, in the analysis, because of a larger time shift in the ignition of cars next to the column. The deformed shape and the vertical displacement of the structure at collapse (t = 27 min) are illustrated in Figures 9(a) and (b). Figure 9(c) shows the evolution of the vertical displacements at the two critical sections highlighted in Figure 7.



Notes: (a) At the top of the column (HEB220); (b) in the secondary beam (IPE400)

Figure 8.
Hasemi model – FS2: temperature distribution in significant sections at failure (t = 27 min)



Notes: (a) Deformed shape at failure amplified by a factor of ten; (b) vertical displacements at failure; (c) evolution of the vertical displacements at the critical sections of the HEB220 column and of the IPE400 secondary beam

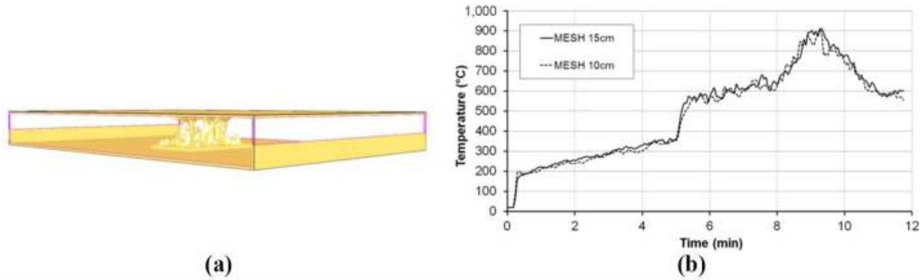
Figure 9.
Hasemi model – FS2

4.5 Fire analysis of the car park with the FDS–SAFIR coupling approach

4.5.1 Modelling of the fire development. To minimise border effects with respect to the smoke flow, more than half of the car park was modelled in FDS, and the fire development under the most critical scenario (FS2) was analysed. According to the proposed strategy, no structural elements across the compartment were included in the CFD model, see Figure 10(a). Thus, the influence of beams and columns on the smoke flow was initially neglected. The boundary conditions were consistently modelled with physical parameters that describe the thermal properties of the concrete slab, floor and parapets (EN 1992-1-2, 2004). The burning cars were simulated by assigning to the obstructions located at 30 cm from the floor, i.e. the wheel mean height, the relevant Class 3 car RHR curve according to the INERIS (2005) document. The default fire parameters according to FDS version 5.5.3 (McGrattan *et al.*, 2007) were used. However, to better represent the real properties of a car fire, a value of soot yield equal to 0.22 was chosen (Deckers *et al.*, 2014), and a value of heat of combustion equal to 44.4 MJ/kg, typical of gasoline, was selected. The mesh of the compartment was selected by means of a sensitivity analysis performed to provide an adequate grid capable of accurately modelling the characteristics of the localised fire. Figure 10(b) shows the temperature evolution with different cell grid dimensions at the ceiling level above the three-car fire with slightly time-modified RHR to reach the peak in a shorter time. The difference in temperature is very small between the two grids; thus, a $15 \times 15 \times 15$ cm mesh grid was deemed adequate to model such a localised fire. Furthermore, the appropriateness of this mesh was also verified according to Ma and Quintiere (2003) and to the guidelines included in the FDS user manual McGrattan *et al.* (2007) that confirmed its adequacy. Possible wind effects were not taken into account inside the CFD model.

At the end of the analysis, the transfer file with the relevant information about the fire development was created to be exploited by SAFIR for the thermal analysis.

For this structure, the ratio between the beam and the ceiling heights suggested an additional analysis that included the beams in the CFD model because they likely act as a barrier that traps the hot gases to some extent influencing the smoke flow. Hence, the effect of modelling the beams in the CFD model was analysed. They were approximately and conservatively included into the CFD model by means of adiabatic surfaces of the same height of the actual beams, as shown in Figure 11(a). Moreover, Figure 11(a) also provides indication of the obstruction extent of the beams in relation to the height of the compartment. Then, the fire development analysis was re-run, and the results of the two



Notes: (a) Fire development modelling; (b) temperature development at the ceiling level with different mesh grids owing to a Class 3 three-car time-shifted fire

Figure 10. FDS-SAFIR – FS2

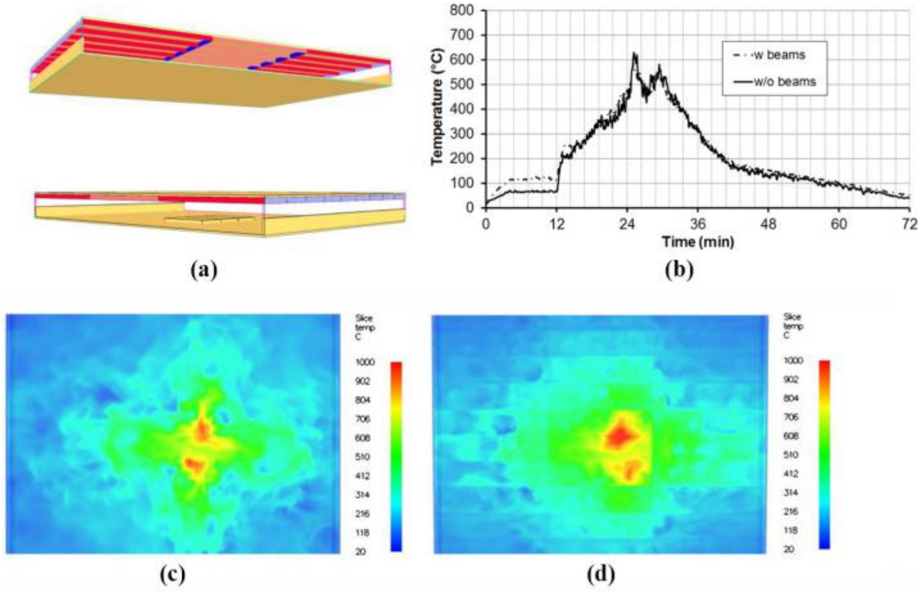


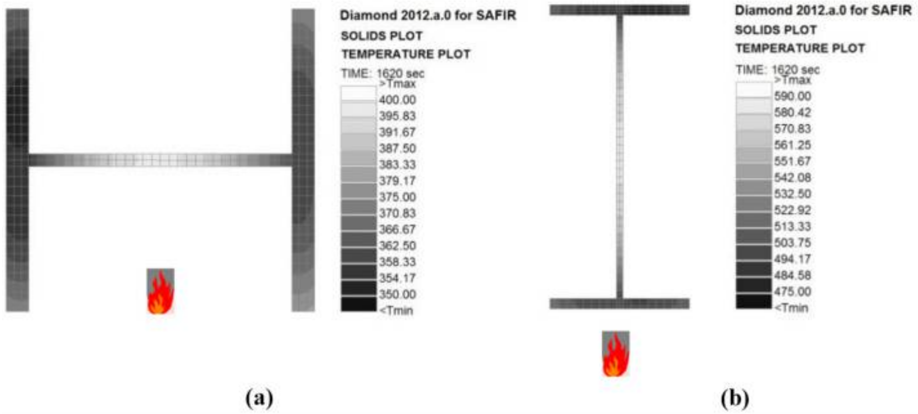
Figure 11.
FDS-SAFIR – FS2

Notes: (a) Compartment modelling with beams included in the CFD model; (b) gas temperature evolution around the top of the HEB220 column without (w/o) and with(w) beams included in the CFD model; (c) gas temperature distribution at ceiling level at 30min without including beams; (d) gas temperature distribution at the ceiling level at 30 min, including beams

analyses are compared in Figures 11(b)-(d). In greater detail, the temperature distribution at the ceiling level in the compartment after 30 min and the gas temperature evolution around the top of the nearest column to the fire, i.e. HEB220 in Figure 7, are shown. As expected, the influence of the beams on the smoke flow exists and locally the increase in gas temperature is not negligible. Therefore, for this structural typology, the influence of beams on the CFD modelling has to be always carefully checked. Nonetheless, it will be shown that this local effect on the global mechanical behaviour is small.

4.5.2 Thermal analysis. To perform the thermal analyses in each section, the data obtained from the CFD analyses were then exploited by SAFIR. The results at the most critical sections in the case without beams included in the CFD model are shown in Figures 12 and 13(a). From Figure 13(a), it is possible to note that the temperatures obtained from the Hasemi model are much higher than those obtained from CFD data. The main reasons of this marked difference are the following:

- The Hasemi model has been derived by means of experimental tests performed with a ceiling made of perlite boards, i.e. an insulating material, so that heat absorption through the ceiling was negligible, whereas the concrete slab behaves as a heat sink that causes a decrease in gas temperature at the ceiling level.



Notes: CFD model w/o beams; temperature distribution at 27 min in the critical section: (a) of the column (HEB220) and; (b) of the secondary beam (IPE400)

Figure 12.
FDS-SAFIR – FS2

- The Hasemi model implicitly assumes that the flame impacts the ceiling, but as observed in the CFD analysis and as estimated by the Heskestad model (EN1991-1-2, 2004), it only occurs for about one-sixth of the fire duration.
- The heat flux computed by means of the Hasemi model was applied to structural sections without considering any shadow effects and flux orientation with respect to the position of the structural elements.

The ability of the proposed methodology of taking into account flux orientation and shadow effects is clearly visible in Figure 12.

4.5.3 Mechanical analysis. The comparison of the mechanical analyses [Figure 13(b)] highlights that no failure occurred when the integrated strategy FDS-SAFIR was applied owing to a more advanced analysis of the fire development that resulted in lower thermal actions on structural elements, above all along the columns. The presence of the beams in the CFD model influences the smoke flow; however, they did not affect the global behaviour to a large extent, as illustrated in Figure 13(b). For example, the difference in terms of vertical displacement experienced by the column between the cases “FDS w/o beams” and “FDS w beams” is very small [Figure 13(b)]. Note a sensitive reduction of vertical displacement at 27 min, as illustrated in Figures 13(c) and (d), with respect to the Hasemi model analysis [Figures 9(a) and (b)].

5. Conclusions

This article presented an integrated modelling strategy between a CFD software and an FE software that has been recently applied to FDS and SAFIR. Although it implies some simplifications, the proposed weak coupling approach is more desirable for practical applications with respect to a full coupling approach because it can cover a wide number of likely-to-occur scenarios in compartment fires by being at the same time less computational demanding and handier to use. The potential benefit of the integrated methodology was

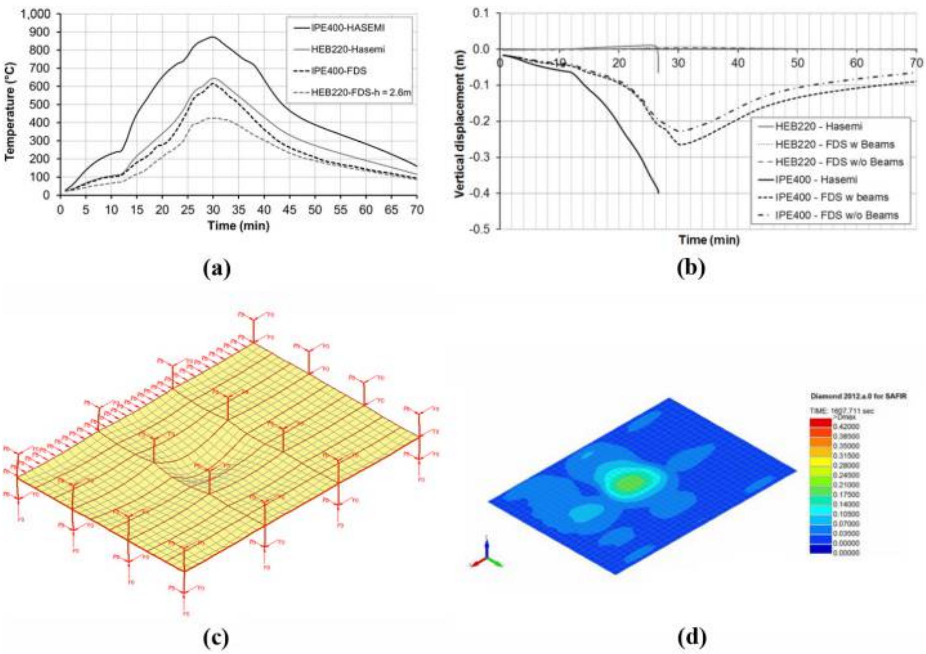


Figure 13.
FDS-SAFIR – FS2

Notes: (a) Comparison of the temperature evolution in the web of critical sections of the column (HEB220) and of the secondary beam (IPE400), CFD model w/o beams; (b) comparison of the mechanical response of the critical sections of the column (HEB220) and of the secondary beam (IPE400); (c) deformed shape at 27 min amplified by a factor of 10; (d) vertical displacements at 27 min

shown when applied to a steel-concrete composite open car park and then compared with the simplified Hasemi model. In fact, the fire performance analysis of the open car park highlighted that the FDS–SAFIR methodology allows overcoming shortcomings of simplified models by performing the thermal analysis in the structural elements based on more advanced modelling of the fire development, provided that a careful assessment of all assumptions be performed. Conversely, the Hasemi model revealed to be more conservative in terms of thermal action. In particular, its application entailed the collapse of the structure under study after 27 min, whereas by means of the proposed integrated modelling FDS-SAFIR, the structure survived for the whole duration of the most critical fire scenario.

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