Open Steel Car Parks Design for the Polish Market

Design Guide

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1 *Introduction*

This document is the final report for the project “Open Steel Car Park Design for Polish Market”. It contains detailed description of all the investigations and analysis performed in the scope of the project.

The main aim of the projects is to propose fire engineering approach to the open steel car park design. Based on the experimental test and research the appropriate fire scenarios are proposed and applied to selected structures. The geometry of the structure is based on the common practice as well as the requirements coming from the Polish Building Regulations in respect to the definition of the open car park, minimum dimensions and safety regulations.

All the proposed structures are designed in cold conditions and then verified in the fire scenarios. The fire analyses are performed using Finite Element Calculation Code SAFIR, developed by the University of Liege and consist of heat transfer analysis and stress/displacement analysis. The modelling assumptions and results obtained are explained in terms of structural behaviour and elements interaction.

It is important to notify that the fire engineering proposed in this document refers to design of composite slab and beams. The columns are not part of the investigation and therefore they have to be designed in compliance with the building and fire regulations.

Furthermore, for the performed simulations the stability of the models is assumed – guaranteed by the boundary conditions. This means that the stability of the structure needs to be additionally considered for each and every design as it depends on various conditions not taken into account in this study.

The final delivery from the project is a methodology to design slab and beams of an open steel car park without fire protection by applying fire engineering.

2 *Application And Regulations*

2.1 Open Car Park

Design method presented in this document applies, as indicated from the very beginning, to the open steel car parks. According to the Building Regulations the car park is considered open if it satisfies the following conditions:

- Total area of openings (at each level) > 35% of the overall wall area
- Distance between walls with openings < 100 m

These two conditions ensure the natural ventilation as it is shown in Figure 2-1, which helps to avoid accumulation of smoke and additional increase of temperature.

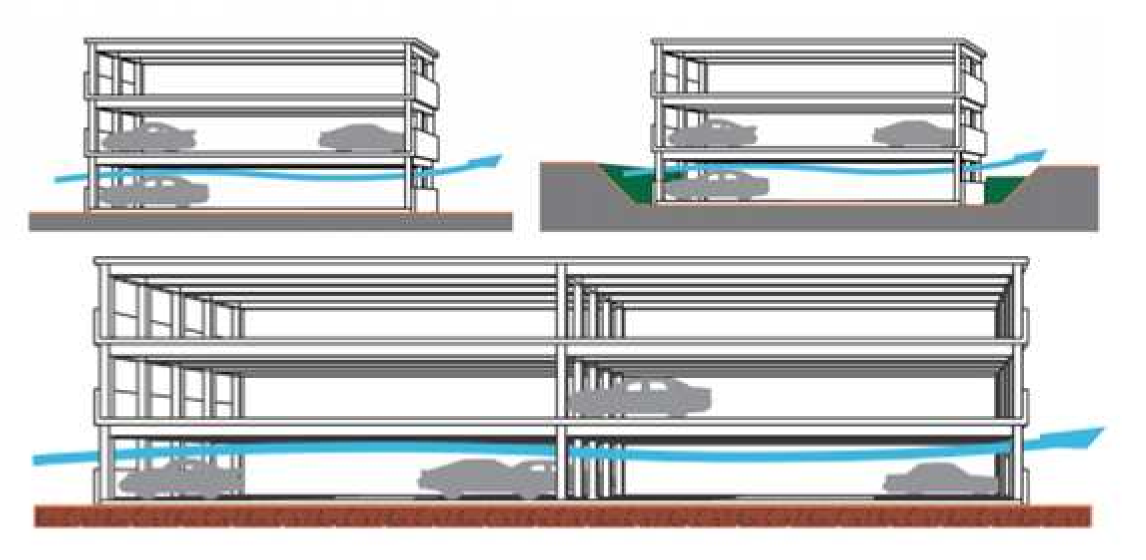


Figure 2-1 Natural ventilation in open car parks

2.2 Structure

All the research and analysis leading to these results were performed for structures with composite slab system and hot rolled steel beams.

In the predesign presented only one slab system had been used – Cofraplus 60. Specification of this slab is presented in Annex 5.

2.3 Geometry

Considering Polish Regulations and Recommendations the following minimum dimensions have to be ensured for open car parks:

- Single parking space : 2.3m x 5m minimum (width x length)
- Height (between floor and ceiling): 2.2m minimum
- Height (between floor and installations under ceiling): 2m minimum
- Width of access road: 5.7m minimum (when cars park perpendicularly to the road)

Considering common practice and tendency observed in various countries it is suggested to use for a single parking space dimension 2.5m x 5m and 6m for the width of access road. It is worth mentioning that all the tests, to which references are made, were performed for 2.5m width of the parking space.

2.4 Upper Surface Of The Slab

Concrete slab in the car park floor plays important role as a structural element in composite steel deck or composite steel beam, and also as a surface for car traffic. Due to this it must be enough strong and hard on its upper part. The floor concrete must be also resistant against corrosion from moisture and in case of unroofed top floor area the frost and defrost of water and salt used in winter time for de-icing.

Considering risk of corrosion of intermediate floor the environmental condition of concrete can be classified as XC1 according to tabl.4.1 [PN-EN-1992-1-1]. For this exposure class the indicative strength class of concrete from table E.1N [PN-EN-1992-1-1] is C20/25. However, estimating minimum value of cover of reinforcement from table 4.3N it is recommended for the same class of exposure XC1 the strength class of concrete not less than C30/37 (service life of 100 years). So in case of floor exposed on climatic influence the minimum class of concrete can be precisely selected, depends on corrosion protection of reinforcement by concrete cover that can be improved by upper surface floor finishing.

There are two main method of finishing of upper surface of car park floor.

DST - dry shake topping. This method of finishing consists in spreading on a top of poured concrete some hardening surface material that is mechanically smooth over the surface. After this it is necessary to spry over the surface some of impregnating agent.

Epoxy finishing. This protection layer of thickness 1 to 5mm is created by painting or spraying on a dry top surface of concrete some polymer materials. The painting beside water protection characterise high strength and abrasion resistance. It can be also coloured by adding some pigments to the painting materials.

2.5 Open Steel Car Parks in Other European Countries

2.5.1 France

The requirements regarding fire resistance of the structure imposed by the regulations from January 31st, 1986 and by the law on the classified structures, which basically says:

- single storey open car park: R 30;
- open car parks with at the most two levels: R 60;
- open car parks of more than two levels but not exceeding 28 m: R 90;
- open car parks of more than 28 m: R 120.

New approach

The current evolution of the French statutory regulations concerning the opened car parks drives to a new approach. The research works and the real scale tests of led to a development of a methodology of calculation to verify the fire performance of open car parks under real fire scenarios. A building to be classified as an open car park and benefit from the research and new calculation method has some limitation related to evacuation requirements, ventilations via minimum openings in the façade, maximum distance between walls, floor area etc.

Finally, there are approved fire scenarios for open car parks in France and the stability of the structure in fire conditions is justified by the performance based approach calculation with natural fire concept.

All the fire calculations have to be approved by qualified check office.

2.5.2 Germany

There is no fire resistance requirement for open car parks up to 20m of height.

The natural fire concept is in general accepted, but as all the fire designs it has to be verified by a competent body and approved.

2.5.3 United Kingdom

Building regulations in the United Kingdom are very clear regarding requirements and allowed approach to fire safety, fire resistance and structural fire engineering.

There are small difference regarding building regulations between England & Wales, Scotland and Northern Ireland. However, the design based on the prescriptive methods has to satisfy 15min fire resistance for open car parks up to 30m of height. The majority of universal steel sections have 15 minutes inherent fire resistance and thus most steel-framed open deck car parks do not now require structural fire protection.

Steel in open deck car parks is now predominantly unprotected.

In respect to fire engineering, the regulations leave a lot of flexibility considering a method of design as long as the building maintains its stability for reasonable time in fire condition.

3 Fire Scenario

In the fire engineering approach with application of the natural fire concept it is important to establish location of the fire and its power represented by rate of heat release (RHR). Both, the location and the fire load compose so called fire scenario.

It is essential that fire scenario, which is the most critical for the structure is selected for the design. However, it doesn't mean the most severe, but the most realistic, based on the tests, research and experience. As this is a crucial decision to be made, some background information is presented before defining the fire scenario for the design in Poland.

3.1 Classification Of Cars

It has been already mentioned that to specify fire scenario it is necessary to know rate of heat release (RHR) of the cars. RHR is a measure of Megawatts produced by a burning item in time [MW]. This value is determined experimentally by setting a car on fire under calorimetric hood as shown in Figure 3-1.

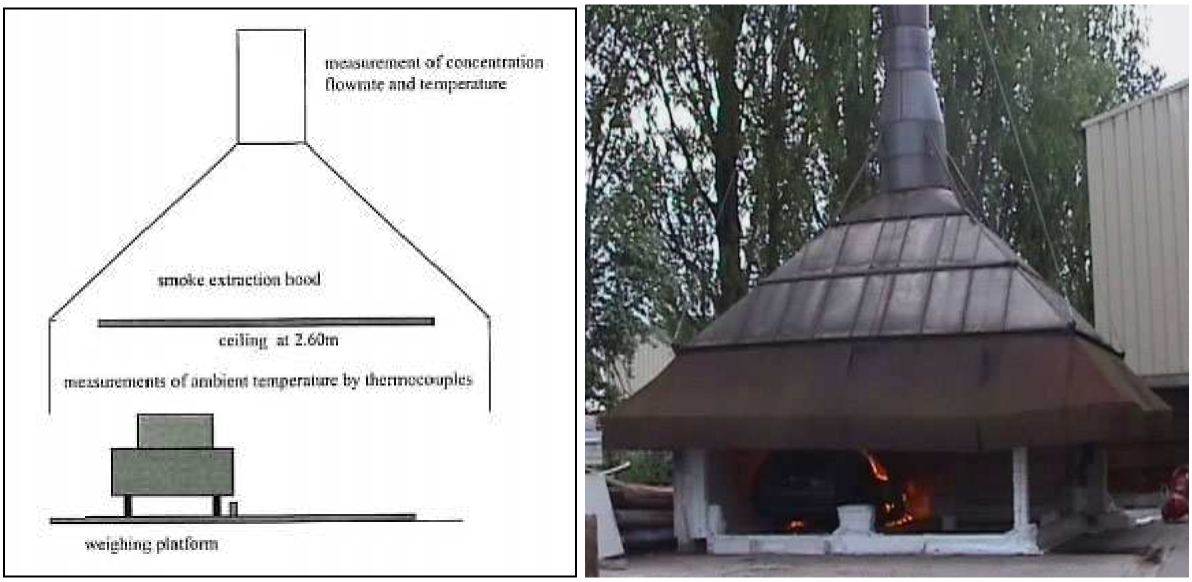


Figure 3-1 Calorimetric hood

Vehicles tested under calorimetric hood are equipped as if they were in operating state. They have four tires and one spare wheel, a tank filled in two thirds of its capacity with petrol. Additionally the cars have airbags and air conditioning. All the doors and windows are closed when the car is set on fire with 1.5 litters of petrol. The car was equipped with thermocouples as shown in Figure 3-2.

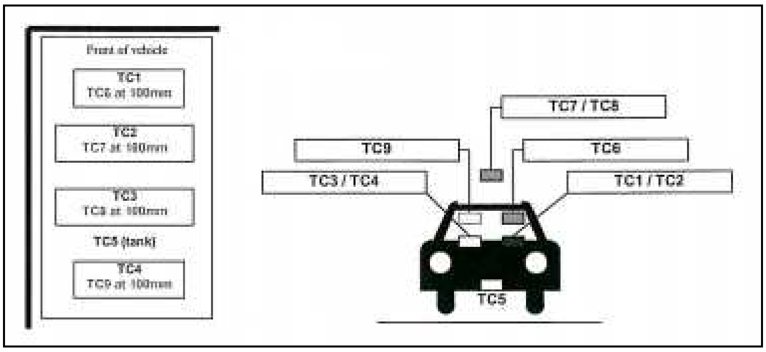


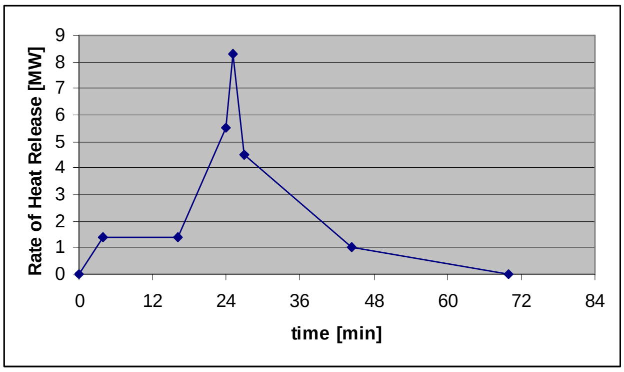
Figure 3-2 Position of thermocouples

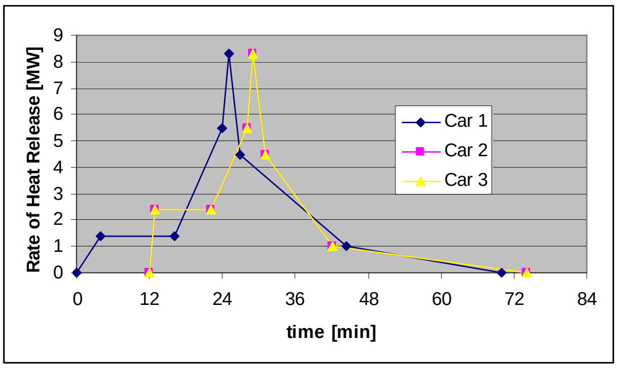
These tests allowed classifying cars in five classes according to their rate of heat release. The RHR depend on the car characteristic such as size of the vehicle, its load, its age, etc. An example of classification of types of specific make falling into specific class is illustrated in Figure 3-3.

Make	Class 1	Class 2	Classe 3	Classe 4	Classe 5
Peugeot	106	306	406	605	806
Renault	Twingo/Clio	Megane	Laguna	Safrane	Espace
Citroen	Saxo	ZX	Xantia	XM	Evasion
Ford	Fiesta	Escort	Mondeo	Scorpio	Galaxy
Opel	Corsa	Astra	Vectra	Omega	Frontera
Fiat	Punto	Bravo	Tempra	Croma	Ulysse
Volkswagen	Polo	Golf	Passat	//	Sharan

Figure 3-3 Classification of cars

RHR curves of cars in fire were obtained by the tests of the CTICM (1995-1996) [Sch1, 99]. Specific time dependent RHR corresponds to each of these 5 classes of cars. Graph in Figure 3-4 on the left represents RHR for car class 3. This is the class of car that is most commonly used in the fire scenarios. The pick RHR for this class is obtained after 25min of fire and reaches value of 8.3 MW.





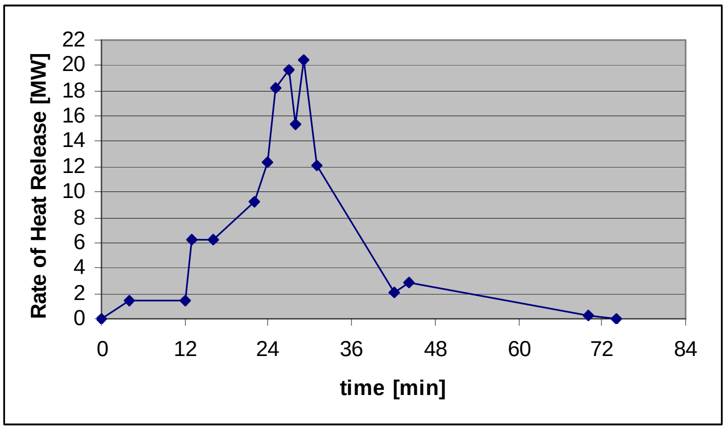


Figure 3-4 RHR for car class 3 (top left), RHR for each of the three cars with propagated fire (top right) and cumulated RHT from the three burning cars (bottom)

The same experimental test was used to analyze propagation of fire from one car to another. It had been determined that second car is ignited 12 minutes after the first car went on fire. Also the RHR was measured for the second car in fire. Despite of the fact the both cars were from the same class the second curve is slightly different as shown in Figure 3-4 (top right). The RHR for the second car starts 12 minutes later. Based on the RHR for each car involved in the fire the thermal action on structural elements of the car park can be determined.

3.2 Statistics

Statistics, if available, is one of the instruments that help to define critical scenario. Statistical analysis related to fire involving cars is presented below.

Number of cars involved in a fire

3 cars: 10% of the car fires;

2 cars: 10% of the car fires

1 car: 80% of the car fires

Classification of burning cars

Class 1: 45% (Renault Twingo, …)

Class 2: 25% (Renault Megane, …)

Class 3: 20% (Renault Laguna, …)

Classes 4 and 5: 10% (Renault Espace, …)

Time to extinction

5.5% of car fires: extinguished before the arrival of firemen

30 and 60 min for the extinction of fires involving **several cars** (50 % of cases)

70 % of fires involving **1 car**: stopped **before 15 min**

80 % of fires involving **2 cars**: stopped **between 6 and 30 min**

84 % of fires involving **3 cars**: extinguished by the firemen **between 16 and 60 min**

3.3 Identified Fire Scenarios

Considering results of the fire tests presented in the previous sections as well as forthcoming simulations and statistics car class 3, which are cars comparable to Renault Laguna, Oper Vectra, Ford Mondeo or Volkswagen Passat, had been selected to be used in the fire scenarios. This is the most frequently used class for fire analysis of car parks since it is higher class than the most common on the roads, therefore guarantee statistically safe approach to the design.

Various configurations and numbers of cars had been tested and simulated. The results show that large number of cars used in the fire scenario doesn't lead to continues increase of temperature in the structure, as the fire starts moving rather than cumulate. Additionally, more than three cars simultaneously in fire is so rear case that it isn't represented by a significant number in the statistics. Therefore, two scenarios have been chosen:

- four cars around a central column (Figure 3-5)
- three cars in line at the corner of the car park (*Figure 3-6*)

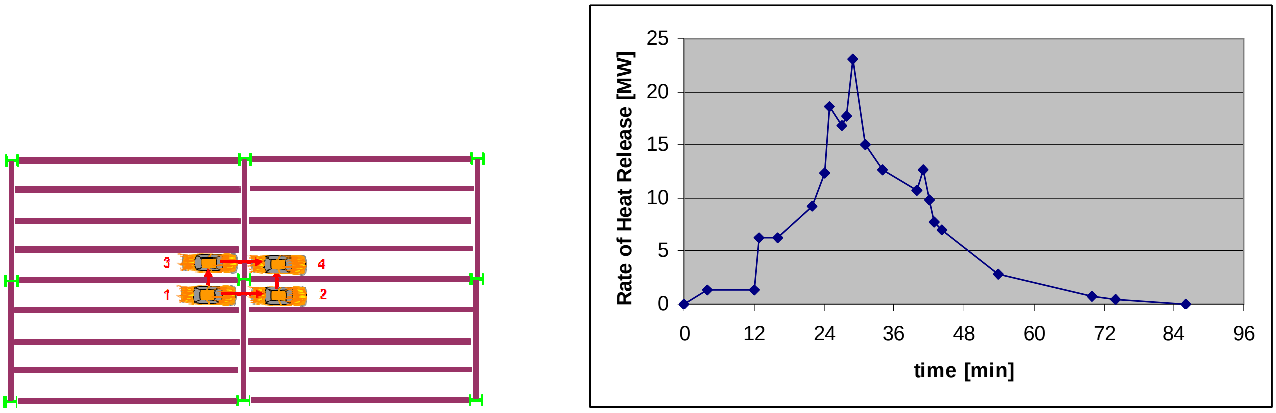


Figure 3-5 Four cars class 3 placed around a columns and cumulated RHR from all the four cars

The aim of the first scenario is to calculate the behaviour of the structure exposed to 4 burning cars around one of the columns in the middle of the car park.

The fire starts at time t = 0s with car n°1. In the first step the fire spreads out to car n°2 and n°3 after the time Δt = 12min, and in the next step to the car n°4 after Δt = 24min from the beginning of the fire. The rate of heat release for a car class 3 is given in Figure 3-5, where the maximum rate of the heat release is equal to 23 MW and it is obtained after 29min.

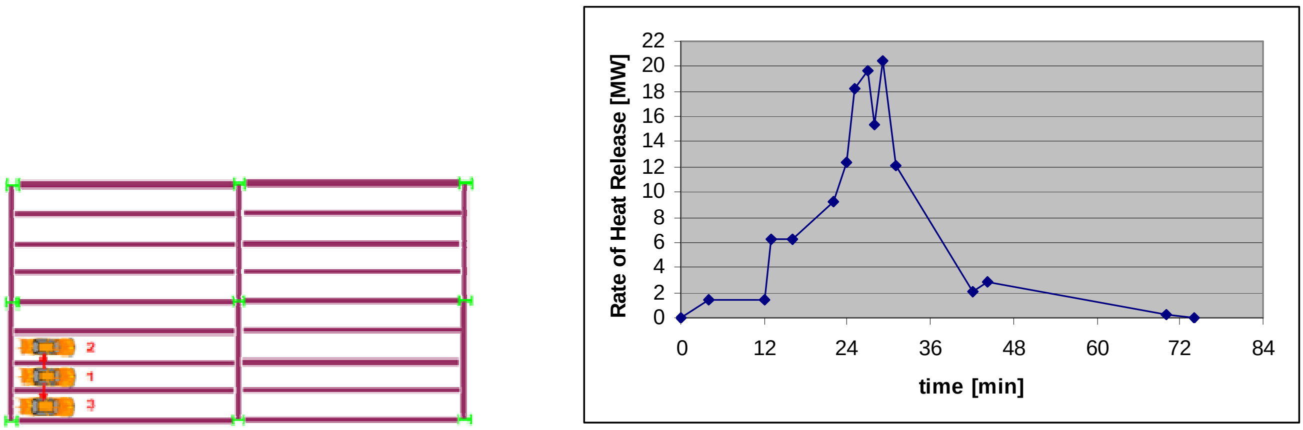


Figure 3-6 Three cars class 3 aligned and cumulated RHR from all the three cars

In the second scenario, 3 cars are positioned next to each other in the corner on the car park. The edge of the car park is the most vulnerable part of the structure.

The fire starts at time t = 0 with the car n°1, and spreads out to the two other cars (n°2 and n°3) after the time Δt = 12min. As before the simulations are performed for cars class 3. The rate of heat release is given in *Figure 3-6*, where the maximum RHR equals 20.5 MW.

4 Actions On The Structure

Structures of car parks are submitted on various dead and live loads in the normal and incidental situations. These loads are different in a stage of construction and service of construction.

For the construction stage the most important loads are self weight of steel construction, own weight of wet concrete of floor slab and some uniformly distributed technological live load (pouring of concrete). For service stage the most important is own weight of steel, weight of composite elements of construction and usable load of floor.

Climatic loads as snow load, wind load and temperature load should also be taken into calculation of car park construction. Due to a specific construction of open car parks with vertical bracings or rigid concrete cores, climatic loads has a secondary influence on floor and column design and they are not taken into consideration in this manual. However, if the last floor doesn't have a roof it has to be additionally checked for the snow load.

The separate problem is a fire protection and behaviour of the construction during fire when the temperature is high. This is an incidental situation and must be taken into account in design with an adequate load combination.

4.1 Localised Fire

The heat flux received by the elements of structures is calculated bases on the principle of the localized fires. According to the adopted scenario heat fluxes received by elements will be a function of their positioning with regards to vehicles in fire and time. The impact of flames on the structure is calculated as a function of following parameters indicated in Figure 4-1:

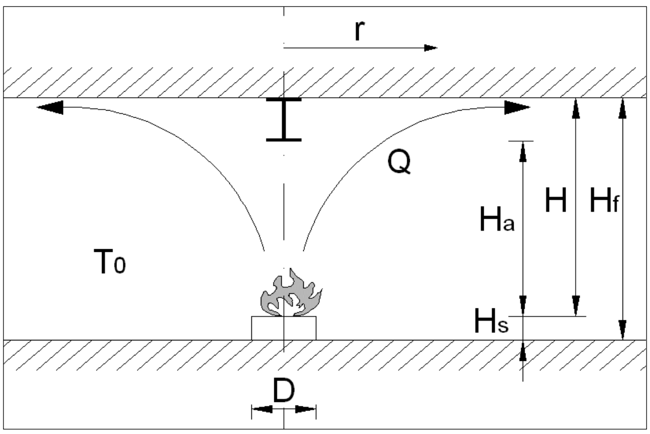


Figure 4-1 Parameters of the localised fire

Q (W) – RHR of cars

Ha (m) – vertical distance from the beam lower flange to the floor (if beam concerned)

Hs (m) – Vertical distance from the fire source to the floor. For the fire coming from a car the distance is taken as **Hs = 0.3m [Sch1, 99]**

D (m) – Fire diameter. For the car park calculations **D = 3.9m [Sch1, 99]**

r (m) – Distance between the fire axis to the point where the net heat flux is computed

In the analysis of the car park it is accepted hypothesis that the fire is impacting the ceiling and therefore Hasemi method of calculation is applied [Sch2, 99]. The method is described in Annex C of EN 1991-1-2.

When the flame is impacting the ceiling the heat flux $\dot{h}$ [kW/m2] received by the fire exposed unit surface area at the level of the ceiling is given by:

$$For \quad y < 0.3 \qquad \dot{h} = 100$$

$$For \quad 0.3 < y < 1 \qquad \dot{h} = 136.3 \quad to \quad 121\, y$$

$$For \quad y > 1 \qquad \dot{h} = 15\, y^{-3.7}$$

where

$y = \dfrac{r + H + z'}{L_h + H + z'}$; it's a non-dimensional parameter [-]

$L_h = (2.9\, H\, (Q_H^*)^{0.33}) - H$; it's the horizontal flame length [m]

$Q_H^* = Q / (1.11 \cdot 10^6\ H^{2.5})$; it's a non-dimensional rate of heat release [-]

$z' = 2.4\, D\, (Q_D^{*2/5} - Q_D^{*2/3})$ when $Q < 1$
$z' = 2.4\, D\, (1 - Q_D^{*2/5})$ when $Q \geq 1$; it's the vertical position of the virtual heat source [m]

$Q_D^* = Q / (1.11 \cdot 10^6\ D^{2.5})$; it's a non-dimensional rate of heat release [-]

In case of a several localized fires the heat flux received by an element of structure corresponds to the sum of heat flux obtained each of the localised fires. However, the total heat flux is limited to max of 100 kW/m² following Annex C of EN 1991-1-2.

4.2 Heat Transfer

From the thermal actions determined to the previous stage towards the elements of structure, the temperatures reached by the elements of structure are determined according to time.

When the field of temperature in the elements of structure is not homogeneous, the calculation of the heat transfer must be performed by means of software considering the heat transfer in "at least" 2 dimensions. Should the opposite occur, with a field of homogeneous temperature, the simplified model of calculation according to the Eurocode 3 Part 1-2 can be used.

From the total heat flux received by the structure, the net heat flux $\dot{h}_{net}$ received by the fire exposed unit surface area on the level of the ceiling needs to be deducted. The net heat flux calculation considers ventilation effect coming from the fact that the car park is open.

$$\dot{h}_{net} = \dot{h} - \alpha_c\, (\Theta_m - 20) - \Phi\, \varepsilon_m\, \varepsilon_f\, \sigma\, [(\Theta_m + 273)^4 - (20 + 273)^4]$$

where

α_c - the coefficient of heat transfer by convection of the material of the element

Θ_m - the surface temperature of the element [C °]

Φ - the shape factor

ε_m - the emissivity of the surface of the element

ε_f - the emissivity of the fire

σ - Stephen Boltzmann's constant (= 5.67 10^{-8} W/m² K^4)

For an equivalent uniform temperature distribution in the cross-section, the increase of temperature $\Delta\theta_{a,t}$ in an unprotected steel member during a time interval Δt should be determined from:

$$\Delta\theta_{a,t} = k_{sh} \frac{A_m / V}{c_a \rho_a} \dot{h}_{net} \Delta t$$

where:

k_{sh} is correction factor for the shadow effect;

A_m / V is the section factor for unprotected steel members [1/m];

A_m is the surface area of the member per unit length [m²/m];

V is the volume of the member per unit length [m³/m];

c_a is the specific heat of steel [J/kgK];

$\dot{h}_{net}$ is the design value of the net heat flux per unit area [W/m^2];

Δt is the time interval [sec];

ρ_a is the unit mass of steel [kg/m^3].

4.3 Mechanical Action

The beams and slabs of floor have to be first designed by a cold calculation with ULS and SLS load combinations.

In ULS at strength design (STR – PN-EN-1993-1-1) under normal situation most severe combination of actions can be obtained according to following formula:

$$\sum_{i\geq 1} \gamma_{G,i} G_{k,i} + \gamma_{Q,i} Q_{k,1} + \sum_{j\geq 1} \gamma_{k,j} \psi_{0,j} Q_{k,j}$$

Where:

$G_{k,i}$ is a characteristic values of permanent actions

$Q_{k,1}$ is a characteristic leading variable action

$Q_{k,j}$ is a characteristic values of accompanying variable actions

$\gamma_{G,i}$ is a partial load factor for permanent actions

$\gamma_{Q,i}, \gamma_{k,j}$ are partial load factors for variable actions

$\psi_{0,j}$ combination factors

Therefore in case of car park structural elements the combination of loads at strength design (STR) is as follow:

$$1,35\sum_{i\geq 1} G_{k,i} + 1,5Q_{k,1}$$

Where according to PN-1991-1-1 (and PN 80/B- 02000, 02001, 02002):

- at service stage

  $G_{k,i} =$ weight of dry concrete+ weight of steel deck(+ weight of steel beams)

  $Q_{k,1} = 2{,}5$ kN/m^2

- at construction stage

  $G_{k,i} =$ weight of wet concrete+ weight of steel deck(+ weight of steel beams)

  $Q_{k,1} = 0{,}6$ kN/m^2

In ULS deflection of steel elements calculated for frequent, reversible load combinations:

$$\sum_{i\geq 1} G_{k,i} + Q_{k,1},$$

should not exceed values presented in PN-EN1993-1-1 that is;

- for secondary beams L/250
- for primary beams L/350

Under fire situation, the applied loads to structures can be obtained according to following formula from EN1990:

$$\sum_{i\geq 1} G_{k,i} + (\Psi_{1,1} \; or \; \Psi_{1,2})\, Q_{k,1} + \sum_{i\geq 1} \Psi_{2,i}\, Q_{k,i}$$

where:

$G_{k,i}$ is a characteristic values of permanent actions

$Q_{k,1}$ is a characteristic leading variable action

$Q_{k,i}$ is a characteristic values of accompanying variable actions

$\Psi_{1,1}$ is a factor for frequent value of a variable action

$\Psi_{2,i}$ is a factor for quasi-permanent values of variable actions

The recommended values of Ψ_1 and Ψ_2 are given in table A1.1 of EN1990 but could be modified in National Annex. In the Polish National Annex it is recommended to use frequent value $\Psi_{1,1}\, Q_1$ as a representative value of the variable load Q_1. Therefore the combination for fire situation in the car park is as follow:

$$1G + 0.7Q$$

5 Requirements And Recommendations

5.1 Material – Properties

5.1.1 Steel Beams

Thermal properties:

- Convection coefficient hot = 35
- Convection coefficient cold = 4
- Relative Emission = 0.7

Mechanical properties:

- Young Modulus = 2.1×10^{11} N/m^2
- Poison ratio = 0.3
- Yield strength = 2.35×10^8 N/m^2 or 355×10^8 N/m^2

5.1.2 Normal Concrete

It is recommended to use normal concrete grade C30/37 as in some cases this is the lowest sufficient grade for fire design. Additionally, application of this grade requires less extra finishing on the floor surface, which comes from the environmental conditions and requirements for open car parks. However, application of the grade C20/25 is allowed with extra verification. In the study presented in this document the grade C30/37 was applied.

Thermal properties:

- Convection coefficient hot = 35
- Convection coefficient cold = 4
- Relative Emission = 0.7
- Moisture constant = 2%

Mechanical properties:

- Poisson ratio = 0.3
- Compressive strength = 0.3×10^8 N/m^2
- Tensile strength = 0.3×10^7 N/m^2

5.1.3 Steel For Rebars

Mechanical properties:

- Young Modulus = 2.1×10^{11} N/m^2
- Poison ratio = 0.3
- Yield strength = 5×10^8 N/m^2

5.2 Additional reinforcement

(1) A connection between the edge column and the slab of concrete is required and must be secured by reinforcements minimum diameter of 12 mm mounted on steel column (see Figure 5-1).

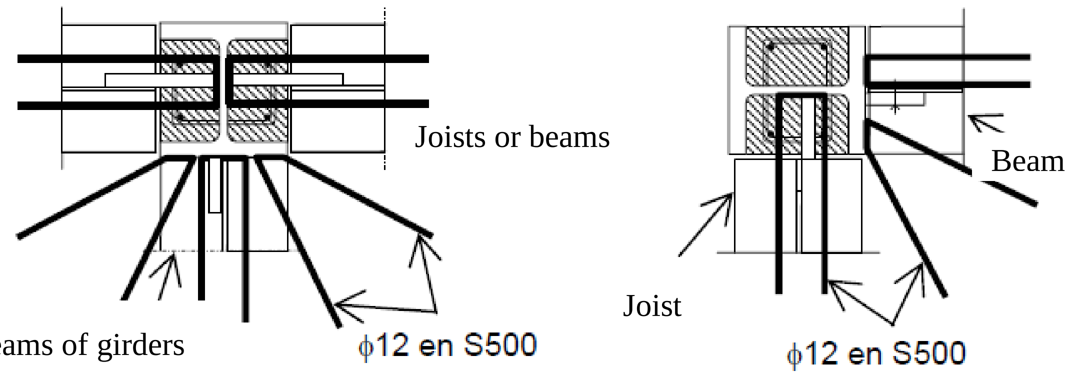


Figure 5-1 Connecting additional reinforcement with edge column

(2) For the central columns, continuity of reinforcement in the concrete slab must be ensured by additional bars (Figure 5-2)

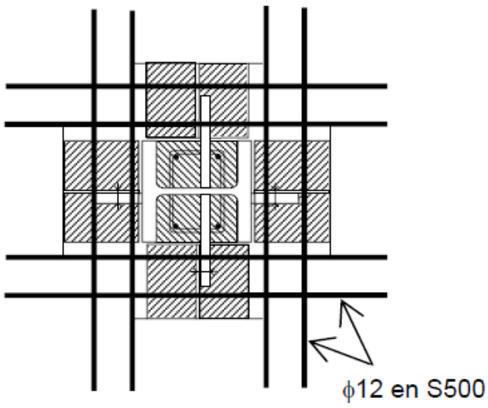


Figure 5-2 Details of additional reinforcement around central column

(3) The sheet of welded mesh must have a sufficient bond, using the head of the stud connectors, with all the edge beams (joists and main beams); this can be achieved with additional reinforcements. All the additional reinforcement must have additional anchorage length sufficient to obtain a firm anchoring of them in the slab.

5.3 Connections

Steel structural elements of main car park structure are designed from I hot rolled profiles. Secondary beams are IPE or HEA cross sections, primary beams (girders) are mostly HEA or in some cases IPE profiles. It is recommended that the cross section of connected together beams are selected in such way that in all cases depth of secondary beam is not greater then primary beam connected to it. Due to this construction of the connection is simple and easy to make.

In case of braced frames system it is recommended to use pinned joints constructed by simple bolt connections.

It is possible to use two types of bolted connections in considered situation:

- Angle cleat connection (Figure 5-3)

- End plate connection (Figure 5-4)

Selection of the type of connection depends on steel construction fabricator and they have to be checked according to PN-EN-1993-1-2:2005.

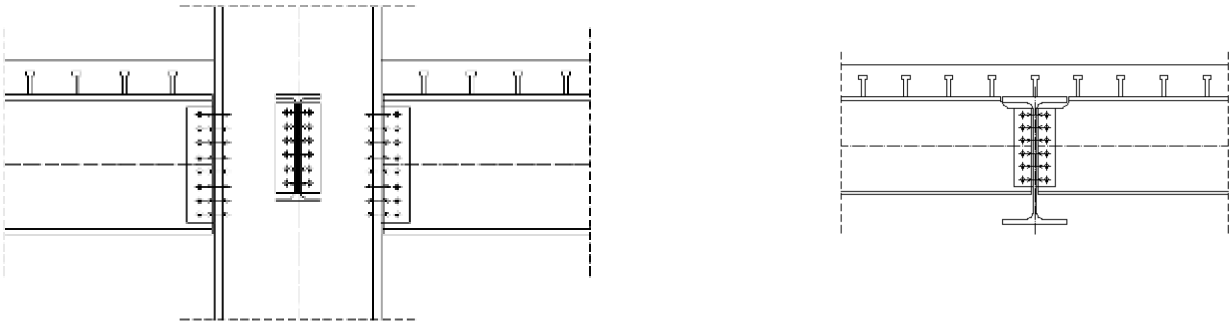


Figure 5-3 Angle cleat connections

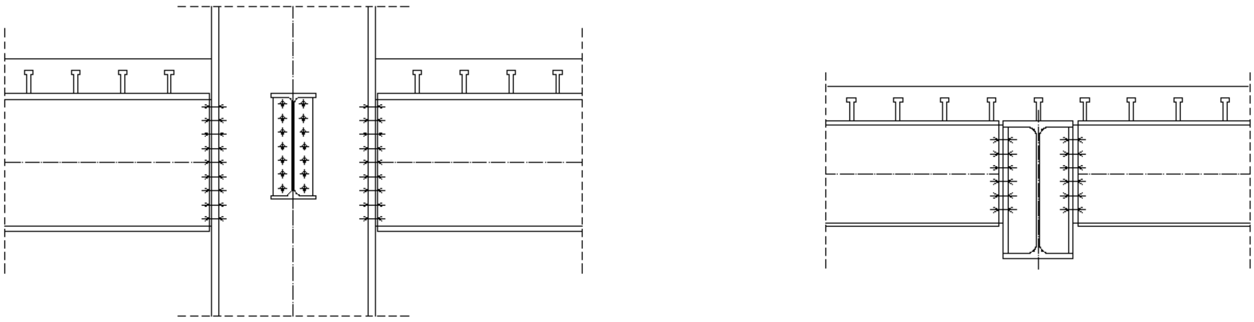


Figure 5-4 End plate connections

When the beam-column and beam-beam connection are made of hinged connection the bottom flange of the beams must comply with a maximum clearance of 15 mm to ensure a negative moment resistance in case of fire (see Figure 5-5). Any different connection assuring at least an identical resistance in negative moment can be used (e.g. end-plate).

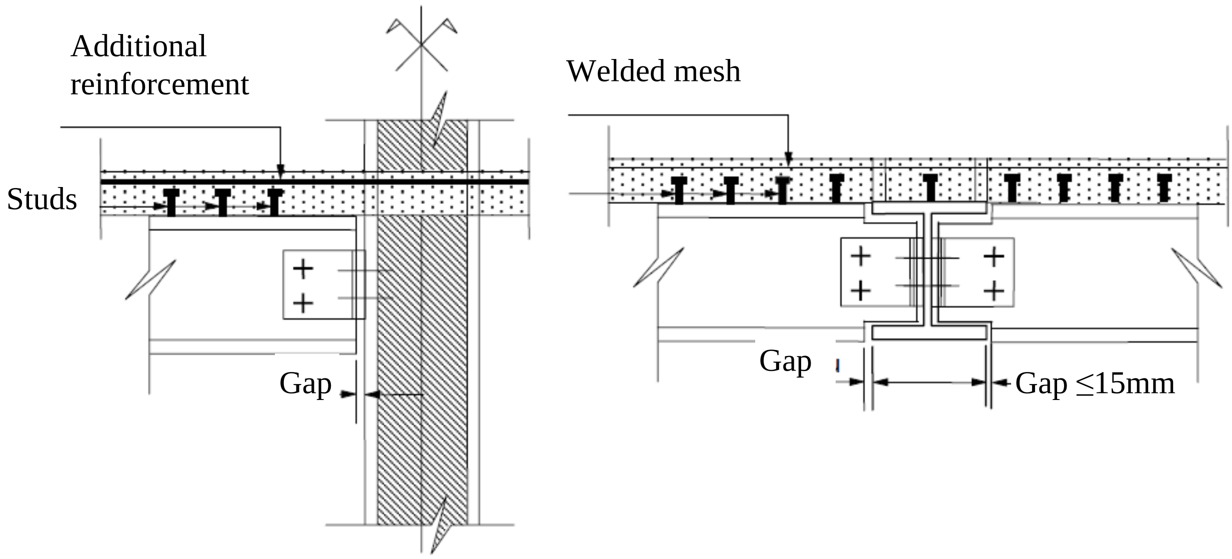


Figure 5-5 Beam-column and beam-beam connection

5.4 Composite Construction

5.4.1 Composite slab

Composite slabs comprise profiled steel decking as the permanent formwork to the underside of "in situ" concrete slabs (construction stage). The decking acts compositely with the concrete under imposed loads (service stage). It supports the loads which are present before the concrete has gained adequate strength and is usually designed to be unpropped during construction. Light mesh reinforcement is placed in the concrete mainly to act as "fire reinforcement" but also to reduce cracking from shrinkage and reverse moment on the supports (Figure 5-6).

Figure 5-6 Composite slab

As a profiled decking for the car park were selected some specially profiled sheets Cofraplus. They achieve a suitable degree of shear connection with the concrete by embossment and indentations (open ribs) around the profile.

The design of steel decking (construction stage) is covered by Eurocode 3(PN-EN-1993-1-1) Part 1.3 which relates to the design of steel sections, decking and roof sheeting. The elastic moment of the section is established taking account of the effective width of the thin steel elements in compression

Composite slab design (service stage) is generally based on information provided by the decking manufacturer in the form of allowable load tables. These values are determined from test results and their interpretation as required in Eurocode 4 (PN-EN-1993-1-4).

5.4.2 Composite beams

The composite I beam is essentially T profile with wide flange. The concrete flange is in compression and the steel section is mainly in tension. The forces between the two materials are transferred by shear connectors. The benefits of composite action are increased strength and stiffness that effects on economy of structure.

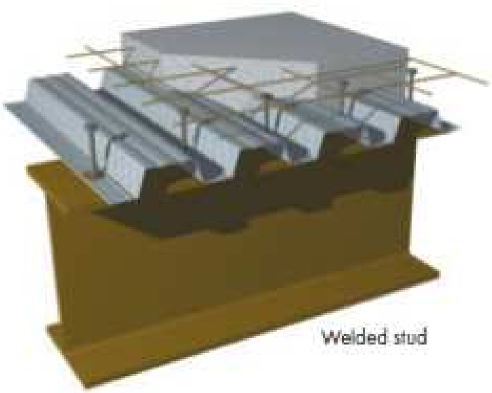


Figure 5-7Composite beam

The steel beam in construction stage is designed in accordance with Eurocode 3 (PN-EN-1993-1-1). Beams are assumed to be laterally restrained by the steel decking in cases where the decking spans perpendicular to the beam (secondary beam) and is directly attached to them by welded through deck studs. In cases when where the decking spans parallel to the beam (primary beams) lateral restraint is provided only by the secondary beams and the buckling resistance of the beam is based on the effective length of the beam between secondary beams.

According to Eurocode 4 (PN-EN-1993-1-4) calculation of the composite beam bases on conception of effective breadth of the concrete compressed flange. The effective breath is limited by the influence of “shear lag” associated with in-plane strains across the concrete.

Resistant bending moment of the composite cross section depends on class of steel profile and degree of shear connection between steel beam and concrete slab.

Resistant shear force of the composite beam is calculated from shear resistance of a steel profile.

Deflection of the composite beam under sagging moment is calculated taking into account equivalent steel cross section obtained by dividing the contribution of the concrete component by modular ratio $n=E_c/E$.

6 Case Study

The method of design presented in this document that includes fire engineering, localised fire, membrane effect and performance-based design had been applied to 5 different geometries of open car parks as illustrated in Figure 6-1. Additionally, two grades of steel had been applied (S235, S355), which makes 10 pre-designed structures.

The main geometrical module of the structure is created by columns located in a grid 16m x 10m (or 5m). This grid enables to locate parking space for the car of the size 5m x 2.5m leaving 6m for the road between the parking spaces. The columns’ are 2.9m high from the floor level to the next floor level. This satisfies the minimum requirement for the high between the floor and the lower flange of the beam and between floor and the ceiling. Although the columns are not part of the design, the high is important to establish size of the flame for the localised fire.

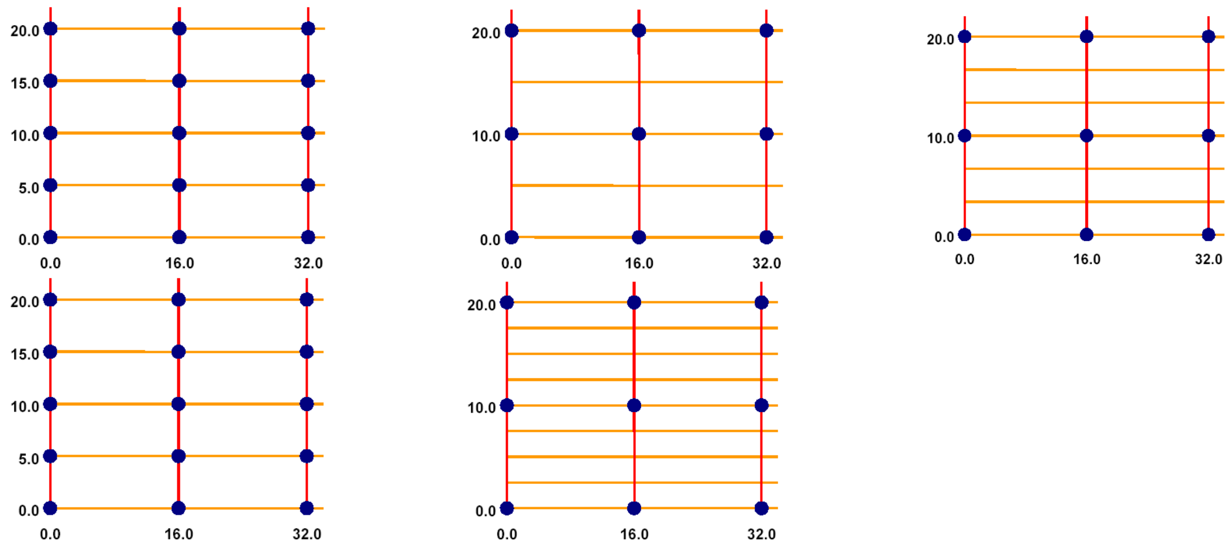


Figure 6-1 Proposed layout of the open car park structure

The slab is a steel decking floor system Cofraplus 60 had been proposed for the structures. The depth of the slab is d=120mm for most of the presented geometry, however in a few cases with larger span a depth of d=150 is needed. The slab is shown in Figure 6-2. The steel deck has a thickness of 0.75mm and normal strength concrete C30/37 was used.

The mesh 150x150mm of diameter from 6mm to 8mm depending on the span is located 3cm from the top of the slab. The 3cm cover is required also by the environmental regulations. Steel grade S500 is always used for the reinforcements.

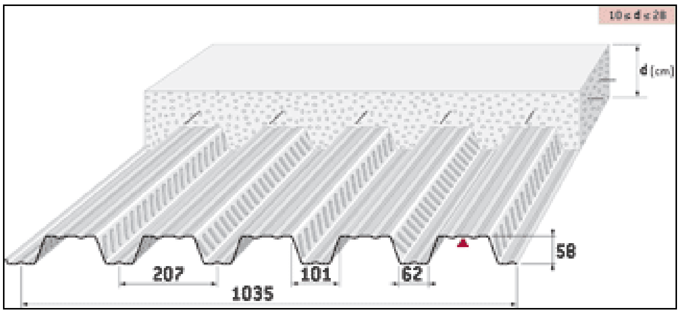


Figure 6-2 Cofraplus 60

7 *Finite Element Modelling*

The approach demonstrated in this document applies the natural fire concept and localised fire approach. Therefore, it is not possible to use tabulated data for the analysis and advance calculation methods need to be utilised. The “hot design” has two steps.

A special purpose computer program for the analysis of structures under ambient and elevated temperature conditions, SAFIR, was used in this work. The program, which is based on the Finite Element Method (FEM), can be used to study the behaviour of one, two and three-dimensional structures. The program (SAFIR) was developed at the University of Liège, Belgium.

As a finite element program, SAFIR accommodates various elements for different idealization, calculation procedures and various material models for incorporating stress-strain behaviour. The elements include the 2-D SOLID elements, 3-D SOLID elements, BEAM elements, SHELL elements and TRUSS elements. The stress-strain material laws are generally linear-elliptic for steel and non-linear for concrete.

Using the program, the analysis of a structure exposed to fire may consist of several steps. The first step involves predicting the temperature distribution inside the structural members, referred to as ‘*thermal analysis*’. The torsional analysis may be necessary for 3-D BEAM elements, a section subject to warping and where the warping function table and torsional stiffness of the cross section are not available. The last part of the analysis, termed the ‘*structural analysis*’, is carried out for the main purpose of determining the response of the structure due to static and thermal loading.

Simulations performed inhere were made as follow.

The thermal analysis is performed on the 2D cross section of the structural member. The structural model is built from beam elements representing the steel beams and columns and shell element representing the slab.

The structural model has to be prepared in advance in order to specify exactly where the source of fire is located within the structure. Since the localised fire is applied, each of the mesh elements of the structural model will have individually calculated time dependent distribution of temperature.

7.1 Thermal Analysis

The thermal analysis is performed for each mesh element of the structural model due to localised fire approach. Each of the elements is represented by 2D model of its cross section to simulate detailed temperature distribution.

7.1.1 Beams

Although the beam and slab are modeled independently for the thermal analysis, in order to obtain real temperature distribution in the beams a layer of concrete slab is added. The concrete slab has a significant influence on the temperature especially in the upper flange of the steel section. It is important that only the temperature of the steel beam obtained in this analysis are transmitted further for the structural analysis.

In Figure 7-1 boundary conditions are indicated. The steel section and bottom part of the slab is exposed to the heat flux obtained from the Hasemi model. The values depend on the location of the element in respect to the fire source. The upper part of the concrete is exposed to ambient temperature at the beginning of the simulation to be changed reflecting the heat transfer through the section.

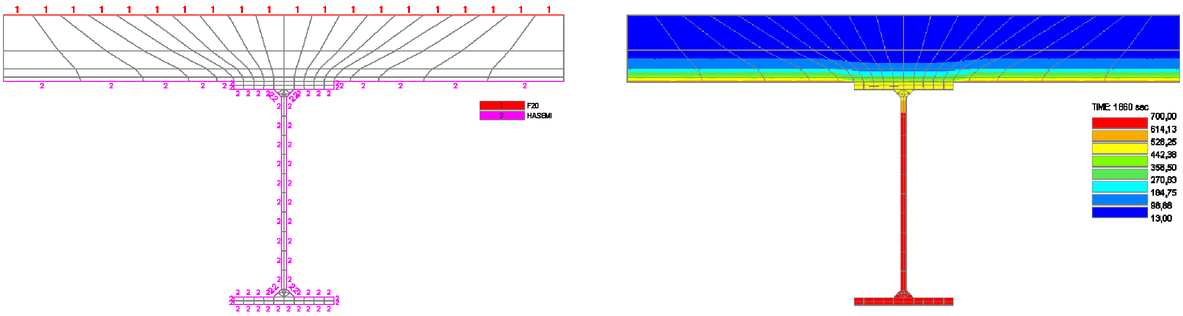


Figure 7-1 Temperature distribution through steel section

7.1.2 Slab

The cross section geometry of the slab system applied in the structure is presented in Figure 7-2. For such a slab EN 1994-1-2:2005 Annex D gives an option to calculate effective thickness of a composite slab and use simplified geometry instead. The effective thickness of a composite slab had been calculated using the following equations:

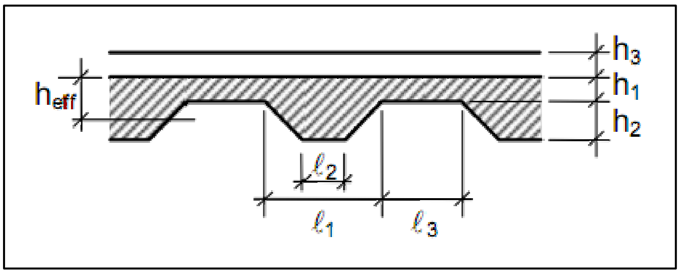


Figure 7-2 Geometry of the Cofraplus 60 slab

$$\begin{cases} h_{eff} = h_1 + 0.5\, h_2 \left(\dfrac{l_1 + l_2}{l_1 + l_3} \right) & for\ \dfrac{h_2}{h_1} < 1.5 \quad and \quad h_1 > 40mm \\ h_{eff} = h_1\ (1 + 0.75 \left(\dfrac{l_1 + l_2}{l_1 + l_3} \right)) & for\ \dfrac{h_2}{h_1} > 1.5 \quad and \quad h_1 < 40mm \end{cases}$$

The finally analyzed slab model is presented in Figure 7-3 where heat flux is applied to the bottom edge based on the Hasemi model and location of the element in respect to the source of fire. Similarly to the beam model the upper edge is initially in ambient temperature, which changes with the heat transfer progressing.

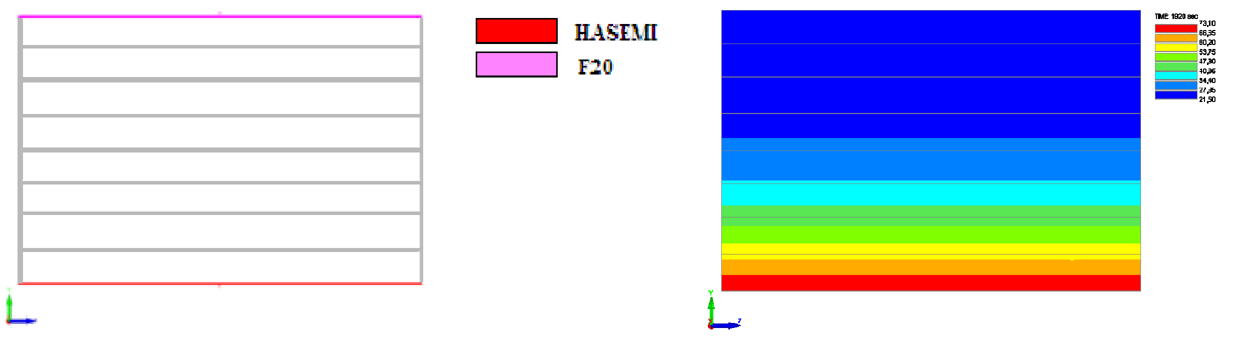


Figure 7-3Temperature distribution through the slab

The effective thickness of a composite slab calculated is used only for the thermal analysis. In the structural analysis the depth of the slab is further reduced to the continuous part only as illustrated in Figure 7-4.

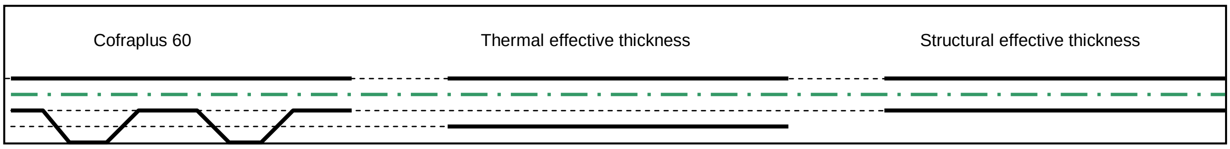


Figure 7-4 Positioning of the equivalent thermal and mechanical heights of the slab

7.2 Structural Analysis

Structural model is composed from “beam elements” representing beams and columns and “shell elements” representing the slab.

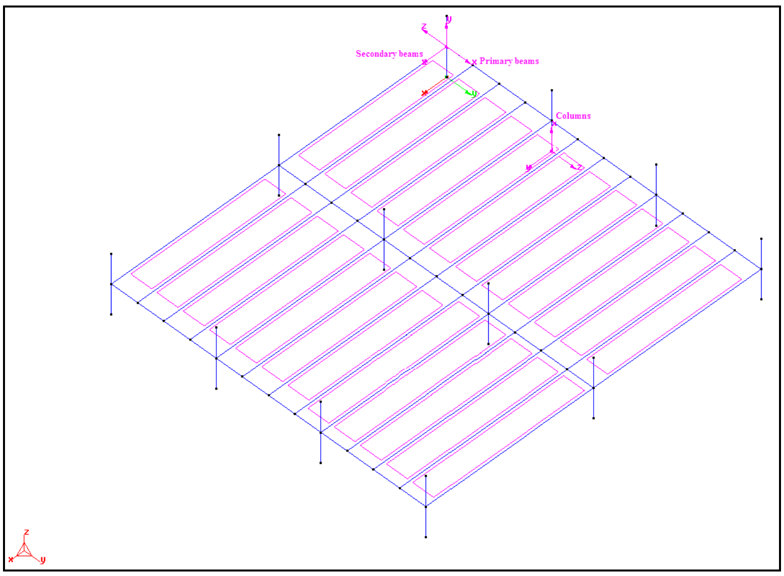


Figure 7-5 Structural model of the car park

7.2.1 Boundary Conditions

Boundary conditions at the supports

In order to reflect reality and be on the save side of the design, the columns are considered pinned at the bottom. For the FE model it means that all three translational degrees of freedom are blocked while the rotations are free.

At the top of columns the horizontal translational degrees of freedom are blocked, while the vertical movement and the rotations are allowed. This is the situation when another floor system is connected to the top of the columns.

Additionally these boundary conditions guarantee the stability of the structure, which is otherwise performed by bracing.

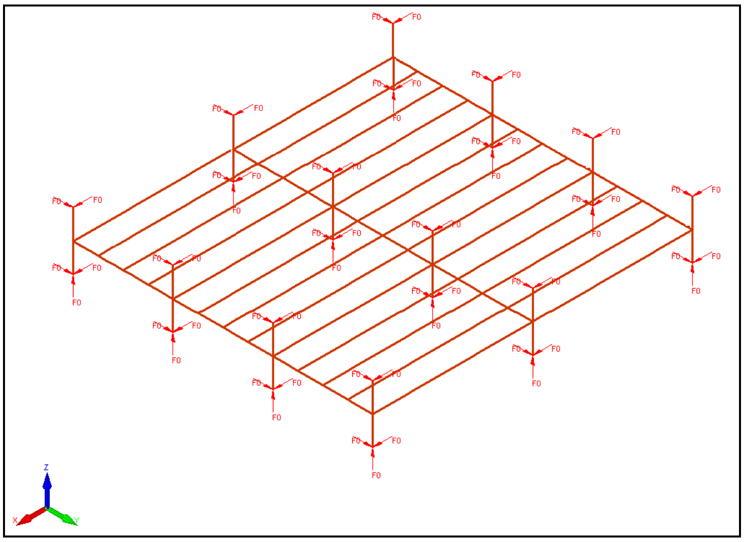


Figure 7-6 Boundary conditions at the supports

Conditions of continuity of the slab

The model represents part of the larger structure. In order to enable the extension of the structure in both horizontal directions additional boundary conditions on the slab level have to be applied. The horizontal movement of the slab is blocked in order to simulate continuity of the slab as shown in Figure 7-7.

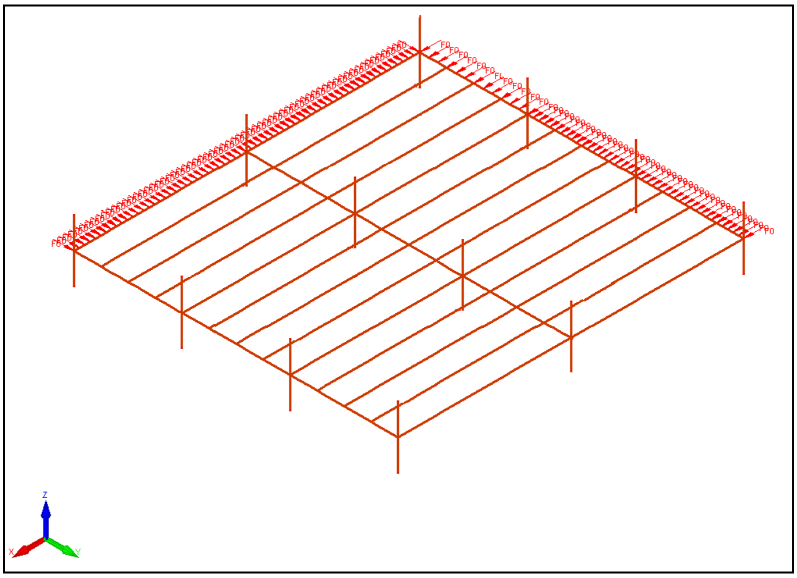


Figure 7-7 Continuity conditions on the level of the slab

Connection between elements in the model

By default SAFIR applies a perfect connection between elements with a common node. Therefore, it is considered that between secondary and primary beams, there is full connection in the node they share. Similarly, the connection between beams and columns.

This connection can be modified manually, but in the case analysed here the full connection is assumed based on the assuptions and recommendations specified for connections and reiforcement.

Thanks to this feature of the software it is easy to apply full composite connection between beams and slabs, just by utilisation of commond nodes between these two elements.

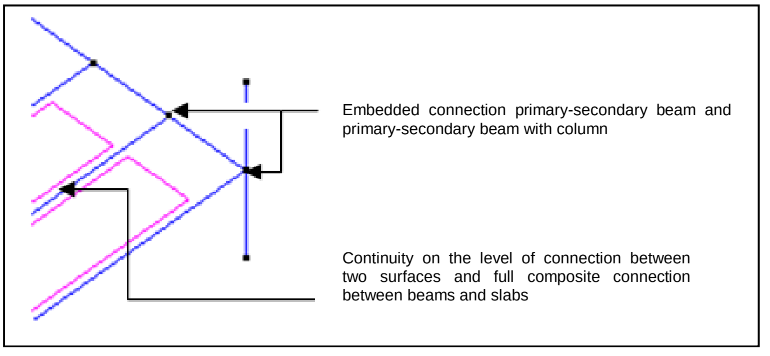


Figure 7-8 Connections between elements of the model

7.2.2 Mesh model

The mesh is modelled by quadrilateral regular elements size 50x50cm in the area where the temperature will be the higher and large deformations are expected. The mesh is finer also in places where it will be beneficial to increase precision.

On the other part of the car parks further from the fire source, the mesh doesn't have to be so fine. Consequently, in this area the mesh elements have dimension 84x50cm.

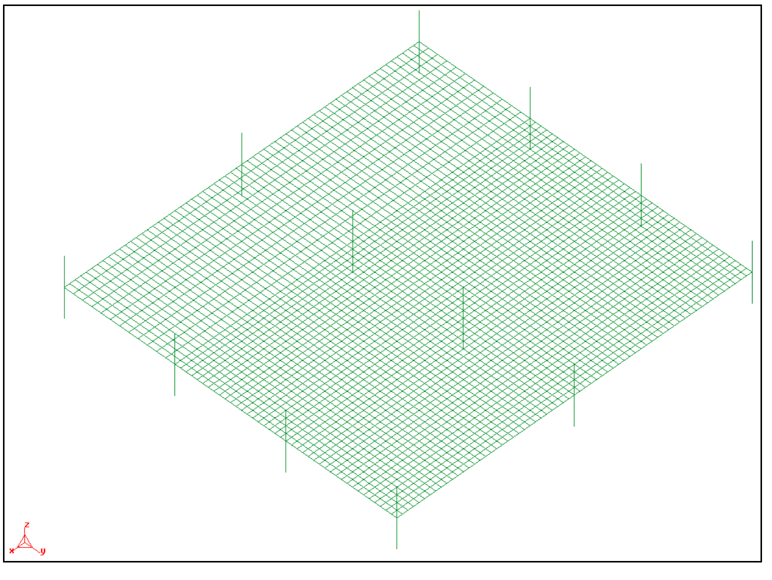


Figure 7-9 Mesh

8 Predesigned Structures

The final result obtained for the presented structures while applying the above described method and fire scenarios are summarised in the table below. Important values in respect to the max deflections and temperature calculated for each individual scenario are presented further in this section and the very detailed results can be found in the Annex 6.

Characteristics			Structural response			
Frame [m] Col 2.9m	Slab span [m]	Steel grade	Secondary beam	Primary beam	Composite slab with concrete C30/37	Steel deck with mesh S500
16x10	2.5m	S235	IPE 450	HEA 650	Cofraplus60 120mm	Ø 8 150x150
		S355	IPE 400	HEA 550		Ø 6 150x150
	3.3m	S235	IPE 550	HEA 700	Cofraplus60 120mm	Ø 7 150x150
		S355	IPE 500	HEA 600		Ø 7 150x150
	5m	S355	IPE 600	HEA 600	Cofraplus60 150mm	Ø 8 100x100
16x5	2.5m	S235	IPE 450	HEA 450	Cofraplus60 120mm	Ø 6 150x150
		S355	IPE 400	IPE 400		Ø 7 150x150
	5m	S355	IPE 600	IPE 160	Cofraplus60 150mm	Ø 8 100x100

Geometry:

Grid 16m x 10m

Slab span 2.5m

Steel grade:

S235

Fire scenario:

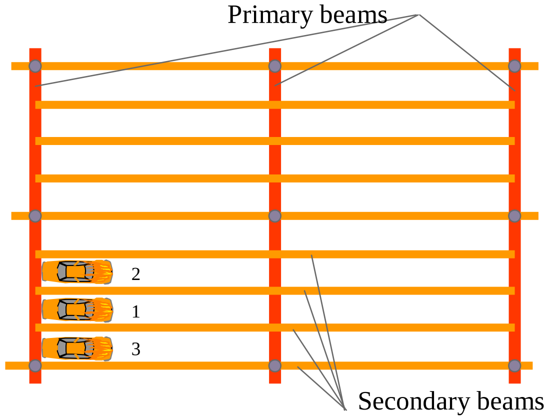
3 cars aligned in the corner

Action:

Permanent: 1 kN/m^2

Variable:2.5 kN/m^2

Combination: 1G + 0.7 Q



Choice of sections:

Secondary beam:	IPE 450
Primary beam:	HEA 650

Choice of floor system:

Slab:	Cofraplus 60 with steel decking 0.75mm
Thickness:	120 mm
Reinforcement:	150mm x150mm Ø6

Position of the reinforcement from the top of the slab: 31mm

Thermal response:

Max temperature in the slab:	775 ºC
Max temperature in the reinforcement:	198 ºC
Location:	in front of the car n º1
Max temperature in the beam:	876 ºC
Location:	on both sides of the car º1

Mechanical response:

Max deflection in the slab:	28.07cm
Location:	above the car n º1
Max deflection in the secondary beam:	23.46cm
Location:	between cars n º1 and º2

Composite connections:

1 row of Nelson steel stubs of Ø19mm, placed every 20.7cm on the secondary beam

1 row of Nelson steel stubs of Ø19mm, placed every 20.7cm on the primary beam

Without propping in the construction stage

Geometry:

Grid 16m x 10m

Slab span 2.5m

Steel grade:

S235

Fire scenario:

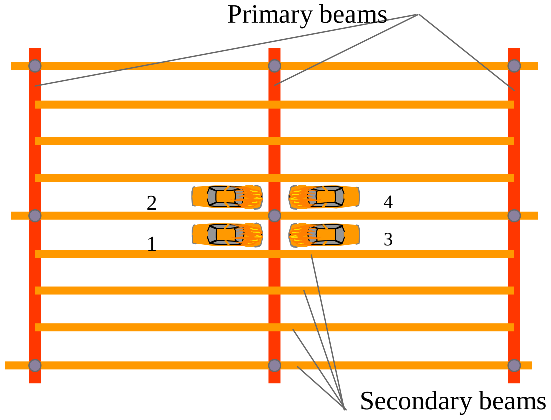
4 cars around a column

Action:

Permanent: 1 kN/m^2

Variable:2.5 kN/m^2

Combination: 1G + 0.7 Q



Choice of sections:

Secondary beam: IPE 450

Primary beam: HEA650

Choice of floor system:

Slab: Cofraplus 60 with steel decking 0.75mm

Thickness: 120mm

Reinforcement: 150mm x 150mm Ø8mm

Position of the reinforcement from the top of the slab: 31mm

Thermal response:

Max temperature in the slab: 763ºC

Max temperature in the reinforcement: 183ºC

Location: above the car nº1

Max temperature in the beam: 875ºC

Location : between car nº1 and nº2

Mechanical response:

Max deflection in the slab: 32.81cm

Location: above the car nº4

Max deflection in the secondary beam: 31.91cm

Location: between cars nº3 and nº4

Composite connections:

1 row of Nelson steel stubs of Ø19mm, placed every 20.7cm on the secondary beam

1 row of Nelson steel stubs of Ø19mm, placed every 20.7cm on the primary beam

Without propping in the construction stage

Geometry:

Grid 16m x 10m

Slab span 2.5m

Steel grade:

S355

Fire scenario:

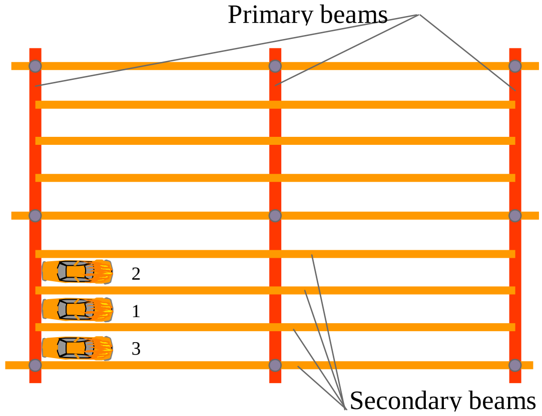
3 cars aligned in the corner

Action:

Permanent: 1 kN/m^2

Variable: 2.5 kN/m^2

Combination: 1G + 0.7 Q



Choice of sections:

Secondary beam:	IPE 400
Primary beam:	HEA 550

Choice of floor system:

Slab:	Cofraplus 60 with steel decking 0.75mm
Thickness:	120mm
Reinforcement:	150mm x 150mm Ø6mm

Position of the reinforcement from the top of the slab: 31mm

Thermal response:

Max temperature in the slab:	775ºC
Max temperature in the reinforcement:	198 ºC
Location:	in from of the car nº1
Max temperature in the beam:	877 ºC
Location:	on both sides oft the car nº1

Mechanical response:

Max deflection in the slab:	30.06cm
Location:	zone above the car nº1
Max deflection in the secondary beam:	27.94cm
Location:	between cars nº1 and nº2

Composite connections:

1 row of Nelson steel stubs of Ø19mm, placed every 20.7cm on the secondary beam

1 row of Nelson steel stubs of Ø19mm, placed every 20.7cm on the primary beam

Without propping in the construction stage

Geometry:

Grid 16m x 10m

Slab span 2.5m

Steel grade:

S355

Fire scenario:

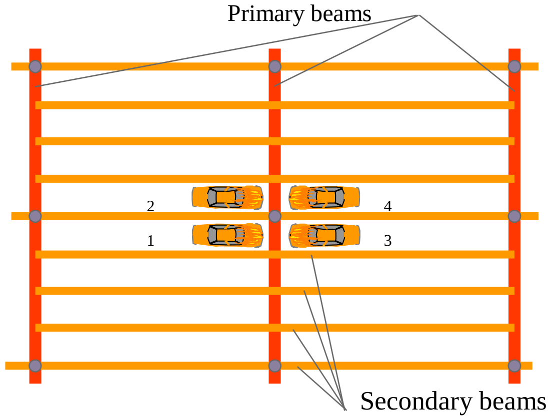
4 cars around a column

Action:

Permanent: 1 kN/m^2

Variable: 2.5 kN/m^2

Combination: 1G + 0.7 Q



Choice of sections:

Secondary beam:	IPE400
Primary beam :	HEA 550

Choice of floor system:

Slab:	Cofraplus 60 with steel decking 0.75mm
Thickness:	120mm
Reinforcement:	150mm x 150mm Ø6mm

Position of the reinforcement from the top of the slab: 31mm

Thermal response:

Max temperature in the slab:	763 ºC
Max temperature in the reinforcement:	183 ºC
Location:	in from of the car n º1
Max temperature in the beam:	876 ºC
Location:	between cars n º3 and nº4

Mechanical response:

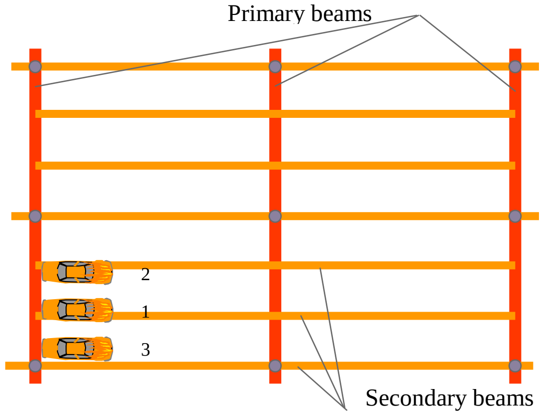
Max deflection in the slab:	37.82cm
Location:	zone above the car n º4
Max deflection in the secondary beam:	34.88cm
Location:	between car n º3 and n º4

Composite connections:

1 row of Nelson steel stubs of Ø19mm, placed every 20.7cm on the secondary beam

1 row of Nelson steel stubs of Ø19mm, placed every 20.7cm on the primary beam

Without propping in the construction stage

Geometry: Grid 16m x 10m Slab span 3.3m	
Steel grade: S235	
Fire scenario: 3 cars aligned in the corner	
Action: Permanent: 1 kN/m^2 Variable: 2.5 kN/m^2 Combination: 1G + 0.7 Q	

Choice of sections:	
Secondary beam:	IPE 550
Primary beam:	HEA 700
Choice of floor system:	
Slab:	Cofraplus 60 with steel decking 0.75mm
Thickness:	120mm
Reinforcement:	150mm x 150mm Ø7mm
Position of the reinforcement from the top of the slab:	31mm
Thermal response:	
Max temperature in the slab:	776º
Max temperature in the reinforcement:	198º
Location:	in front of the car nº1
Max temperature in the beam:	876º
Location:	between car nº1 and nº3
Mechanical response:	
Max deflection in the slab:	20.97cm
Location:	zone above the car nº1
Max deflection in the secondary beam:	17.89cm
Location:	between car nº1 and nº3
Composite connections:	
1 row of Nelson steel stubs of Ø19mm, placed every 20.7cm on the secondary beam	
1 row of Nelson steel stubs of Ø19mm, placed every 20.7cm on the primary beam	
Without propping in the construction stage	

Geometry:

Grid 16m x 10m

Slab span 3.3m

Steel grade:

S235

Fire scenario:

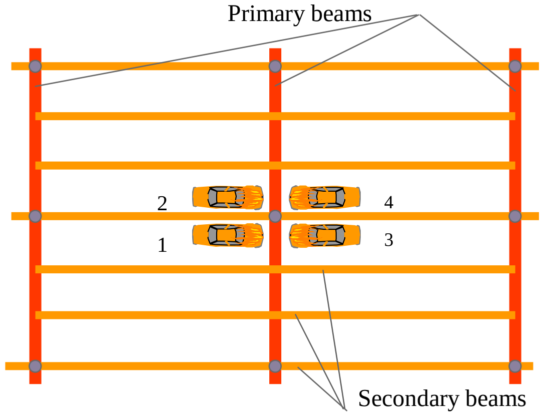
4 cars around column

Action:

Permanent: 1 kN/m^2

Variable: 2.5 kN/m^2

Combination: 1G + 0.7 Q



Choice of sections:

Secondary beam: IPE550

Primary beam: HEA 700

Choice of floor system:

Slab: Cofraplus 60 with steel decking 0.75mm

Thickness: 120mm

Reinforcement: 150mm x 150mm Ø7mm

Position of the reinforcement from the top of the slab: 31mm

Thermal response:

Max temperature in the slab: 758ºC

Max temperature in the reinforcement: 183ºC

Location: in front of the car nº1

Max temperature in the beam: 866ºC

Location: between car nº1 and nº2

Mechanical response:

Max deflection in the slab: 30.51cm

Location: zone above the car nº4

Max deflection in the secondary beam: 25.02cm

Location: between car nº3 and nº4

Composite connections:

1 row of Nelson steel stubs of Ø19mm, placed every 20.7cm on the secondary beam

1 row of Nelson steel stubs of Ø19mm, placed every 20.7cm on the primary beam

Without propping in the construction stage

Geometry:

Grid 16m x 10m

Slab span 3.3m

Steel grade:

S255

Fire scenario:

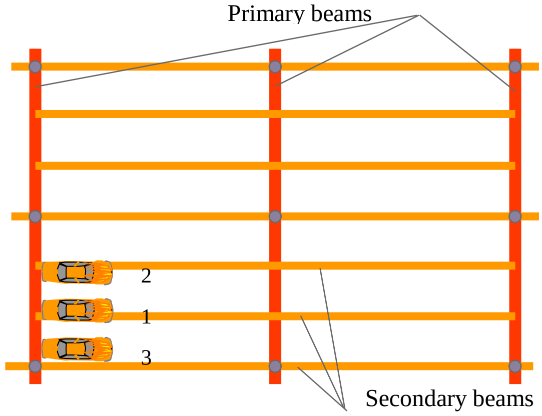
3 cars aligned in the corner

Action:

Permanent: 1 kN/m^2

Variable: 2.5 kN/m^2

Combination: 1G + 0.7 Q



Choice of sections:

Secondary beam:	IPE 500
Primary beam:	HEA 600

Choice of floor system:

Slab:	Cofraplus 60 with steel decking 0.75mm
Thickness:	120mm
Reinforcement:	150mm x 150mm Ø7mm

Position of the reinforcement from the top of the slab: 31mm

Thermal response:

Max temperature in the slab:	776º
Max temperature in the reinforcement:	198º
Location:	in front of the car nº1
Max temperature in the beam:	876º
Location:	between car nº1 and nº3

Mechanical response:

Max deflection in the slab:	25.85cm
Location:	zone above the car nº1
Max deflection in the secondary beam:	22.67cm
Location:	between car nº1 and nº3

Composite connections:

1 row of Nelson steel stubs of Ø19mm, placed every 20.7cm on the secondary beam

1 row of Nelson steel stubs of Ø19mm, placed every 20.7cm on the primary beam

Without propping in the construction stage

Geometry:

Grid 16m x 10m

Slab span 3.3m

Steel grade:

S355

Fire scenario:

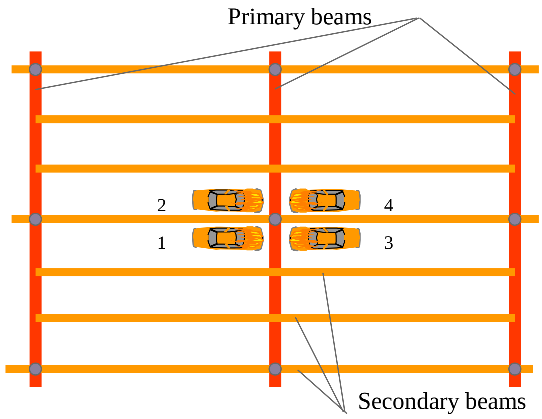
4 cars around column

Action:

Permanent: 1 kN/m^2

Variable: 2.5 kN/m^2

Combination: 1G + 0.7 Q



Choice of sections:

Secondary beam:	IPE500
Primary beam:	HEA 600

Choice of floor system:

Slab:	Cofraplus 60 with steel decking 0.75mm
Thickness:	120mm
Reinforcement:	150mm x 150mm Ø7mm

Position of the reinforcement from the top of the slab: 31mm

Thermal response:

Max temperature in the slab:	758ºC
Max temperature in the reinforcement:	183ºC
Location:	in front of the car nº1
Max temperature in the beam:	866ºC
Location:	between car nº1 and nº2

Mechanical response:

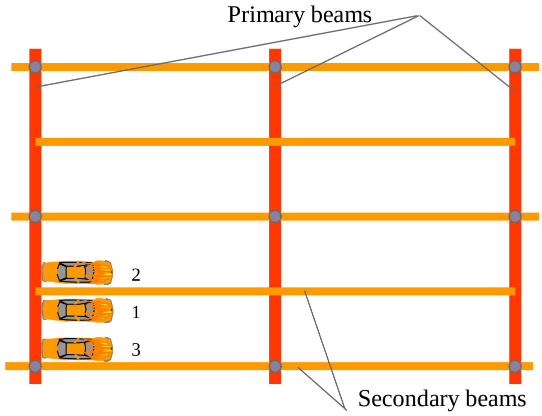
Max deflection in the slab:	31.8cm
Location:	zone above the car nº4
Max deflection in the secondary beam:	26.58cm
Location:	between car nº3 and nº4

Composite connections:

1 row of Nelson steel stubs of Ø19mm, placed every 20.7cm on the secondary beam

1 row of Nelson steel stubs of Ø19mm, placed every 20.7cm on the primary beam

Without propping in the construction stage

Geometry: Grid 16m x 10m Slab span 5m	
Steel grade: S355	
Fire scenario: 3 cars aligned in the corner	
Action: Permanent: 1 kN/m^2 Variable: 2.5 kN/m^2 Combination: 1G + 0.7 Q	

Choice of sections:

Secondary beam: IPE600

Primary beam: HEA600

Choice of floor system:

Slab: Cofraplus 60 with steel decking 0.75mm

Thickness: 150mm

Reinforcement: 100mm x 100mm Ø8mm

Position of the reinforcement from the top of the slab: 46mm

Thermal response:

Max temperature in the slab: 775ºC

Max temperature in the reinforcement : 140ºC

Location: in front of the car nº1

Max temperature in the beam: 867ºC

Location: between car nº1 and nº2

Mechanical response:

Max deflection in the slab: 23.23cm

Location: zones above cars nº1 and nº3

Max deflection in the secondary beam: 19.79cm

Location: between car nº1 and nº2

Composite connections:

1 row of Nelson steel stubs of Ø22mm, placed every 20.7cm on the secondary beam

1 row of Nelson steel stubs of Ø22mm, placed every 20.7cm on the primary beam

The secondary beams have to be propped in at least 2 places and the slab needs to be also propped in the construction stage.

Geometry:

Grid 16m x 10m

Slab span 5m

Steel grade:

S355

Fire scenario:

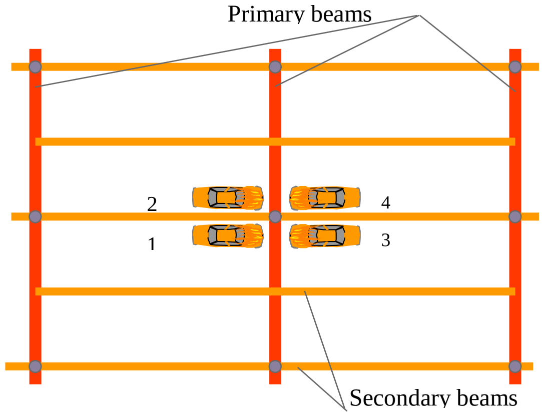
4 cars around a column

Action:

Permanent: 1 kN/m^2

Variable: 2.5 kN/m^2

Combination: 1G + 0.7 Q



Choice of sections:

Secondary beam:	IPE600
Primary beam :	HEA600

Choice of floor system:

Slab:	Cofraplus 60 with steel decking 0.75mm
Thickness:	150mm
Reinforcement:	100mm x 100mm Ø8mm

Position of the reinforcement from the top of the slab: 46mm

Thermal response:

Max temperature in the slab:	766ºC
Max temperature in the reinforcement:	137ºC
Location:	in from of the car nº1
Max temperature in the beam:	863ºC
Location:	between cars nº1 and nº2

Mechanical response:

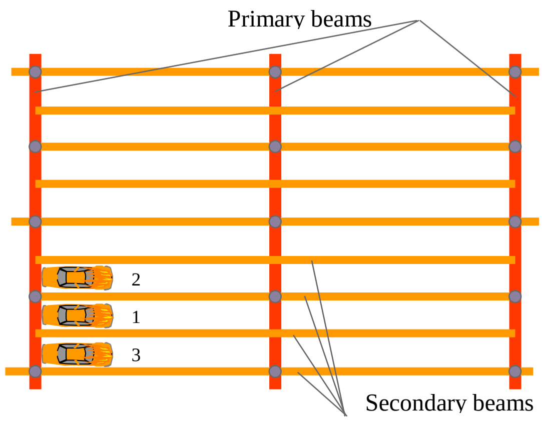
Max deflection in the slab:	26.42cm
Location:	zone above car nº4
Max deflection in the secondary beam:	21.73cm
Location:	between car nº3 and nº4

Composite connections:

1 row of Nelson steel stubs of Ø22mm, placed every 20.7cm on the secondary beam

1 row of Nelson steel stubs of Ø22mm, placed every 20.7cm on the primary beam

The secondary beams have to be propped in at least 2 places and the slab needs to be also propped in the construction stage.

Geometry: Grid 16m x 5m Slab span 2.5m	
Steel grade: S235	
Fire scenario: 3 cars aligned in the corner	
Action: Permanent: 1 kN/m^2 Variable: 2.5 kN/m^2 Combination: 1G + 0.7 Q	

Choice of sections:

Secondary beam: IPE 450

Primary beam : HEA 450

Choice of floor system:

Slab: Cofraplus 60 with steel decking 0.75mm

Thickness: 120mm

Reinforcement: 150mm x 150mm Ø6mm

Position of the reinforcement from the top of the slab: 31mm

Thermal response:

Max temperature in the slab: 775°C

Max temperature in the reinforcement: 198°C

Location: in front car n°1

Max temperature in the beam: 876°C

Location : in both sides of the car n°1

Mechanical response:

Max deflection in the slab: 24.85cm

Location: zone above car n°1

Max deflection in the secondary beam: 23.26cm

Location : between car n°1 and n°2

Composite connections:

1 row of Nelson steel stubs of Ø 19mm, placed every 20.7cm on the secondary beam

1 row of Nelson steel stubs of Ø 19mm, placed every 20.7cm on the primary beam

Without propping in the construction stage

Geometry:

Grid 16m x 5m

Slab span 2.5m

Steel grade:

S235

Fire scenario:

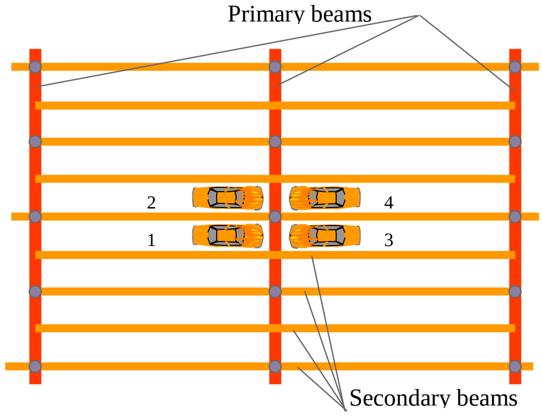
4 cars around a column

Action:

Permanent: 1 kN/m^2

Variable: 2.5 kN/m^2

Combination: 1G + 0.7 Q



Choice of sections:

Secondary beam:	IPE450
Primary beam :	HEA 450

Choice of floor system:

Slab:	Cofraplus 60 with steel decking 0.75mm
Thickness:	120mm
Reinforcement:	150mm x 150mm Ø6mm

Position of the reinforcement from the top of the slab: 31mm

Thermal response:

Max temperature in the slab:	757ºC
Max temperature in the reinforcement:	182ºC
Location:	in front of car nº1
Max temperature in the beam:	875ºC
Location:	between cars nº1 and nº2

Mechanical response:

Max deflection in the slab:	31.65mm
Location:	zone above car nº4
Max deflection in the secondary beam:	31.26cm
Location:	between car nº3 and nº4

Composite connections:

1 row of Nelson steel stubs of Ø 19mm, placed every 20.7cm on the secondary beam

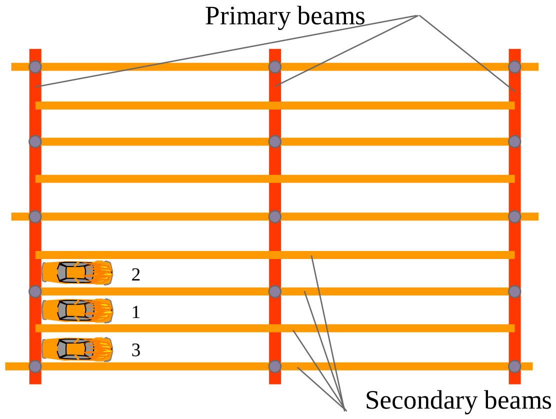
1 row of Nelson steel stubs of Ø 19mm, placed every 20.7cm on the primary beam

Without propping in the construction stage

Geometry:

Grid 16m x 5m

Slab span 2.5m



Steel grade:

S355

Fire scenario:

3 cars aligned in the corner

Action:

Permanent: 1 kN/m^2

Variable: 2.5 kN/m^2

Combination: 1G + 0.7 Q

Choice of sections:

Secondary beam:	IPE400
Primary beam :	IPE 400

Choice of floor system:

Slab:	Cofraplus 60 with steel decking 0.75mm
Thickness:	120mm
Reinforcement:	150mm x150mm Ø7mm

Position of the reinforcement from the top of the slab: 31mm

Thermal response:

Max temperature in the slab:	775°C
Max temperature in the reinforcement:	198°c
Location:	in front of car n°1
Max temperature in the beam:	876°c
Location :	on both sides of car n°1

Mechanical response:

Max deflection in the slab:	26.81cm
Location:	zone above the car n°1
Max deflection in the secondary beam:	25.23cm
Location :	between car n°1 and n°2

Composite connections:

1 row of Nelson steel stubs of Ø 19mm, placed every 20.7cm on the secondary beam

1 row of Nelson steel stubs of Ø 19mm, placed every 20.7cm on the primary beam

Without propping in the construction stage

Geometry:

Grid 16m x 5m

Slab span 2.5m

Steel grade:

S355

Fire scenario:

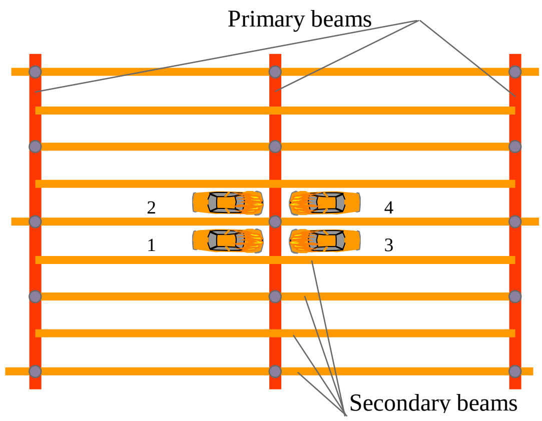
4 cars around a column

Action:

Permanent: 1 kN/m^2

Variable: 2.5 kN/m^2

Combination: 1G + 0.7 Q



Choice of sections:

Secondary beam:	IPE400
Primary beam :	IPE400

Choice of floor system:

Slab:	Cofraplus 60 with steel decking 0.75mm
Thickness:	120mm
Reinforcement:	150mm x150mm Ø8mm

Position of the reinforcement from the top of the slab: 31mm

Thermal response:

Max temperature in the slab:	757°C
Max temperature in the reinforcement:	182°C
Location:	in front of car n°1
Max temperature in the beam:	875°C
Location:	between cars n°1 and n°2

Mechanical response:

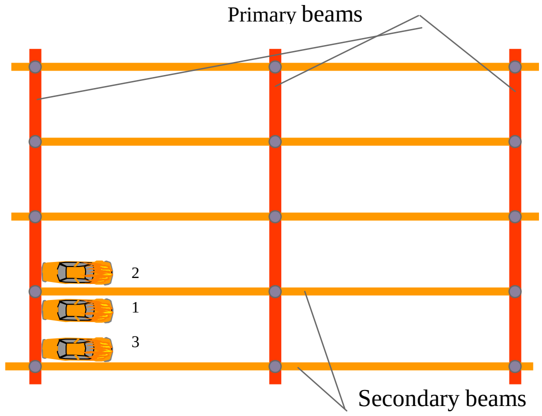
Max deflection in the slab:	33.86cm
Location:	zone above car n°4
Max deflection in the secondary beam:	33.51cm
Location :	between car n°3 and n°4

Composite connections:

1 row of Nelson steel stubs of Ø 19mm, placed every 20.7cm on the secondary beam

1 row of Nelson steel stubs of Ø 19mm, placed every 20.7cm on the primary beam

Without propping in the construction stage

<table>
<tr><td>Geometry:
Grid 16m x 5m
Slab span 5m</td><td rowspan="4">
</td></tr>
<tr><td>Steel grade:
S355</td></tr>
<tr><td>Fire scenario:
3 cars aligned in the corner</td></tr>
<tr><td>Action:
Permanent: 1 kN/m^2
Variable: 2.5 kN/m^2
Combination: 1G + 0.7 Q</td></tr>
<tr><td colspan="2">Choice of sections:
Secondary beam: IPE600
Primary beam : IPE 160</td></tr>
<tr><td colspan="2">Choice of floor system:
Slab: Cofraplus 60 with steel decking 0.75mm
Thickness: 150mm
Reinforcement: 100mm x100mm Ø8mm
Position of the reinforcement from the top of the slab: 46mm</td></tr>
<tr><td colspan="2">Thermal response:
Max temperature in the slab: 766ºC
Max temperature in the reinforcement: 137ºC
Location: in front of the car nº1
Max temperature in the beam: 863ºC
Location: between car nº1 and nº2</td></tr>
<tr><td colspan="2">Mechanical response:
Max deflection in the slab: 23.57cm
Location: zone above cars nº1 and nº3
Max deflection in the secondary beam: 16.63cm
Location: between cars nº1 and nº2</td></tr>
<tr><td colspan="2">Composite connections:
1 row of Nelson steel stubs of Ø 22mm, placed every 20.7cm on the secondary beam
The primary beams don’t act as composite with the slab
The secondary beams need to be propped in two places and the slab needs to be propped in the middle</td></tr>
</table>

Geometry:

Grid 16m x 5m

Slab span 5m

Steel grade:

S355

Fire scenario:

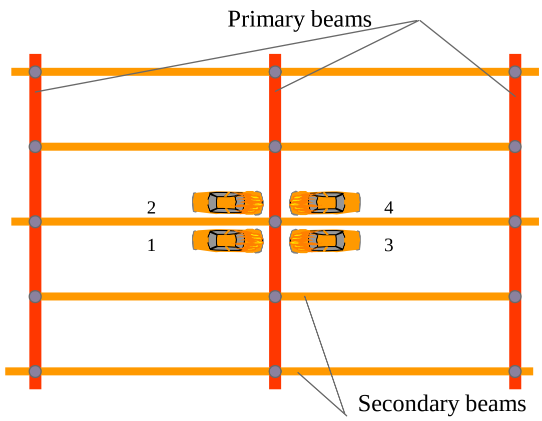
4 cars around a column

Action:

Permanent: 1 kN/m^2

Variable: 2.5 kN/m^2

Combination: 1G + 0.7 Q



Choice of sections:

Secondary beam: IPE600

Primary beam : IPE160

Choice of floor system:

Slab: Cofraplus 60 with steel decking 0.75mm

Thickness: 150mm

Reinforcement: 100mm x100mm Ø8mm

Position of the reinforcement from the top of the slab: 46mm

Thermal response:

Max temperature in the slab: 766ºC

Max temperature in the reinforcement: 137ºC

Location: in front of the car nº1

Max temperature in the beam: 863ºC

Location: between car nº1 and nº2

Mechanical response:

Max deflection in the slab: 24.8cm

Location: above the car nº3

Max deflection in the secondary beam: 22.22cm

Location: between cars nº3 and nº4

Composite connections:

1 row of Nelson steel stubs of Ø 22mm, placed every 20.7cm on the secondary beam

The primary beams don’t act as composite with the slab

The secondary beams need to be propped in two places and the slab needs to be propped in the middle

9 Annex 1: Membrane action

In the elevated temperature strength and stiffness of the steel elements is reduced. This has a direct consequence towards the behaviour steel frame structure subjected to fire. In structure such as the presented in this documents car parks, which are built from the steel frame and composite slab system, development of the tensile membrane action is observed when the structure is exposed to fire.

The membrane action is developing in the slab when the beams loosing their strength and stiffness, which is accompanied by increasing deflections. The deflection can reach the level of 30 - 40 cm.

Membrane action of concrete floor slabs is due to the development of in-plane forces within the depth of the slab. The membrane effect is characterized by the balance between the compression in the concrete and the tension in rebars placed inside of the slab.

“For concrete slabs, which are horizontally restrained around their perimeter and subjected to large vertical displacements, membrane action will develop with the reinforcement utilizing its full tensile capacity and supporting the load by acting as a kind of net. This type of behaviour is commonly referred to as tensile membrane action. For slabs that have no horizontal restraint around their perimeter, membrane action can still develop provided the slab is two-way spanning. The slab supports the load by tensile membrane action occurring in the centre of the slab and compressive membrane action forming a supporting ‘ring’ around the perimeter of the slab” [BAI, 02].

This phenomenon is illustrated using a simple example. For this purpose a single frame with diameter 16x10m is used, where distance between the 16m long secondary beams is 2.5m. Only one car class3 is submitted to fire, in order to clearly observe the development of the membrane. As shown in Figure 9-1, the car is positioned in the middle-span of the central secondary beam.

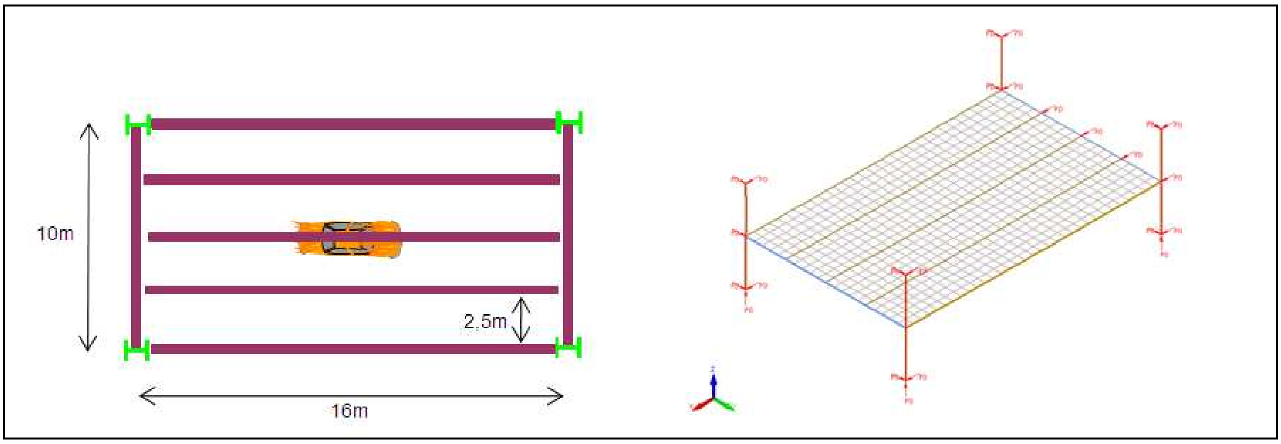


Figure 9-1Scheme of the structure and localisation of fire

The evolution of the deformation in time was measured in the mid-span of the central secondary beam, in order to observe behaviour of the structure at different stage of the fire development. The results are presented in the Figure 9-2.

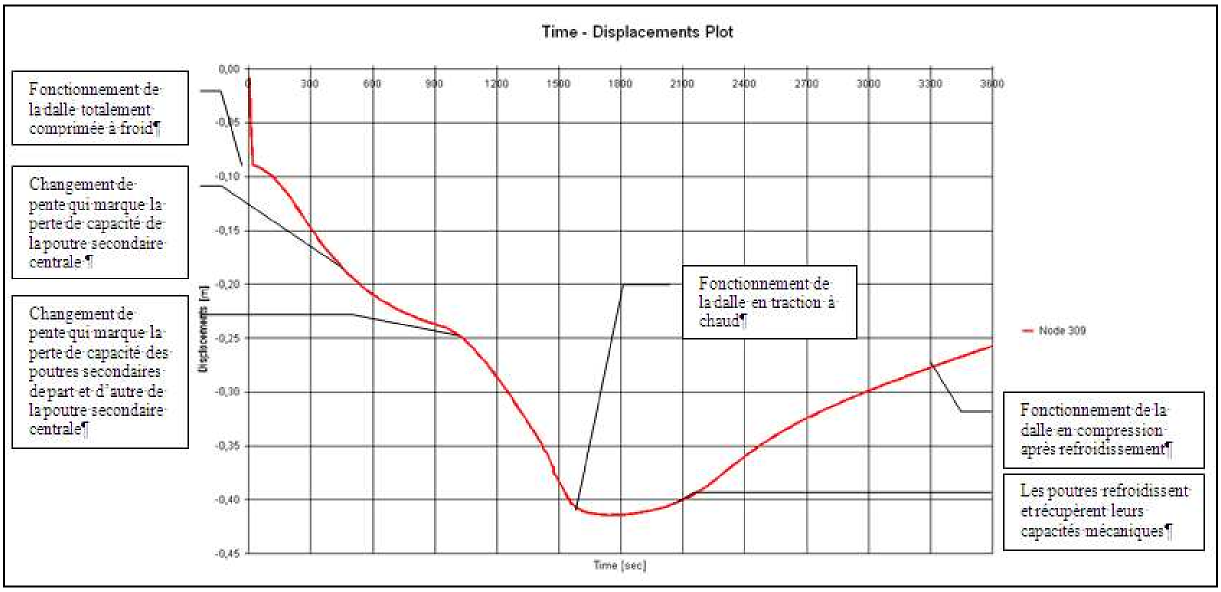
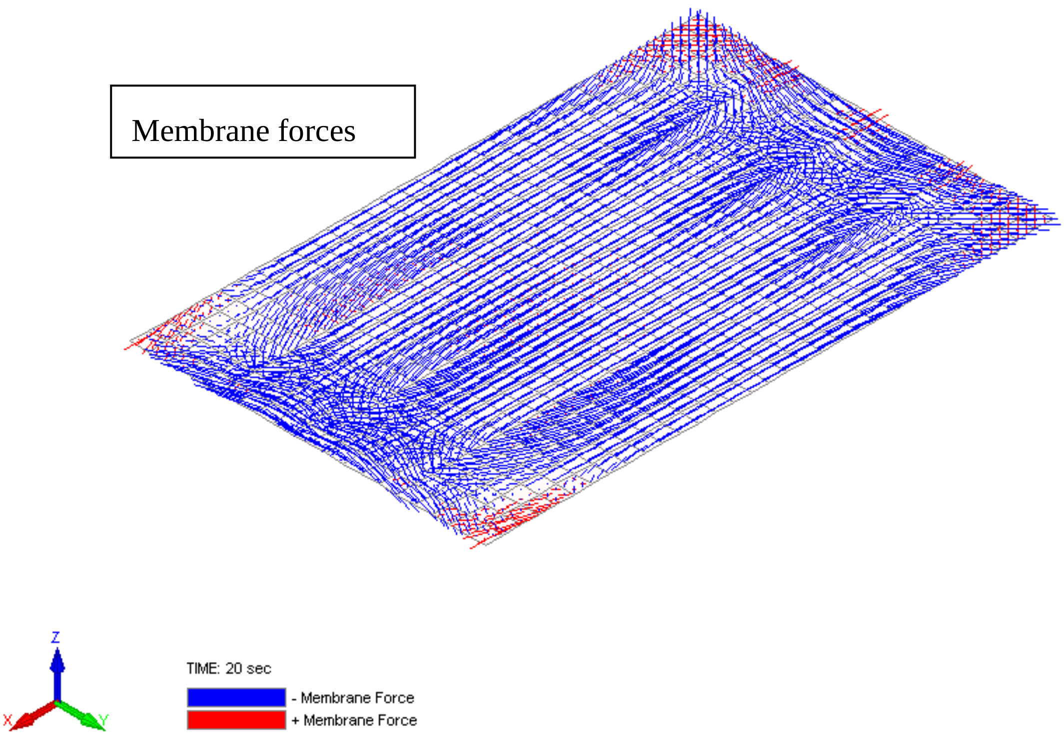


Figure 9-2 Time-displacement chart for the middle of the central secondary beam

The structure and fire scenario had been modelled using finite element software SAFIR.

In order to avoid dynamic effect coming from the simultaneous load of the structure, the static load had been applied successively during the first 20 seconds, while the structure remained in ambient temperature. The effect of the static load on the distribution of forces is presented in Figure 9-3. It can be observed that the slab works mainly in compression, while the secondary beams are subjected to tension and bending.



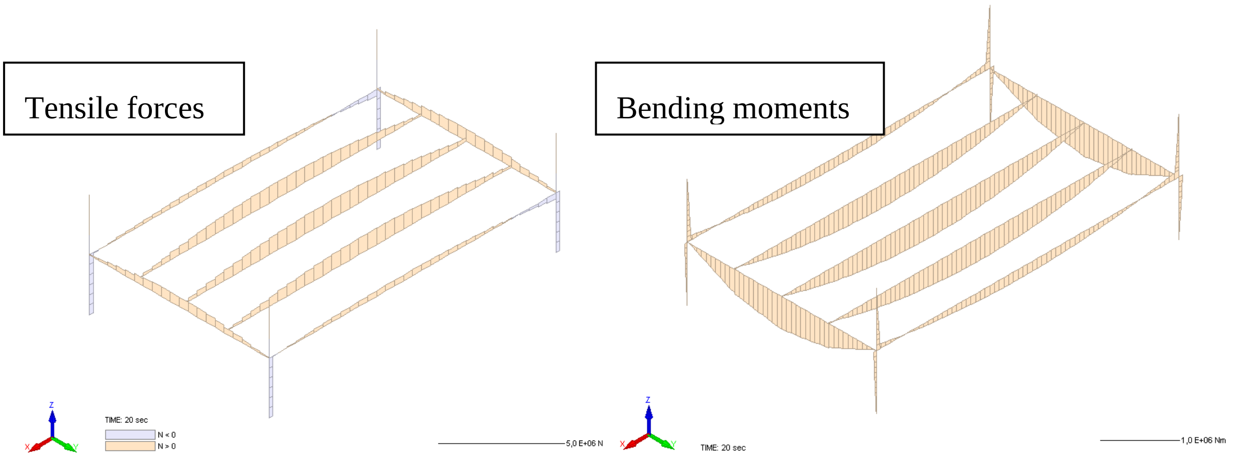


Figure 9-3 Distribution of forces coming from static load in ambient temperature

In 500 seconds the fire is developed. Above the source of fire it can be notice the slab starts turning into tension. It corresponds to the appearance of the first plastic hinge in the secondary beam directly above the burning car.

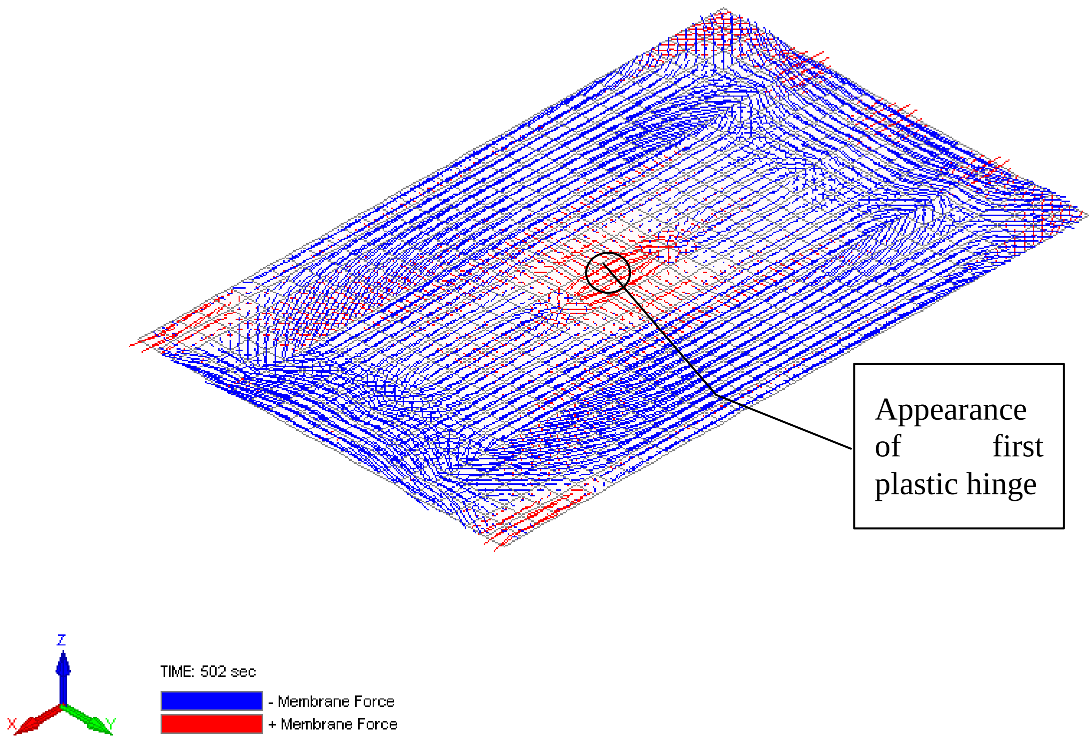


Figure 9-4 Development of the first plastic hinge in the beam and tension in the slab

After 1000 seconds the tension in the slab begins diffuse, and additional two secondary beams form plastic hinges in the mid-span.

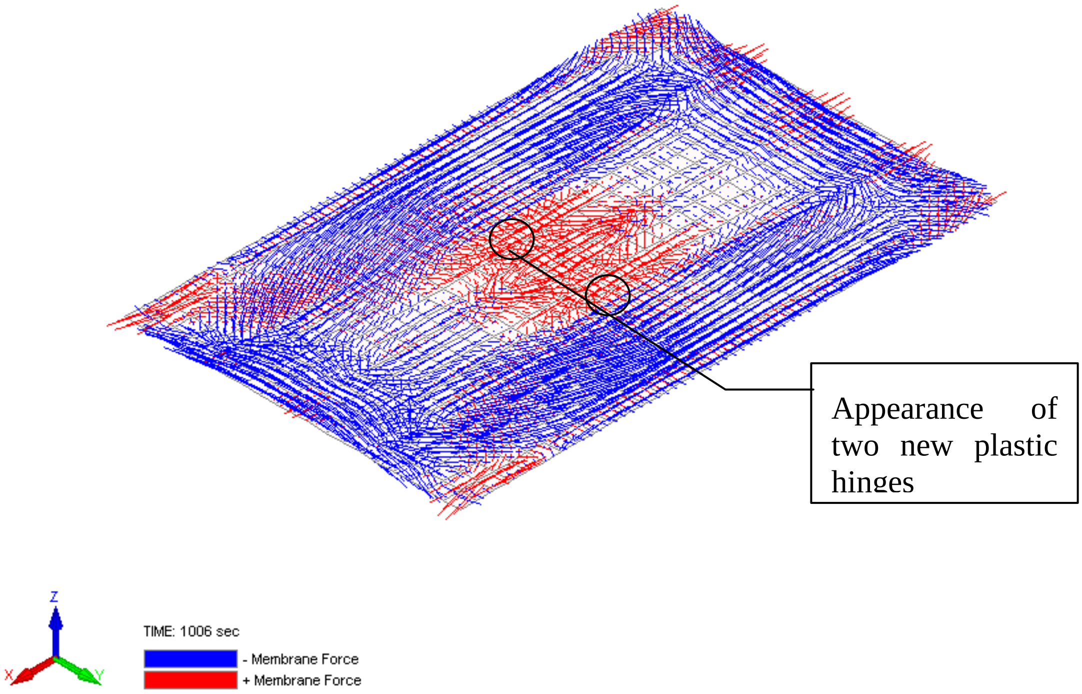
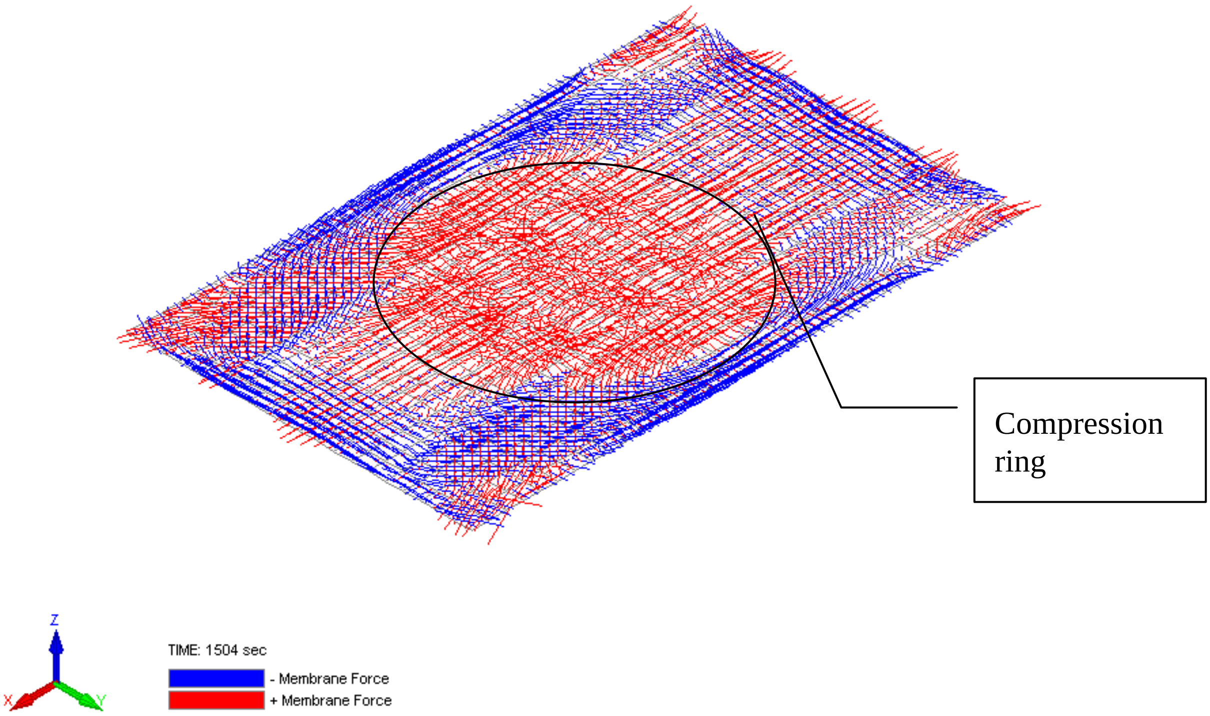


Figure 9-5 Further development of tension in the slab (1000sec in fire)

After 1500 seconds the maximum deflections and the maximum temperature are obtained in the structure. The large deflection appears together with significant membrane forces in the slab.

The tension extends in the slab utilising tensile capacity of the rebars until around the tensile zone a compression ring is created in the concrete slab. The secondary beam directly above the car works in compression whereas both secondary beams on both sides of the car remain in tension.



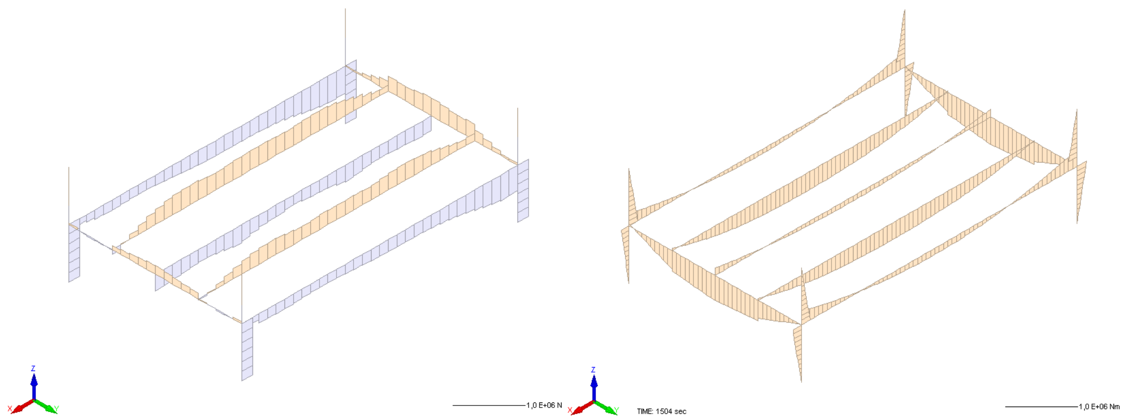


Figure 9-6 Maximum forces developed (1500sec in fire)

The beams do not restrain any relevant strength or stiffness due to very high temperature transferred to the steel. Therefore, the entire load is carried by the membrane.

Figure 9-6 shows the maximum deflections of the slab and the beams in scale.

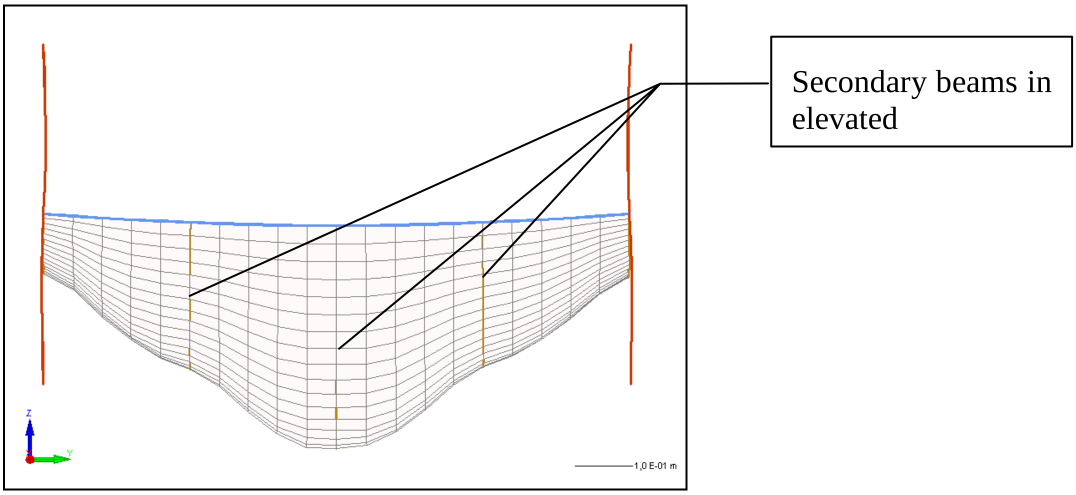


Figure 9-7 Maximum deflections. Front view of the structure

After the peak of temperature all the elements are cooling down as the fire is stopped. Consequently, the beams are regaining their mechanical properties; strength and stiffness. In 2000 seconds, disappearance of the compression ring in the slab can be observed. Fractions of the ring can be still noticeable at extremities of the slab, while in the centre the tension is being slowly replaced by compression. The secondary beam in above the car is also moving from compression to tension.

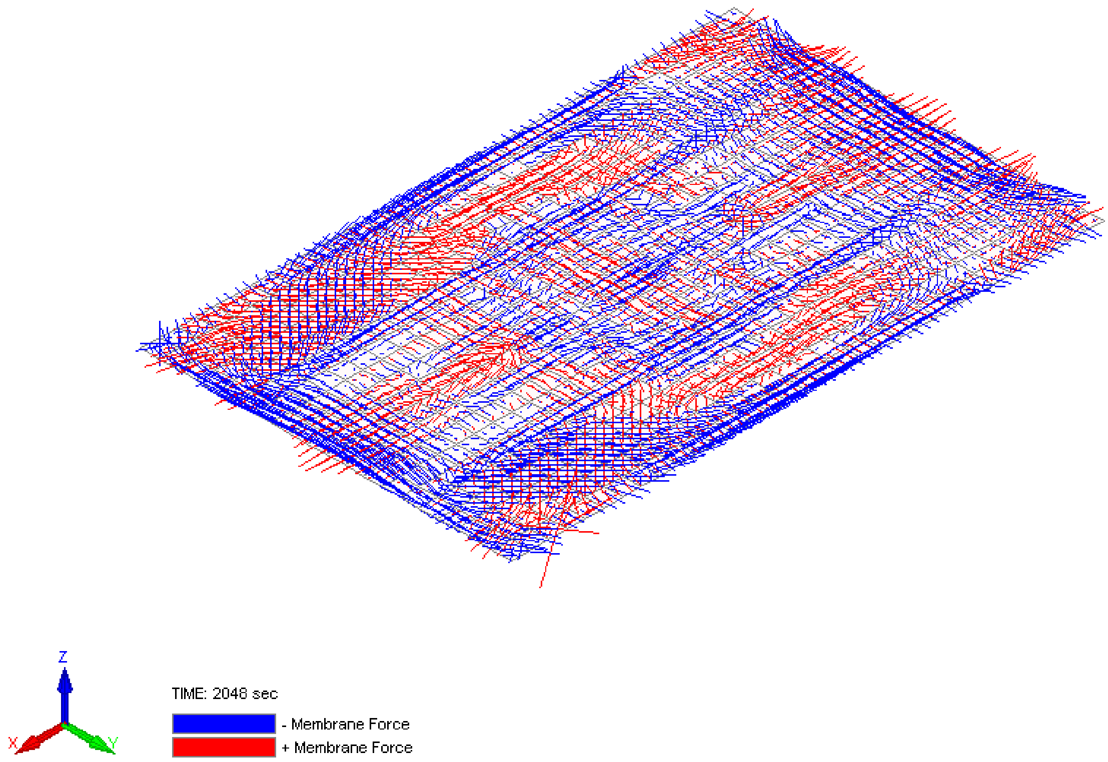


Figure 9-8 Membrane forces in the slab in the cooling phase

The recovery of the mechanical properties of the secondary beams is observed in faster than in the slab reduction of the deflection of these beams during the cooling phase.

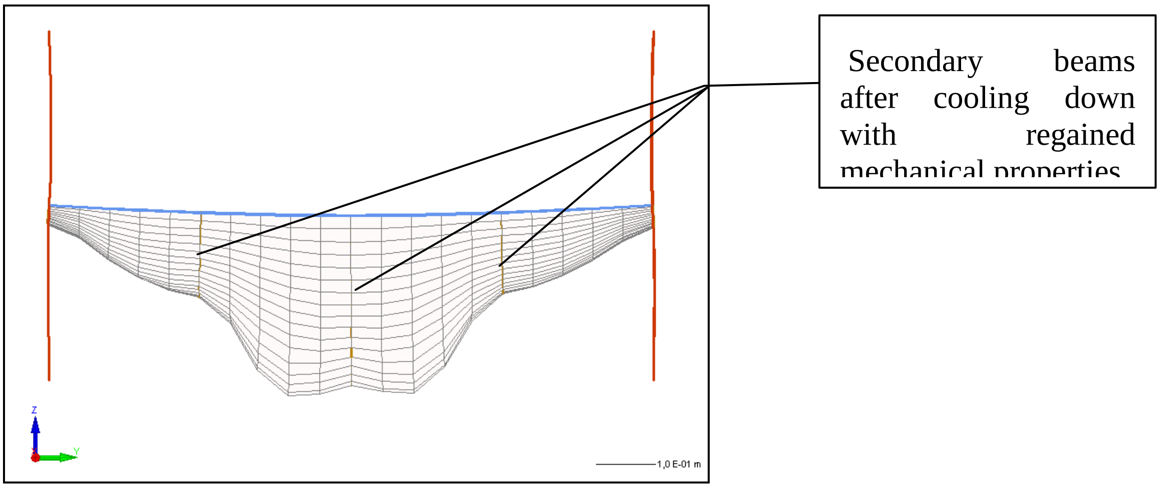


Figure 9-9 Reduction of the deflection in the beams during cooling

The structure is back in ambient temperature after 2700 seconds. The entire slab is back in compression. This compression is more important after the fire than before, especially in the central part of the slab. This is due to the differential expansion that the slab was subjected to during the fire. All the beams are back in tension as it was before the fire. However, the stresses are higher in all the elements due to remaining plastic deformation.

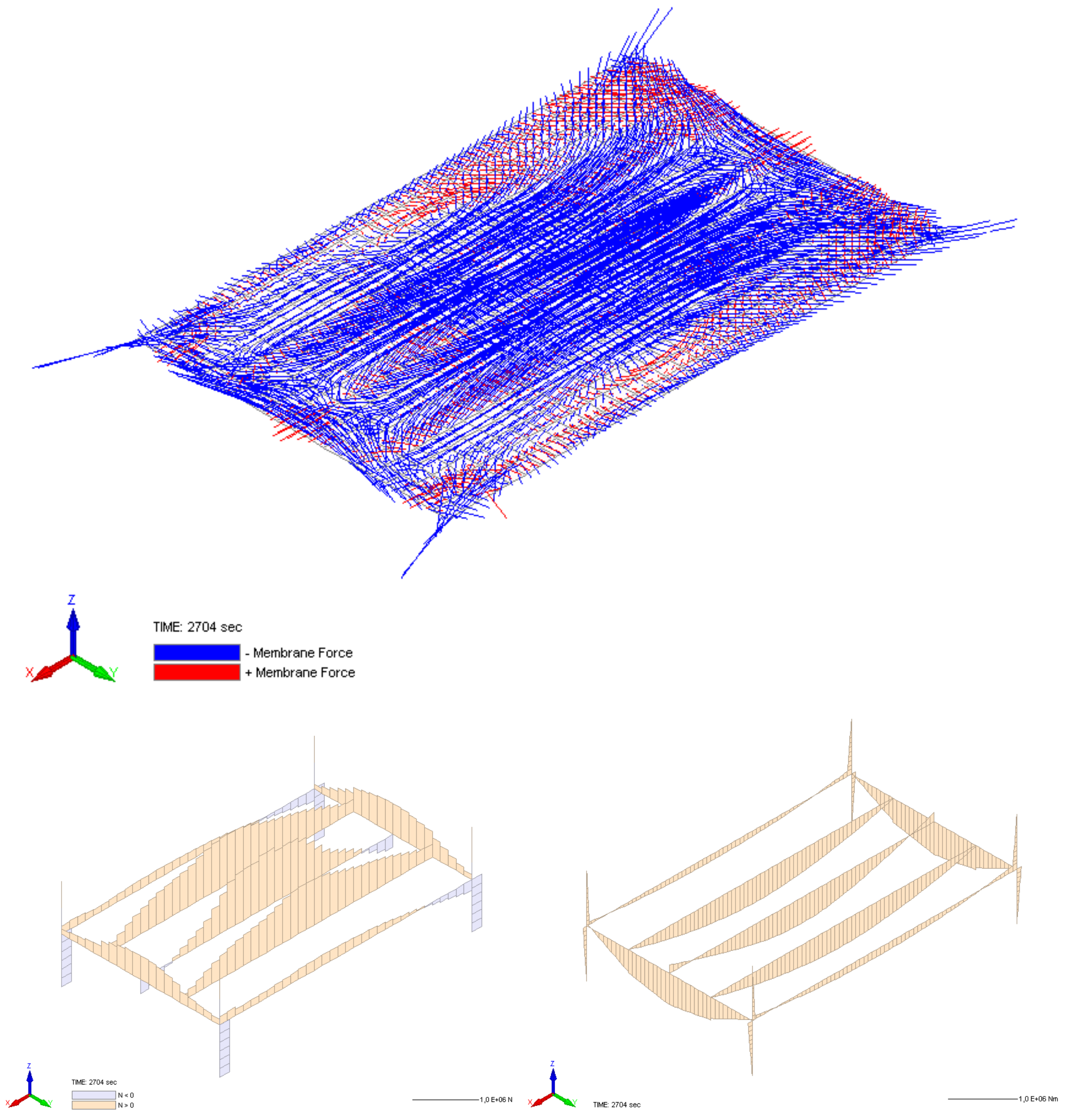


Figure 9-10 Membrane forces in the slab and stresses in the beams in ambient temperature after the fire

10 Annex 2: Cofraplus60

10.1 Technical description of the product

The profiled steel sheeting COFRAPLUS 60 produced by ArcelorMittal Construction are designed for composite floor slabs. After hardening of the concrete the sheets cooperate with the concrete as reinforcement in tension of the floor slab.

The profiled steel sheeting is made of S350GD steel grade galvanized on both sides. The sheet thicknesses and the profile heights are given in the figure below.

Composite floors on profiled steel sheeting by ArcelorMittal Construction are made of at least B25 concrete class. Composite action of the sheeting and concrete is provided by adherence of steel and concrete without studs.

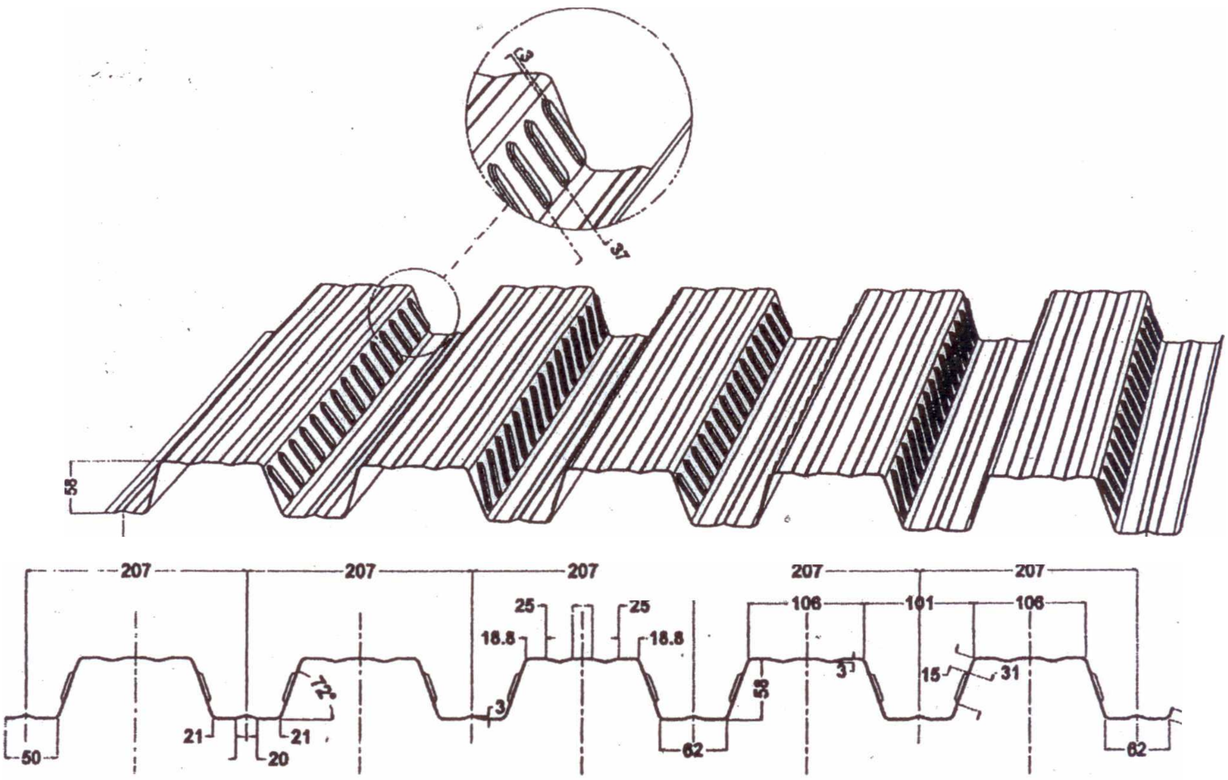


Figure 10-1Profiled steel sheeting COFRAPLUS 60

Name	Thickness (mm)	Profile height (mm)
COFRAPLUS 60	0,75	58
	0,88	
	1,00	
	1,25	

Table 10.1 Geometrical characteristics of steel sheeting

Maximum span length: 15,0 m

Width of the sheeting: 1,5 m

10.2 Analysis of the available documentation concerning determination of floor fire resistance

The European code PN-EN 1994-1-2 is the basic document, which is used in determining fire resistance of the floors made of ArcelorMittal Construction sheeting. Using resolutions of the code, as well as floor technical data of ArcelorMittal Construction, the principles of determining fire resistance were established.

10.3 Principles of determining fire resistance for the floors on profiled steel sheeting COFRAPLUS 60

Fire resistance of steel-concrete composite floors made with profiled steel sheeting COFRAPLUS 60 with at least B25 concrete class, should be determined in accordance with PN-EN 1994-1-2: 2005. The evaluation of fire resistance concerns conditions of standard fire only.

Principles for the evaluation of fire resistance for COFRAPLUS 60

A/ Fire integrity for the floors (criterion E) is maintained up to the moment the floors lose their fire load capacity.

B/ Fire insulation for the floors (criterion I) is preserved throughout the fire *t*, provided that the minimum total floor thickness *h* is maintained. It is given in Table 10.2.

t [min]	h [mm] COFRAPLUS 60
30	110
60	120
90	140
120	160
180	190

Table 10.2 Minimum total floor thickness h essential for meeting the fire insulation criteria*

*floor total thickness *h* = height of sheeting rib + thickness of concrete slab

C/ Fire resistance for the floors (criterion R) with profiled steel sheeting, with or without reinforcement bars amounts to at least 30 minutes.

Determining fire resistance requirements for the floors in classes R60, R90 and R120 requires carrying out calculation analysis according to the principles presented in point D/. These principles are valid only under the conditions of standard fire impact under the floor. Fire resistance within fire conditions is determined for reinforced concrete cross-sections without taking into account profiled steel sheeting which is in accordance with the resolutions of PN-EN 1994-1-2.

D/Principles of floor fire resistance calculation (criterion R)

The calculations should demonstrate that after the determined time *t* of standard fire under the floor (*t* = 60, 90, 120 min) the condition of ultimate limit state for bending is fulfilled:

$M_{fi,Sd,t} \leq M_{i,Rd,t}$

where:

$M_{fi,Sd,t}$ is a calculating value of the effect of fire activity (bending moment) after the defined time *t*,

$M_{fi,Rd,t}$ is a calculating value of floor load capacity in bending under fire conditions.

This condition should be tested in cross-sections for which maximum span moments (positive) and support moments (negative) occur.

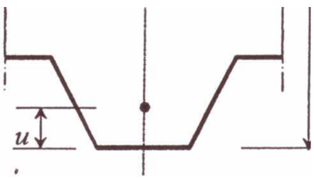
The effect of $M_{fi,Sd,t}$ should be determined for load values and load combinations established in accordance with the principles given in PN-EN 1991-1-2 and PN-EN 1994-1-2.

The principles of determining floor ultimate load in bending under fire conditions $M_{fi,Rd,t}$ are given below.

10.3.1 Load capacity in positive bending moment $M_{fi,Rd}^{+}$

For positive moment bearing reinforcement bars put into rib cavities are taken into consideration, whereas sheeting participation is neglected on the tension side. Reinforcement, whose cross-section and distance from the bottom floor surface is determined individually, depending on the required floor fire resistance, is located in the axis of rib (a single bar in every rib or in some of them).

The temperature of reinforcement in the rib axis, in the distance *u* [mm] from the rib bottom is defined by the following correlation:



$T = T_o (1 – u/u_o)$

where values T_o and u_o are given in Table 10.3 for all 4 types of tested floors.

t	COFRAPLUS 60	
[min]	T_O	u_O
60	750	97

90	923	119
120	1014	138

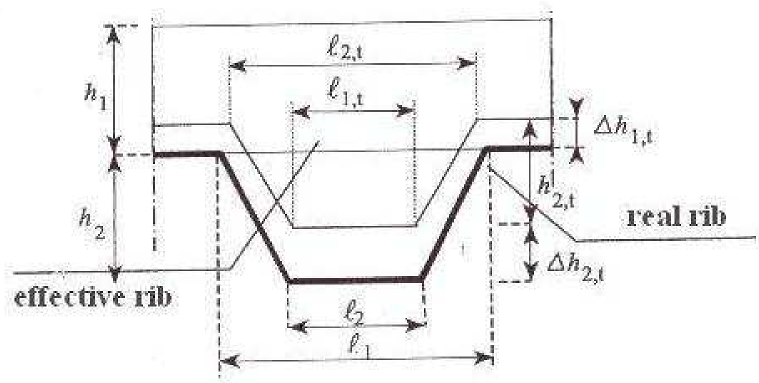
Table 10.3 Parameters for determining the temperature in reinforcement

Load capacity for positive bending moment $M_{fi,Rd}^{+}$ should be determined taking into account temperature dependent resistance of reinforcement steel.

These characteristics are given in the code.

10.3.2 Load capacity for negative bending moment $M_{fi,Rd}^{-}$

When calculating load capacity in negative bending moment, reduced calculating dimensions of concrete effective ribs are taken into account. All this takes place during fire activity as the following diagram shows:



	COFRAPLUS 60
l_1	101
l_2	62
h_2	58

Table 10.4 Dimensions of real ribs [mm]

	COFRAPLUS 60		
Time	t=60	t=90	1=120
Dim.			
$l_{1,t}$	48	41	36
$l_{2,t}$	90	87	85
$H_{2,t}$	56	55	53
$\Delta h_{1,t}$	8	11	14
$\Delta h_{2,t}$	10	14	18

Table 10.5 Dimensions of effective ribs [mm] in the function of fire activity time t [mm].

	COFRAPLUS 60		
u	t=60	t=90	t=120
95	1000	1000	1000
85	1000	1000	1000
75	1000	1000	1000
65	434	404	381
55	397	363	337
45	360	323	293
35	323	282	249
25	286	242	205
15	249	201	0
5	0	0	0

Table 10.6 Width of effective ribs for the distance u [mm] at the bottom of ribs per 1 m of sheeting width [mm/m]

In order to determine load capacity in negative bending moment $M_{fi,Rd}^{-}$ the calculations for the effective cross-section of the floor should be carried out taking into account concrete and steel resistance conditions at room temperature.

10.4 Advantages of Cofraplus

The ribbed steel profile fixed onto the framework of the building serves as horizontal wind brace, a work platform, shuttering and flexural reinforcement of the bottom of the slab. It can, therefore, immediately contribute to wind bracing and the stability of the building due to a diaphragm effect.

The steel profiles are fixed onto the supports and serve as a work platform, thereby allowing trafficking in good working and safety conditions before the concrete is laid. Once the profiles have been installed, the underside of the floor is watertight, efficient and clean with finished appearance. Pre-painting is possible.

The shape of the ribs sets the steel profile securely in the concrete. The reinforcement of the Cofraplus60 section often makes it unnecessary to have span reinforcements. All you need to do is finish off the slab with a welded mesh and possibly top bars. Without adding any extra reinforcement at the bottom, the composite floors have a half an hour firewall.

The use of mixed slab systems enables you to save in many ways:

- in the time spent on the worksite and on the use of lifting appliances,
- in the weight of the concrete due to the shape of the ribbed profile, about 100 daN/m^2.

Reduction of the weight of the slab affects the dimensions of the rest of the structure, beams and columns that are thereby lighter and lessen the load on the foundations. The steel profiles can be manually carried and once they have been placed on the floor girders, they can be rapidly moved, which is a great asset in renovating work. There are other advantages in the use of a mixed slab system compared to the prefabricated concrete slab, such as the possibility to achieve irregular shapes, curves or special floor openings.

Technical properties and requirements as well as fire design recommendations for the steel sheeting COFRAPLUS 60 can be found in **ITB TECHNICAL APPROVAL AT-15-6138/2009**

11 Annex 3: Details of the predesigned structure – hot calculations

A structure of open steel car park illustrated in Figure 11-1 is used to present detailed results obtained from the FE software SAFIR while concept of natural, localised fire was adapted. The calculation was running to simulate the response of the structure during 2.5 hours from the beginning of the fire.

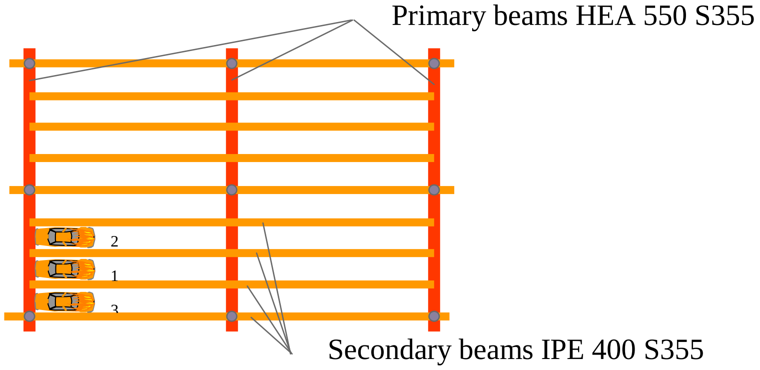


Figure 11-1 Scheme of the analysed structure

At the beginning of the calculation when the structure is still cold the maximum deflection in the slab and the beams is smaller than 5mm. It has to be remembered however, that the load applied is the load combination in fire conditions.

The initial situation in terms of stresses and deflections are presented in Figure 11-2. It can be observed in the top right picture that the entire slab is in compression, apart from areas around the columns.

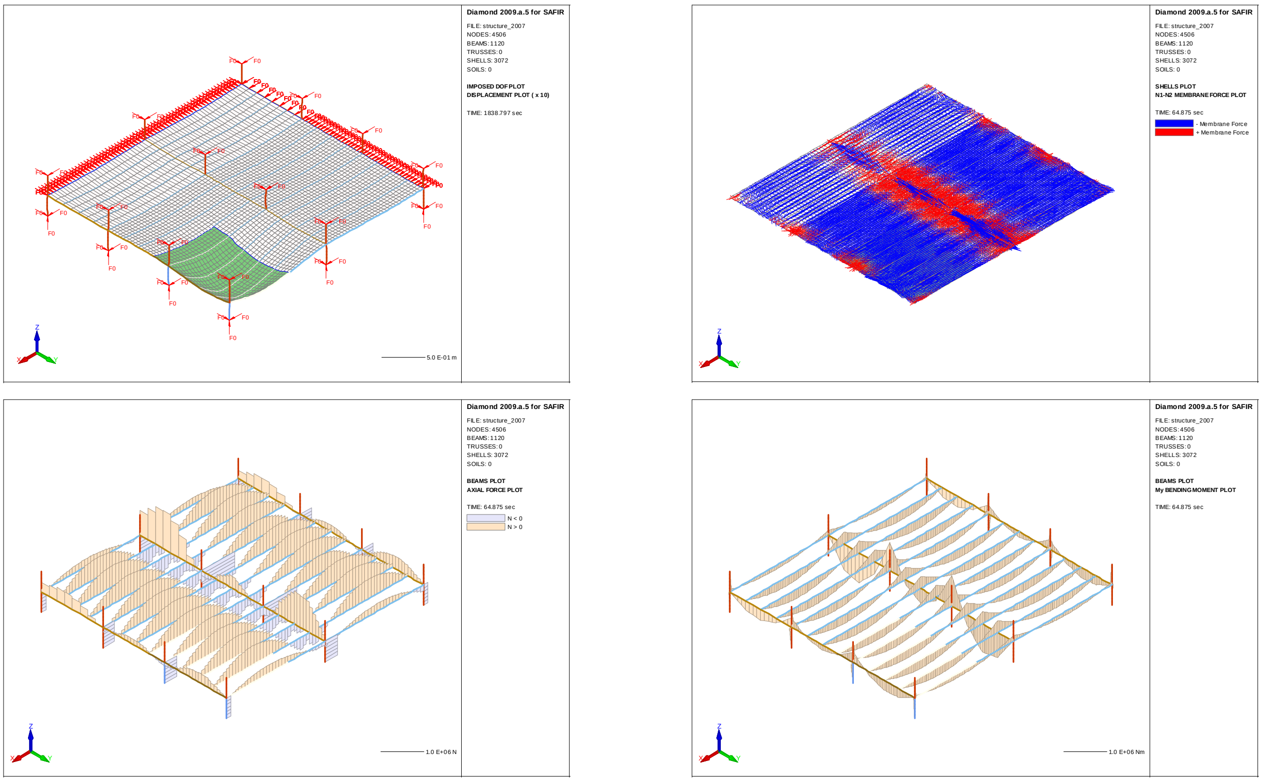


Figure 11-2 Behaviour of the structure in the cold condition. The entire slab is in compression.

The three burning cars used for the simulation are cars class 3. For this class of cars, the rate of heat release was established experimentally and calibrated. The values are presented in Figure 3-4; for individual car as well as for the group of three cars analysed inhere.

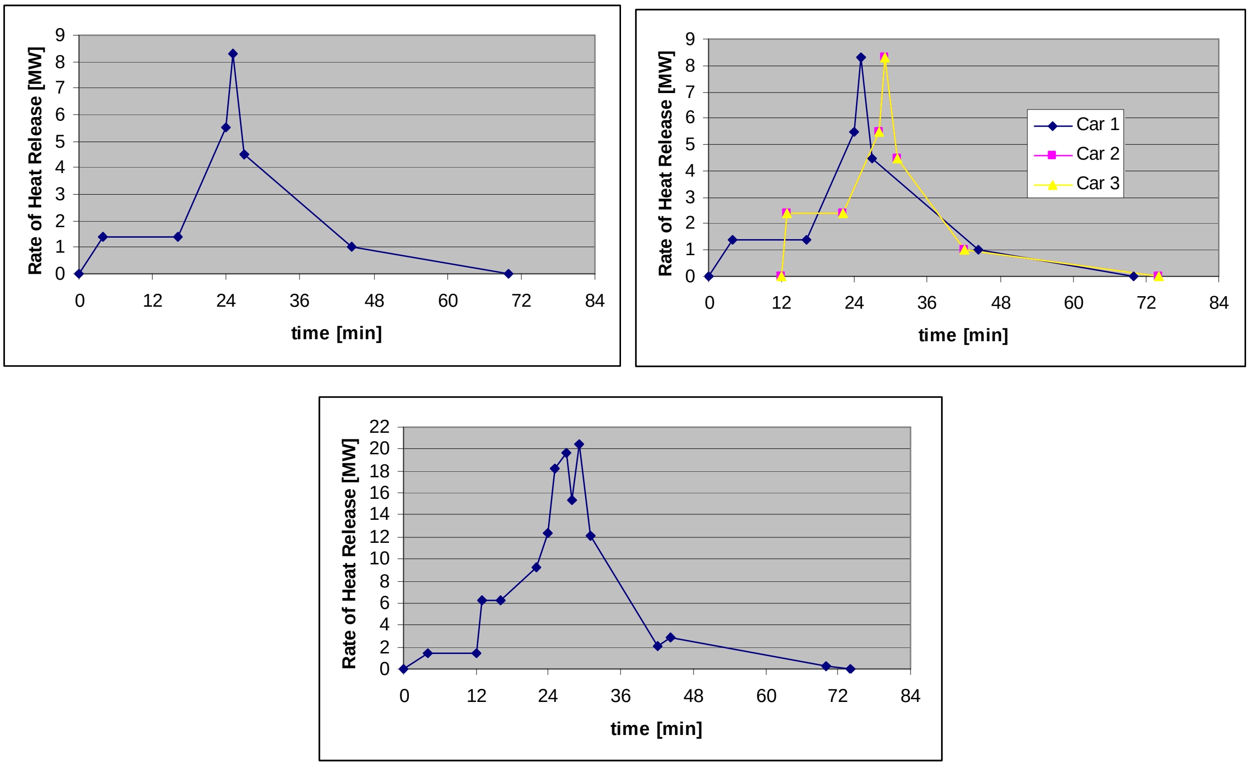


Figure 11-3 RHR for car class 3 (top left), RHR for each of the three cars with propagated fire (top right) and cumulated RHR from the three burning cars (bottom)

The heat release generated by the burning cars is measured in the structure in form of temperature. The maximum temperatures obtained in the beams surrounding the cars and the slabs just above the cars are presented in Figure 11-4 in a function of time. The maximum temperature measure at the bottom of the bottom flange equals 855^{o}C. The maximum temperature at the bottom of the slab equals 828^{o}C.

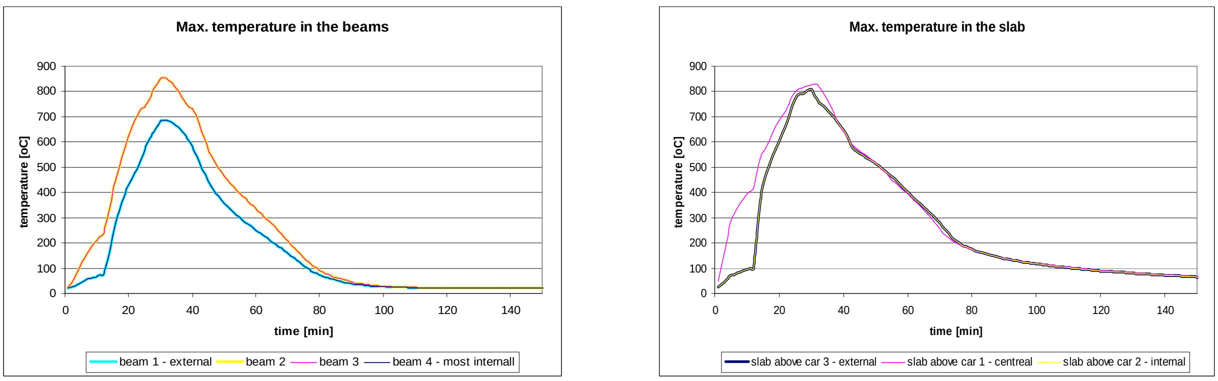


Figure 11-4 Evolution of max temperature in the beams and slab surrounding the burning cars

Following, the time dependent deflection graphs are presented in Figure 11-5. The deflections are measured in the zone, where the burning cars are located. The maximum deflection in the secondary beams equals 0.304m, which is L/52. The same maximum deflection is observed in the slab. However, the plastic deformation in the slab is much larger, as the steel beams are regaining their strength in the cooling phase. The maximum plastic deformation in the beams after the fire is 8cm, which is L/200. At the same time the maximum deflection in the slab remains at around 26cm.

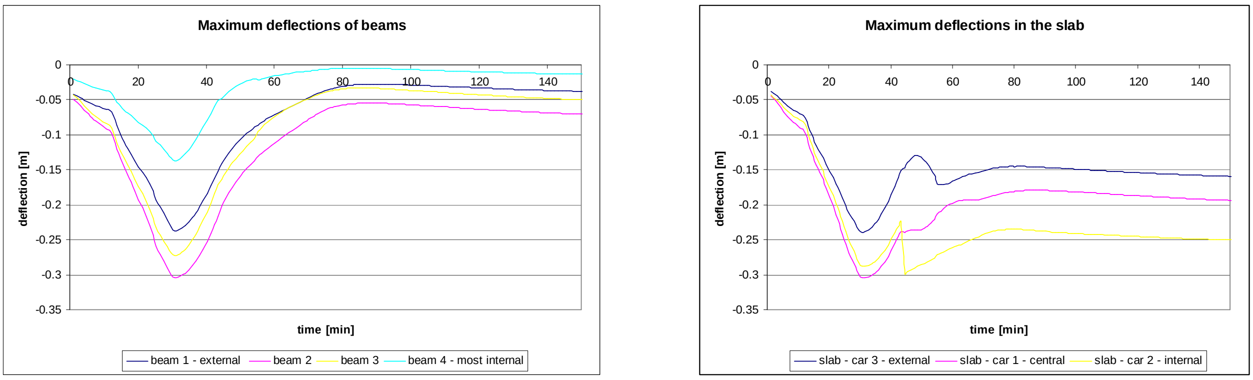


Figure 11-5 Evolution of max deflections in the beams and slab surrounding the burning cars

Figure 11-6 presents forces created in the beams during the fire and cooling phases. The measurement is done in the same point where the deflection reaches its maximum.

It can be seen that the beams go from compression into tension during fire, to go back to much stronger compression in the cooling phase.

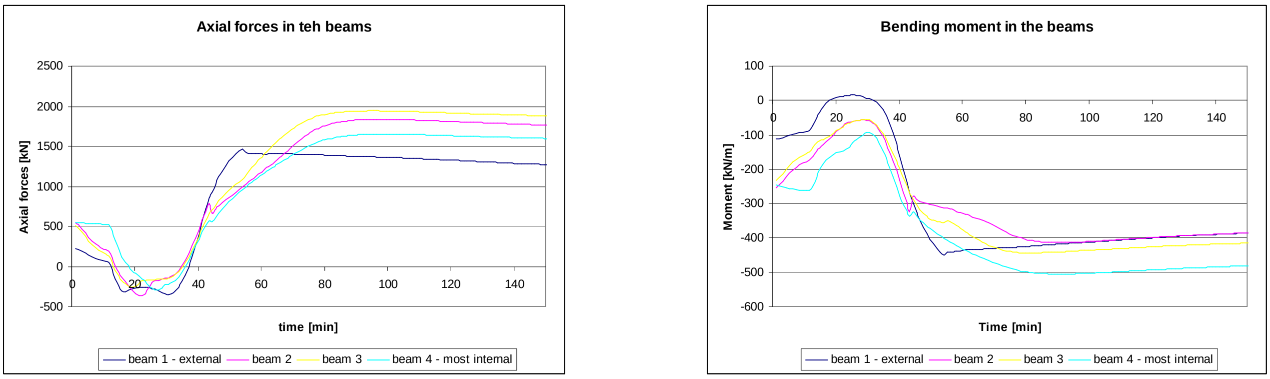


Figure 11-6 Evolution of axial forces and bending moments in the beams in the points of maximum deflections and temperature

Similar behaviour to the secondary beams can be observed for the primary beam as presented in Figure 11-7.

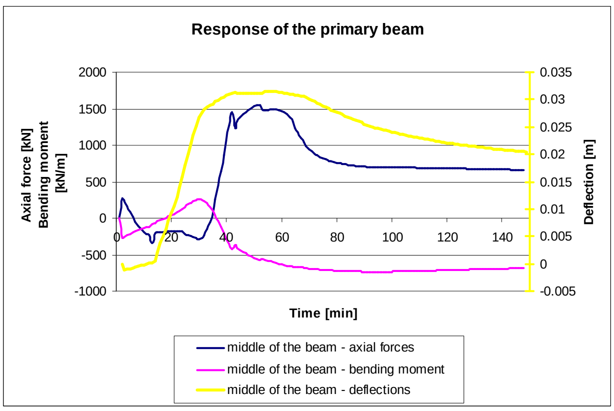


Figure 11-7Response of the primary beam in the centre of its length

Global evolution of the forces in the secondary beams and in the slab are presented in Figure 11-8 - Figure 11-11. The whole structure starts stabilising after about 45-50min from the beginning of the fire and the forces and deflections do not evolve much further.

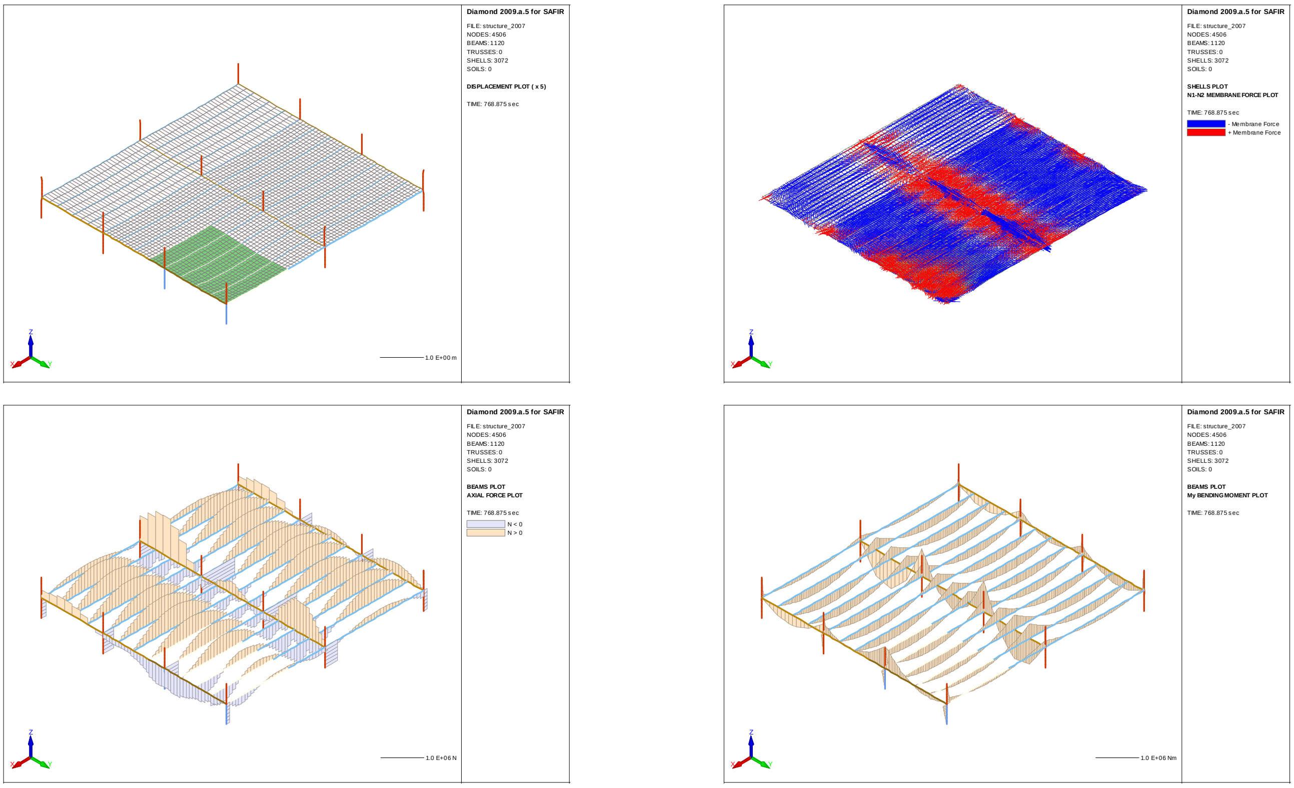


Figure 11-8 After 750sec=12.5min

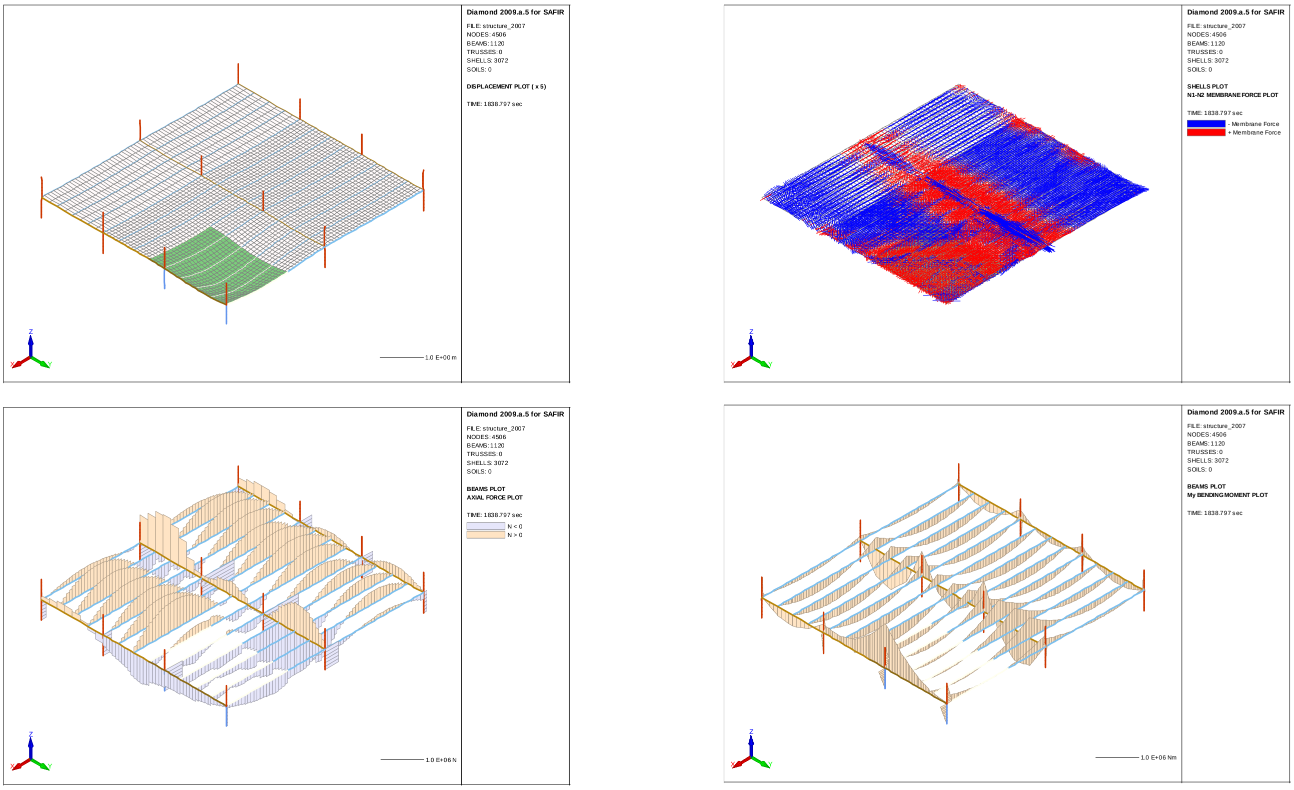


Figure 11-9 After 1800sec=30min

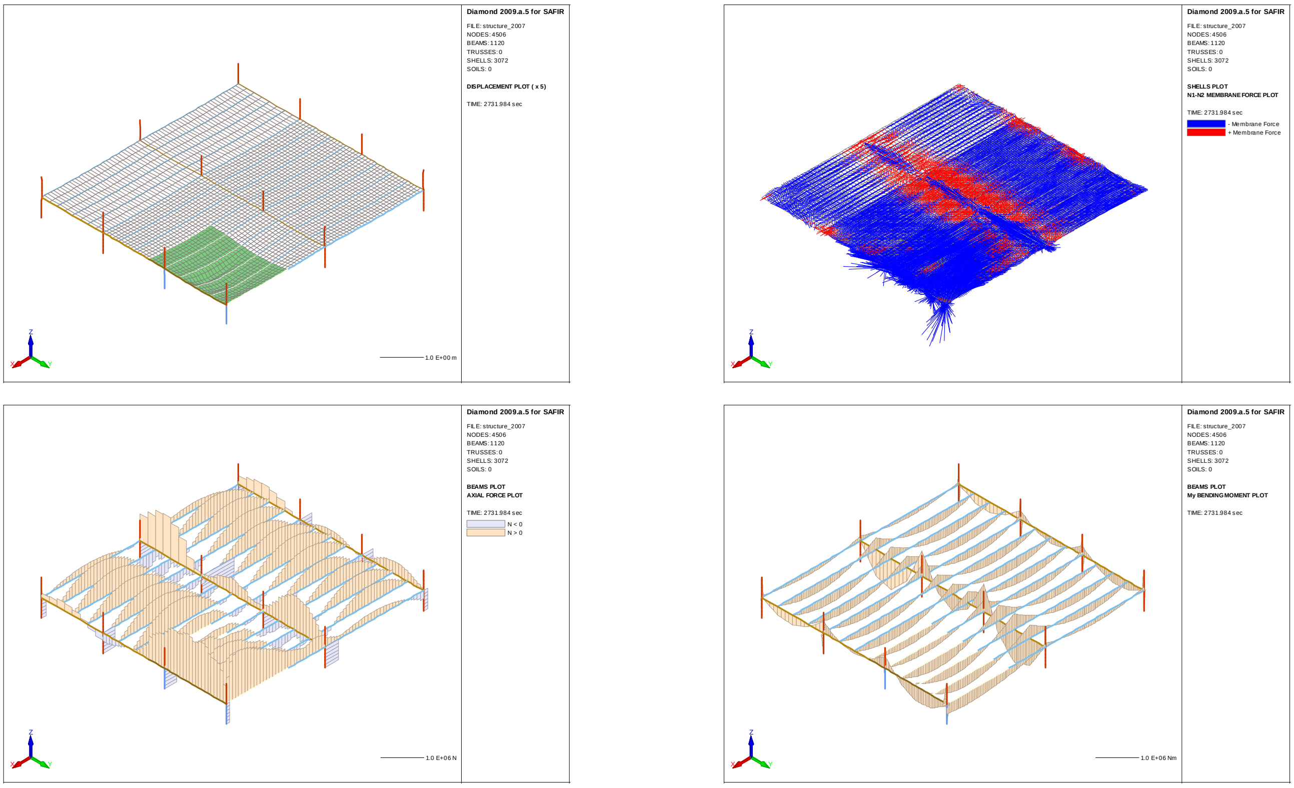


Figure 11-10 After 2700sec=45min

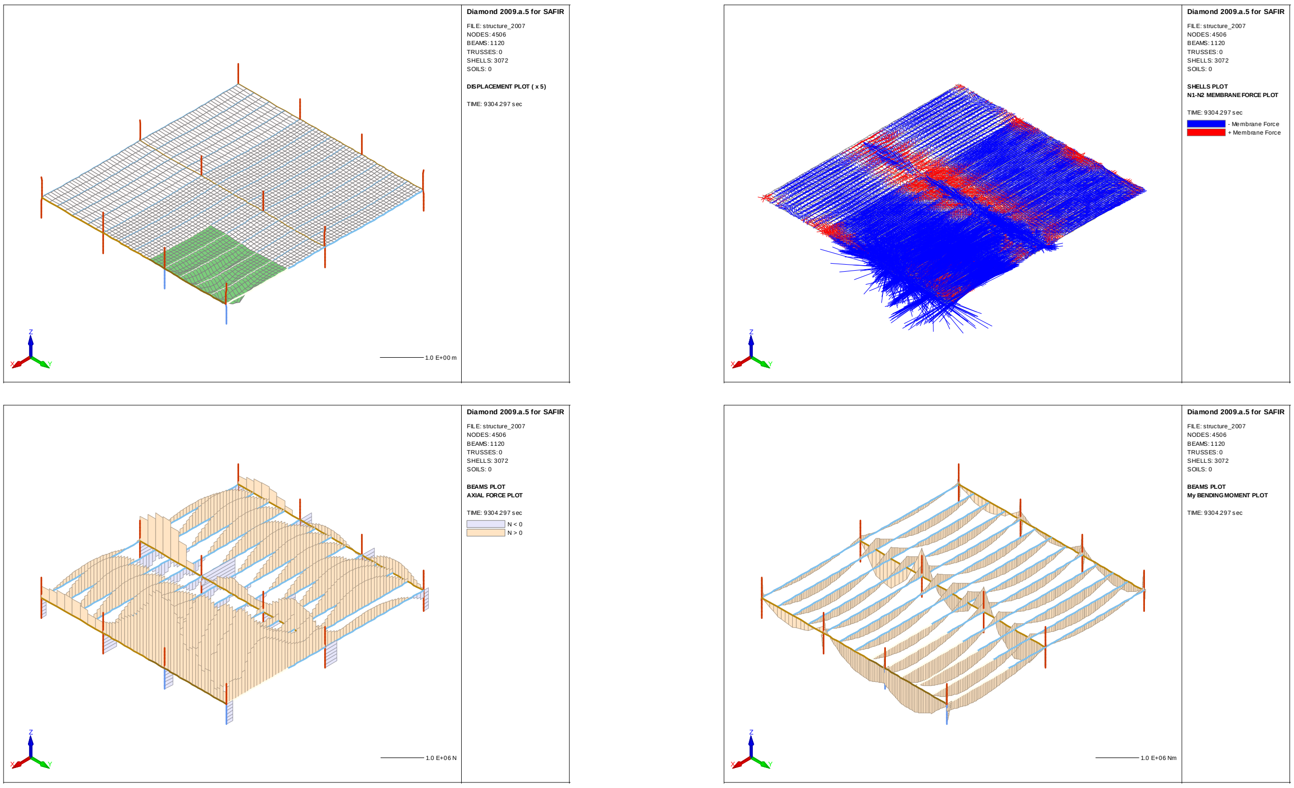


Figure 11-11 After 2.5hours

Characteristics			Structural response			
Frame [m] Col 2.9m	Slab span [m]	Steel grade	Secondary beam	Primary beam	Composite slab with concrete C30/37	Steel deck with mesh S500
16x10	2.5m	S235	IPE 450	HEA 650	Cofraplus60 120mm	Ø 8 150x150
		S355	IPE 400	HEA 550		Ø 6 150x150
	3.3m	S235	IPE 550	HEA 700	Cofraplus60 120mm	Ø 7 150x150
		S355	IPE 500	HEA 600		Ø 7 150x150
	5m	S355	IPE 600	HEA 600	Cofraplus60 150mm	Ø 8 100x100
16x5	2.5m	S235	IPE 450	HEA 450	Cofraplus60 120mm	Ø 6 150x150
		S355	IPE 400	IPE 400		Ø 7 150x150
	5m	S355	IPE 600	IPE 160	Cofraplus60 150mm	Ø 8 100x100

12 References

[Sch1, 99]	J-B. Schleich and others – "*Development of design rules for steel structures subjected to natural fires in closed car parks* ", ECSC project, 1999
[Sch2, 99]	J-B. Schleich and others – "*Development of design rules for steel structures subjected to natural fires in large compartments* ", ECSC project, 1999
[Bai, 02]	Colin Bailey, "*Structural Fire Design Of Unprotected Steel Beams Supporting Composite Floor Slabs*", This paper was presented at the "II International Conference on Steel Construction – II CICOM" – November, 2002 – São Paulo, SP, Brazil.
[Joy,01]	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" – June 2001 – 121 pages
[Caj,05]	L.G. CAJOT, M. HALLER, M. PIERRE – Project DIFISEK – Part 1: Thermal and mechanical actions, 2005
[EC0, 02]	Eurocode 0, *Basis of Structural Design*, April 2002
[EC1,02]	Eurocode 1: *Actions on structures - Part 1-2: General actions - Actions on structures exposed to fire*, November 2002
[EC2,04]	Eurocode 2: Design of concrete structures - Part 1-2: *General rules – Structural fire design*, December 2004
[EC3, 05]	Eurocode 3: Design of steel structures - Part 1-2: *General rules - Structural fire design*, April 2005
[EC4, 05]	Eurocode 4 - Design of composite steel and concrete structures - Part 1-2: *General rules - Structural fire design*, August 2005
[Sch2,01]	J.B. SCHLEICH, J. KRUPPA, G. NEWMANN, L. TWILT for the ECCS - *"Model code on fire engineering - first edition"* - n°111 - May 2001 - 165 pages
[Fran,07]	J-M. FRANSSEN, V-K-R. HODUR, J. MASON - *"Elements of theory for SAFIR 2002 a computer program for analysis of structures subjected to fire"* - July 2007 - 34 pages
[Frau,04]	C. FRAUD, Z. BIN - *"Guide pour la vérification au feu des parcs de stationnement largement ventilés en superstructure métallique"* - Janvier 2004 - 74 pages
[Sav,09]	J.C. SAVOUREUX - Techniques de l'ingénieur: "Parcs de stationnements couverts - conception" - consulté en Décembre 2009 - 16 pages
[Vul,10]	C. VULCU, TH. GERNAY, R. ZAHARIA, J.M. FRANSSEN – "*Structures in Fire – Numerical modeling of Membrane Action of Composite Slabs in Fire Situation*" - 2010 - page 474 to 483
[Sim,10]	L. SIMOES DA SILVA, R. SIMOES, H. GERVASIO - *"Design of steel structures: Eurocode 3: Design of steel structures part 1-1: General rules and rules for building"* - 2010 - pages 154 à 166
[Caj,03]	L-G. CAJOT, J. MATHIEU, L.THOMAS - *"Les structure métalliques pour les*

	parkings ouverts" - Novembre 2003 - 8 pages
[Fran,07]	J-M. FRANSSEN - "Users manual for SAFIR 2007 a computer program for analysis of structures subjected to fire" - April 2007 - 78 pages
[Roz, 02]	ROZPORZĄDZENIE MINISTRA INFRASTRUKTURY z dnia 12 kwietnia 2002 r. *w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie*. (Dz. U. z dnia 15 czerwca 2002 r.)