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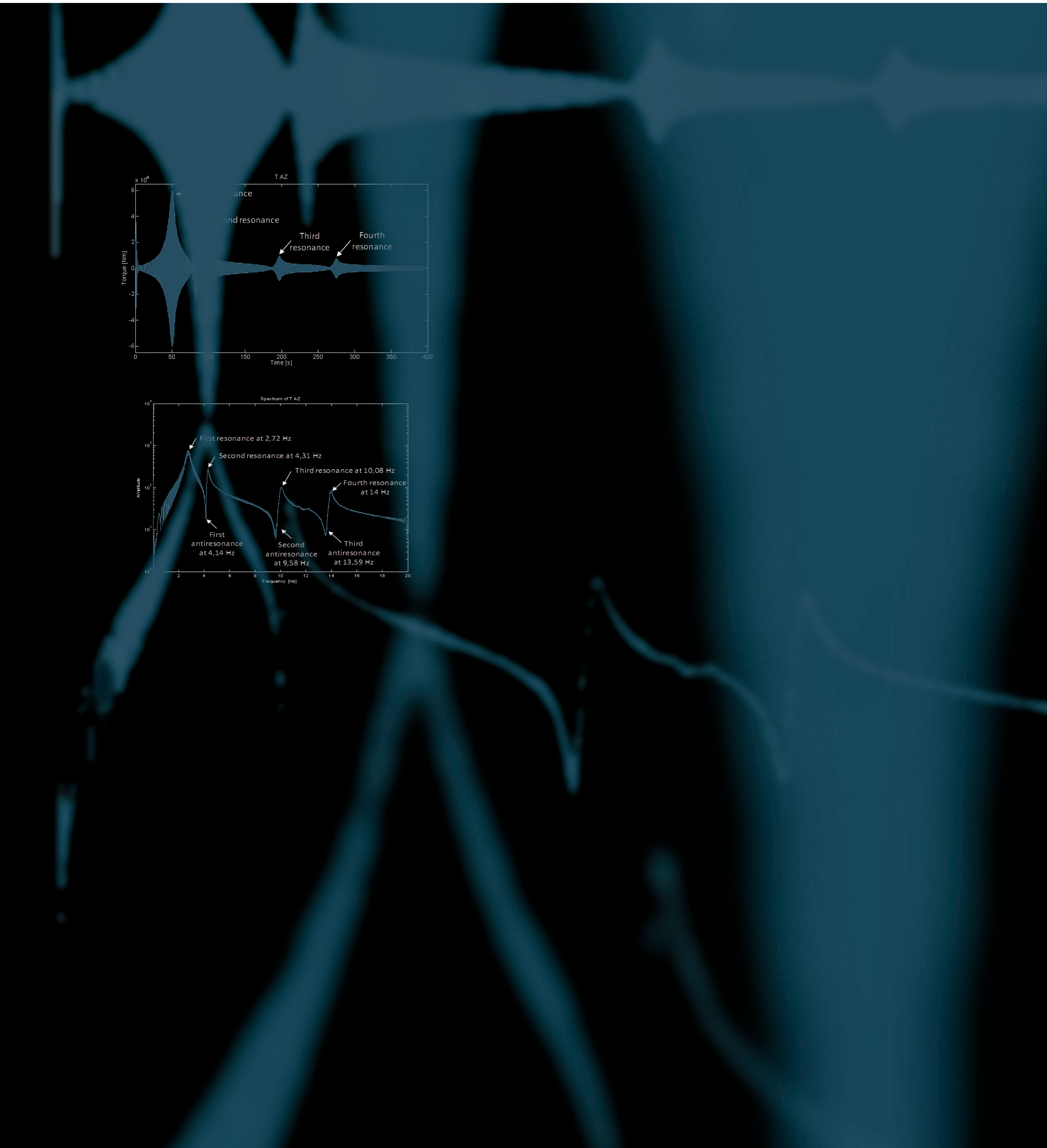

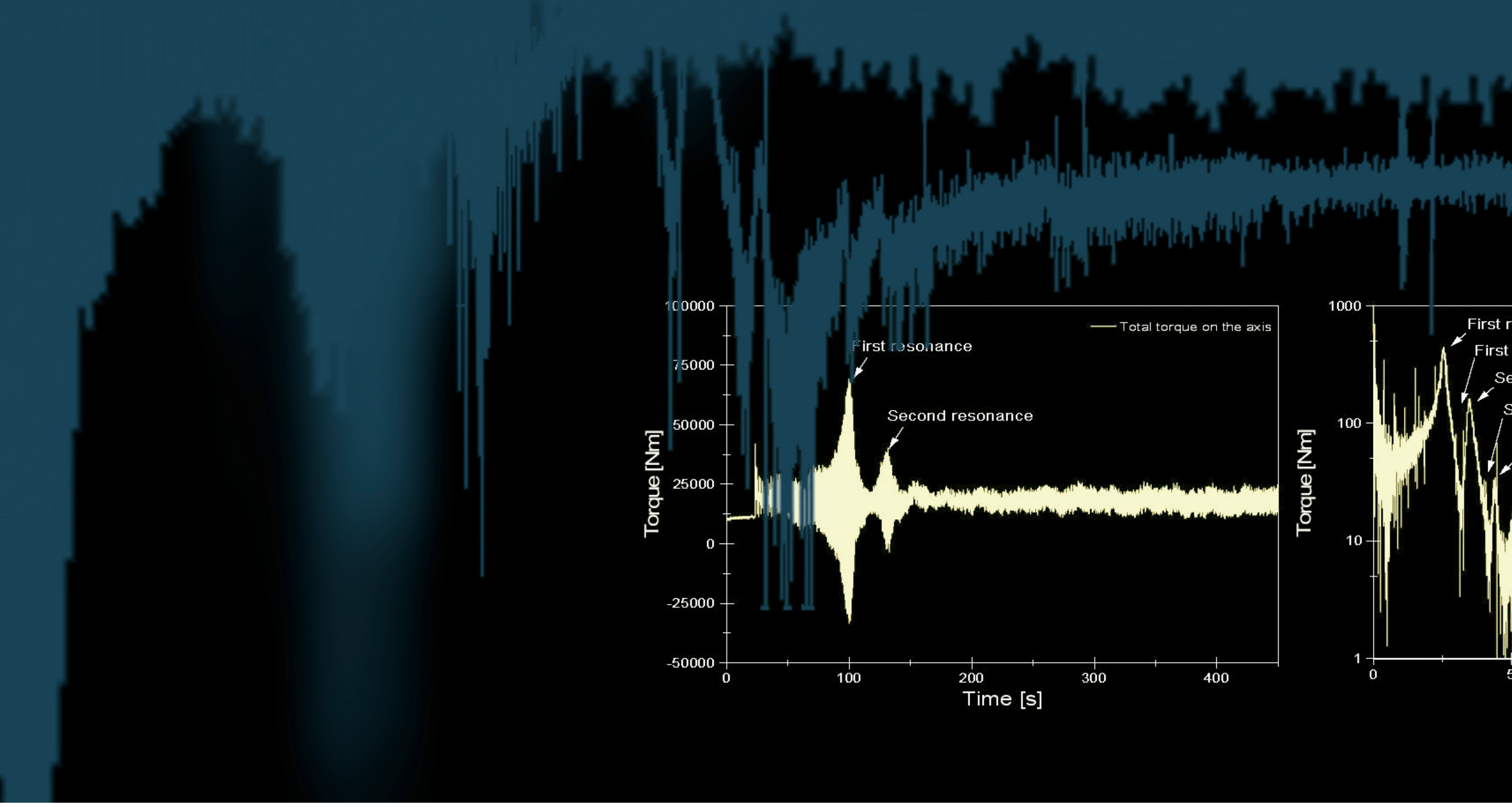


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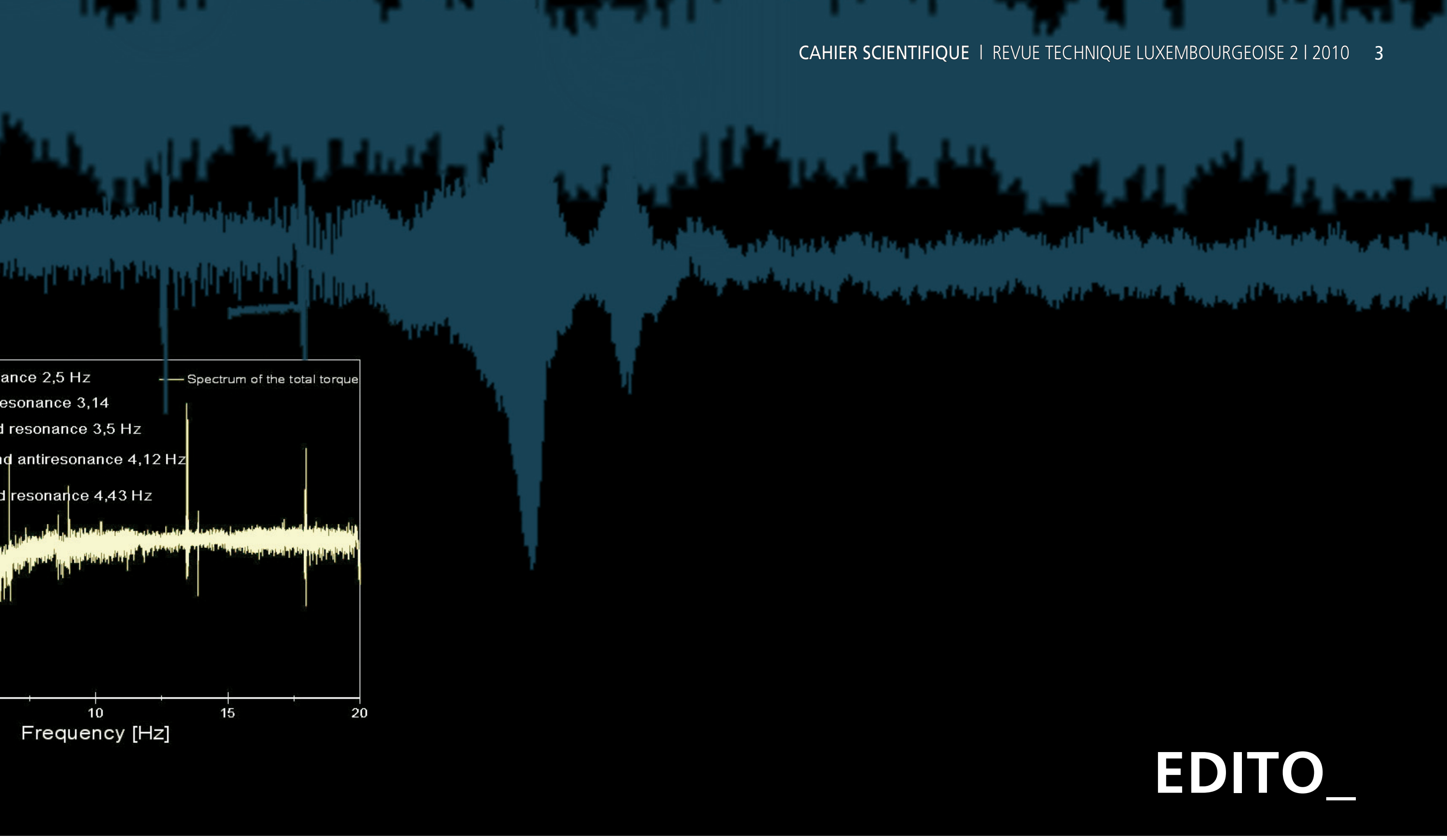


# EDITO_

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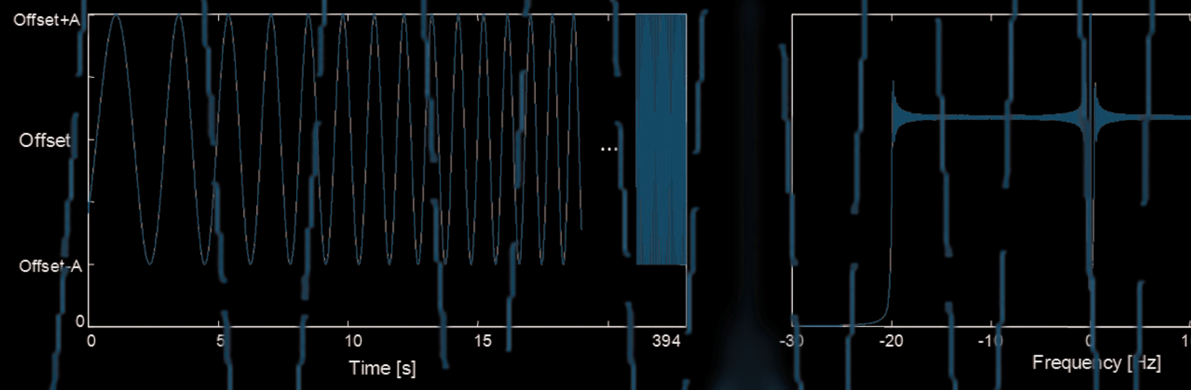
Bonne lecture,

Paul Heuschling
*UNI*

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_comité de lecture

**The control of fire by mankind has definitely enabled it to improve its level of well-being and its conditions of life but fire has also been a source of danger for humans in numerous dramatic cases. By the consequence of evil-minded acts or off-guard moments, fire causes the death of persons and the destruction of material goods. During the second part of the 20th century, an effort was made in Europe to develop and apply more active as well as passive measures in order to limit the damages caused by fire.**

# DISTRIBUTION OF TEMPERATURE IN STEEL AND COMPOSITE BEAMS AND JOINTS UNDER NATURAL FIRE_

Dr. Ing. F. Hanus
Prof. Dr. Ing. J.-M. Franssen

Structural Fire Engineering is one of the disciplines of Fire Safety Engineering. That latter one is a science aimed at limiting the death of people and damages in buildings subjected to fire, by application of engineering. Structural Fire Engineering is one of these disciplines and is aimed at analyzing the effects of fire on a structure and designing members under the combination of thermal and mechanical loadings applied in case of fire. A general analysis of Structural Fire Engineer consists of three basic steps: the modeling of the fire, the thermal analysis and the structural analysis.

In comparison with other types of constructions, unprotected steel structures lose rather quickly their stability when submitted to elevated temperatures: the relative thinness of individual elements causes a fast heating of structural elements and a rapid reduction of their mechanical properties. Consequently, steel structures are often thermally-protected by insulating materials or intumescent paints [1]. However, the cost of fire protection is considerable: the increase of cost may reach 30% of the bare steelwork [2]. Consequently, architects and engineers try to adapt the design of steel structures or to use composite action in order to optimize or avoid the use of fire-protecting materials [3 & 4].

Until recently [5], the analysis of the behaviour of steel and composite structures subjected to fire conditions has not been focused on joints because the less severe exposition and the presence of more material in the joint zone induce lower temperatures in that zone than in the connected members. The large amount of joints typologies, the large number of parameters influencing their behaviour and the difficulty to realize experimental tests have lead to a lack of sufficient knowledge about joints behaviour under fire conditions.

The collapse of WTC Twin Towers on the 11th of September 2001 has highlighted the possibility of connection failures and their detrimental effects on structures. Some experts have alleged that the failure of connections between truss beams and edge columns has played a significant role in the final global collapse of the two towers. Furthermore, the damaged connections (distorted bolts and holes bearing) were documented as a failure mode of the WTC5, a 45-storey building that collapsed several hours after WTC 1 and 2 under the unique effect of fire [6]. Some investigations were conducted during the last years, mainly in Europe, on the behaviour of joints under fire. Some real-scale tests performed in Cardington [7] and Vernon [8] have also shown that steel and composite connections could become a weak point under fire conditions, especially during the cooling phase.

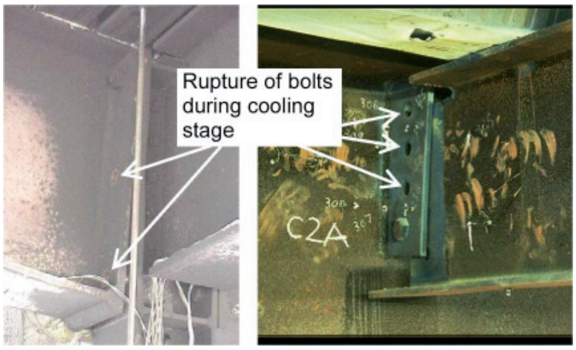



Figure 1_Failure of bolts in steel connections subjected to natural fire

The objective of this article is i) to present the existing methods for predicting distributions of temperature in steel and composite beams and joints, the field of application and the limitations of these methods; ii) to describe new developments aimed at improving these predictions and to compare the results obtained by use of these analytical methods to those given by use of FE models built in the specially-purposed software SAFIR developed at the University of Liège [9].

## EXISTING METHODS FOR PREDICTION OF TEMPERATURE

In the European standards dedicated to the design of steel and composite structures under fire, the temperature in unprotected steel sections is calculated by the Lumped Capacitance Method [10]. The equilibrium is stated between the quantity of heat received by the steel cross-section $\Delta Q_{exchanged}$ and the quantity of heat consumed by this section $\Delta Q_{heating}$ ing to increase its own temperature by $\Delta\theta_{a,t}$ during an incremental interval of time $\Delta t$.

$$\Delta Q_{exchanged} = \dot{h}_{net,d}\ k_{sh}\ A_m\ \Delta t = c_a\ \rho_a\ V\ \Delta\theta_{a,t} = \Delta Q_{heating}$$

(Eq. 1)

$A_m$ and V are the surface area and the volume of steel per unit length of the member, $c_a$ and $\rho_a$ are the specific heat and the unit mass of steel and $h_{net,d}$ is the design value of the net heat flux accounting for thermal exchanges by convection and radiation. The correction factor for shadow effect $k_{sh}$ accounts for the reduced exposure of concave-shaped sections to heat fluxes compared to convex sections with a same section factor $A_m/V$.

In steel beams that support a concrete slab on the upper flange, the distribution of temperature is not uniform due to i) the difference of exposure to heat fluxes between the top and bottom flanges and ii) the existence of heat fluxes between the top flange and the concrete slab. EN 1994-1-2 [11] recommends to apply the Lumped Capacitance Method separately for the different parts of the steel section and to consider a "local" section factor of the flange or the web $A_{p,i}/V_i$ instead of the "global" section factor $A_m/V$, except for members with box-protection where a uniform temperature may be assumed over the height of the profile. For the top flange, the interface with the concrete slab is considered as an adiabatic frontier when at least 85% of the upper surface is in contact with the slab.

For predicting the distribution of temperatures in joints, EN 1993-1-2 recommends the use of the local $A_m/V$ value of the parts forming that joint or, as a simplification, by assuming a uniformly-distributed temperature calculated with the maximal value of the ratios $A_m/V$ of the connected steel members in the vicinity of the joint. In beam-to-column and beam-to-beam steel joints with beams supporting any type of concrete floor, the distribution of temperature may be based on the temperature of the bottom flange at mid-span. The ratio between the temperature in the joint zone at a vertical abscissa h and the temperature of the bottom flange at mid-span is given in Figure 2 for beam depths lower than or equal to 400 mm (left profile) and beam depths higher than 400 mm (right profile).

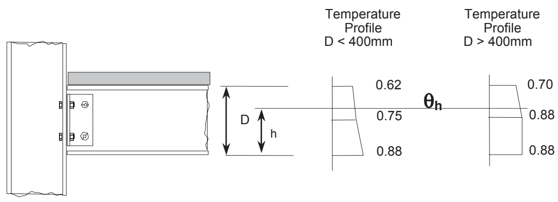
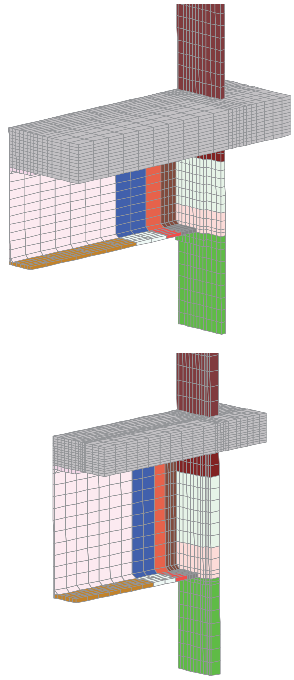



Figure 2_Temperature profile of a beam-to-column or beam-to-beam joint supporting a concrete floor as a function of the temperature of the bottom flange at mid-span

Comparisons have recently been realized between experimental measurements of temperature in steel joints obtained under natural fire conditions and temperatures obtained by three different methods [12]:

- _The temperatures calculated with the "Eurocode Percentages Method" described previously (Figure 2), initially developed for standard ISO fire curve, are much different from test results and this method seems unreliable for heating and cooling phases of real fires.
- _The Lumped Capacitance Method shows good correlation with average connection temperatures but significant discrepancies are observed in the prediction of temperature in individual connection elements. This method can thus not be used for precise analysis of the structural behavior of the joint based on the behavior of individual components.
- _Finally, the numerical simulations performed with the finite element package Abaqus [13] give a good agreement with experimental results and show that the presence of the concrete slab does not affect the temperature of the bottom flange. Numerical analyses can thus be considered as reliable, but are too sophisticated a tool to be used in practical applications.

As already mentioned in the introduction, the new methods developed for predicting temperature in steel beams and joints will be compared to results obtained by use of the finite element package SAFIR [9]. The software SAFIR is a special purpose computer program for the analysis of structures under elevated temperatures conditions. It was developed at the University of Liege and is based on the Finite Element Method. The analysis of a structure exposed to fire consists of a thermal analysis followed by a structural analysis. Thermal analyses are performed with 2-D or 3-D SOLID elements. Conductive, convective and radiative transfers are taken into consideration. The two thermal models built in SAFIR software and considered as a basis of reference for the developed analytical methods are plotted on Figure 3. On the left hand side, an IPE 300 beam covered by a concrete slab is connected to a HEA 300 column. On the right hand side, an IPE 550 beam and a HEM 300 column are connected. In these models, the contact is assumed as perfect between the steel elements and the concrete slab.



(a)

(b)

Figure 3_Numerical models for composite joints built in SAFIR software (a) IPE 300 beam (b) IPE 550 beam

## COMPOSITE SECTION METHOD

In the first method proposed in this article for steel beams supporting a concrete slab, called Composite Section Method, a part of the concrete slab is integrated into the heated zone considered for predicting the temperature at the level of the top flange (Figure 4). The heated section under consideration is composed of the upper half of the steel beam and a trapezoidal part of the concrete slab. For the heated perimeter, the heat fluxes from each half of vertical side of the box surrounding the beam are taken into account. The perimeter considered is thus equal to the beam height.

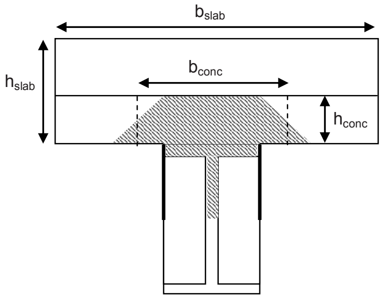



Figure 4_Heated section considered in the Composite Section Method applied to beams

The equation of the Composite Section Method representing the equilibrium between the heat received by the section during a time step $\Delta t$ and the quantity of energy consumed (or produced) by this section $Q_{heating}$ to increase (or decrease) the uniform temperature of the zone is given in Eq. 2, where $A_b$ and $A_{conc}$ are respectively the cross-section area of the steel profile and the concrete section area included into the heated zone (Eqs 3 & 4 and Figure 5). The height of the concrete zone $h_{conc}$ depends on time t (in minutes), the thickness of the beam flange $t_{fb}$ and is limited to the slab thickness $h_{slab}$.

$$\Delta Q_{transferred} = \dot{h}_{net,d}\ k_{sh}\ A_m\ \Delta t = \qquad \text{(Eq. 2)}$$

$$= \left(c_a\ \rho_a\ A_b/2 + c_c\ \rho_c\ A_{conc}\right)\Delta\theta_{a,t} = \Delta Q_{heating}$$

$$h_{conc} = \min\left(20 + 110\left(\frac{t}{60}\right).\left(\frac{t_{fb}}{10}\right); h_{slab}\right) \qquad \text{(Eq. 3)}$$

$$b_{conc} = b_b + h_{conc} \qquad \text{(Eq. 4)}$$

The temperatures obtained by the Component Section Method are compared to the results obtained with SAFIR 2D simulations on Figure 6. On the left, a diagram shows the evolution of temperature in the top flange of two sections characterized by different section factors subjected to the ISO fire curve. On the right, the evolution of temperature in the top flange of a IPE 300 steel beam covered by a concrete slab is given during the heating and cooling phases of a parametric fire curves defined in the Annex A of the EN 1993-1-2 [5]. The durations of the heating phase are 30, 60 and 90 minutes. The analytical prediction of temperature is very good during the heating phase but a delay is observed during the cooling phase.

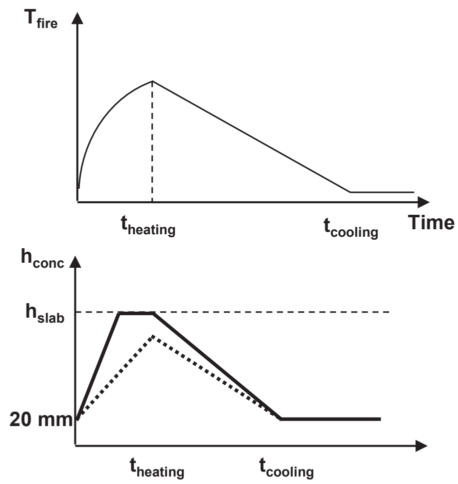



Figure 5_Height of the concrete heated section during heating and cooling phases of a fire

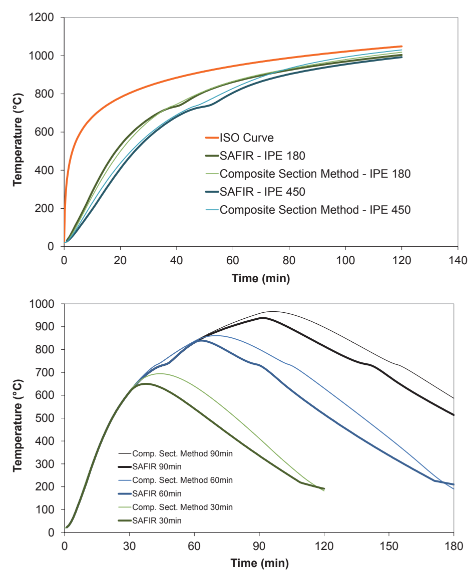



Figure 6_Comparison between temperatures predicted numerically (SAFIR) and analytically (Composite Section Method)

For joints, the heated zone is represented on Figure 7. The length of the beam included into the heated zone $l_b$ is taken equal to half of the beam height. Under ISO fire or heating, the Composite Section Method gives very good predictions of temperature at the level of the top flange. However, the delay observed in 2-D beam sections during the cooling phase is still more significant in 3-D joint zones (Figure 8).

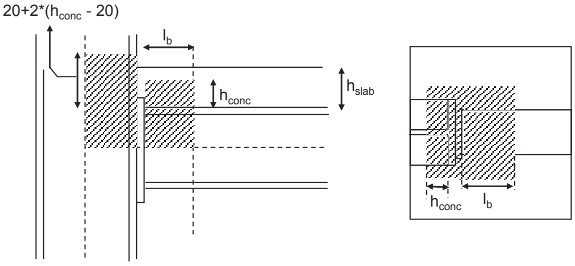



Figure 7_Heated zone considered in the Composite Section Method applied to joints

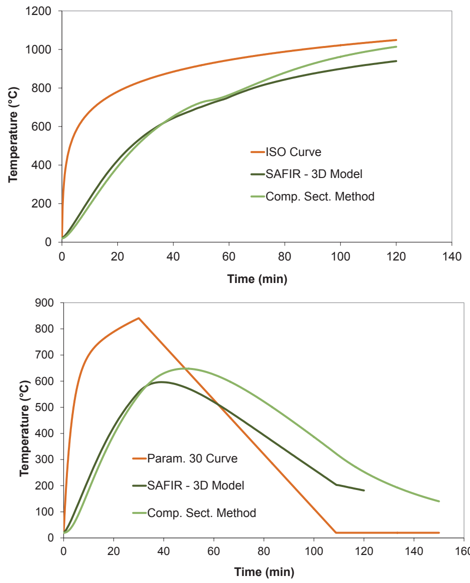



Figure 8_Comparison between temperatures predicted numerically (SAFIR) and analytically (Composite Section Method) – IPE 300 configuration

The precision of the Lumped Capacitance Method and Composite Section Method to evaluate the temperature at the level of the beam top flange (beam or joint sections) is in some cases reduced because the heat transfers between this top flange on one side and the other parts of the steel section and/or the concrete slab on the other side are not taken into account explicitly.

## HEAT EXCHANGE METHOD

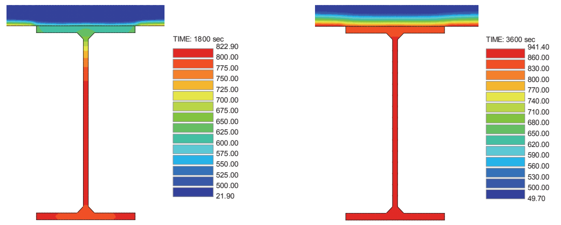
A new method is proposed where the heat exchanged between the top flange and the gas $\Delta Q_{gas}$, the heat exchanged between the top flange and the concrete slab $\Delta Q_{top\text{-}bottom}$ and the quantity of heat transferred between the top flange and the rest of the steel section $\Delta Q_{concrete}$ are calculated individually (Eq. 5).

$$\Delta Q_{exchanged} = \Delta Q_{gas} + \Delta Q_{top-bottom} + \Delta Q_{concrete} = = c_a\, \rho_a\, V\, \Delta\theta_{a,t} = \Delta Q_{heating} \qquad \text{(Eq. 5)}$$

The heat exchanged by convection and radiation between the top flange and the gases of the compartment is calculated, according to the EN 1994-1-2 recommendations, by considering that the top flange is heated on 3 sides.

The results of numerical simulations show that the distribution of temperature in a composite beam is approximately uniform in the web and the bottom flange (Figure 9). A gradient of temperature is observed at the junction between the web and the top flange and heat is exchanged by conduction in that zone.

It is proposed to evaluate the heat transfer between the top flange and the rest of the steel section during a given time step $\Delta t$ by use of Eq. 6. This energy can be positive (heat received by the top flange) or negative (heat lost by the top flange). In Eq. 6, $\lambda$ is the thermal conductivity of steel, x is the length of heat transfer (chosen equal to the radius of the root fillet), $T_1$, $T_2$ are the temperatures in the top and bottom flanges and $t_{wb}$ is the thickness of the beam web. The temperature of the bottom flange $T_2$ is evaluated with the Lumped Capacitance Method (EN 1994-1-2).




(a) (b)

Figure 9_Thermal distribution in a composite beam under ISO fire – (a) 30 min – (b) 60 min

$$\Delta Q_{top-bottom} = \lambda \frac{(T_2 - T_1)}{x} t_w\, \Delta t \qquad \text{(Eq. 6)}$$

In beam-to-column joints, the expression of the heat flux $\Delta Q_{top\text{-}bottom}$ is an adaptation of Eq. 6 to 3-D zones (Eq. 7). Heat is transferred through the cross-section area $A_{top\text{-}bottom}$ (Eq. 8), in which $t_p$, $b_p$, $t_{wb}$ and $A_c$ are respectively the thickness of the end-plate, the width of the end-plate, the thickness of the beam flange and the cross-section area of the column and where the length of the beam included in the joint zone $l_b$ is taken equal to the half of the beam height.

$$\Delta Q_{top-bottom} = \lambda \frac{(T_2 - T_1)}{x} A_{top-bottom}\, \Delta t \qquad \text{(Eq. 7)}$$

$$A_{top-bottom} = l_b\, t_{wb} + t_p\, b_p + A_c/2 \qquad \text{(Eq. 8)}$$

The quantity of heat $\Delta Q_{concrete}$ transferred from the beam top flange to the concrete slab is quite difficult to estimate because the distribution of temperature in the concrete slab is not uniform. It is proposed here to calculate this quantity as a function of two parameters: the temperature of the top flange and the parameter $\Gamma$ used to determine the shape of the parametrical fire curves in the Annex A of the EN 1991-1-2. Numerical simulations of an isolated steel flange covered by a slab and submitted to parametrical fires have been performed. The quantity of heat transferred from the top flange to the slab has been obtained by calculating the difference between the quantity of heat received by the flange from the gases and the quantity of heat consumed to increase its temperature. The flux is the ratio between the heat transferred and the contact surface. During the cooling phase, the distribution of temperature in the slab depends on the history of the thermal loading because the evolution of the flux is not reversible.

This procedure has been followed for heating and cooling phases of several parametric curves ($\Gamma$ varying between 0.4 and 2) and simple analytical expressions have been defined in order to approach the heat fluxes obtained from the numerical simulations (Eqs 9a to 9d). The parameters $\phi_{150}$ and $\phi_{475}$ are given in Table 1. $T_{heating}$ and $\phi_{heating}$ are the temperature of the top flange and the flux at the end of the heating phase. The evolution of the heat fluxes from the flange to the slab is plotted on Figure 10. The strong discontinuities observed around 735°C are due to the peak value of the specific heat of steel at this temperature.

$$\phi_{heating}(T) = \phi_{150} \frac{(T-20)}{(150-20)} \quad ; \quad T \leq 150°C$$

(Eq. 9a)

$$\phi_{heating}(T) = \phi_{475} - (\phi_{475} - \phi_{150})\left(\frac{475-T}{325}\right)^2$$

$$150°C \leq T \leq 730°C$$

(Eq. 9b)

$$\phi_{heating}(T) = \phi_{475} - 0.616*(\phi_{475} - \phi_{150}) - 0.035*(T-730)$$

$$T \geq 730°C$$

(Eq. 9c)

$$\phi_{cooling}(T) = \phi_{heating} - (\phi_{heating} + 5)\sqrt{1 - \left(\frac{T}{T_{heating}}\right)^2}$$

$$20°C \leq T \leq T_{\max,heating}$$

(Eq. 9d)

| | Γ = 0.4 | Γ = 0.7 | Γ = 1 | Γ = 1.5 | Γ = 2 |
|---|---|---|---|---|---|
| | Flux (kW/m²) | Flux (kW/m²) | Flux (kW/m²) | Flux (kW/m²) | Flux (kW/m²) |
| 20 | 0 | 0 | 0 | 0 | 0 |
| 150 | 17 | 20 | 23 | 26 | 28 |
| 475 | 24 | 28 | 31 | 34 | 36 |

Table 1_Tabulated data of $\phi_{150}$ and $\phi_{475}$ in function of the parametrical fire curve

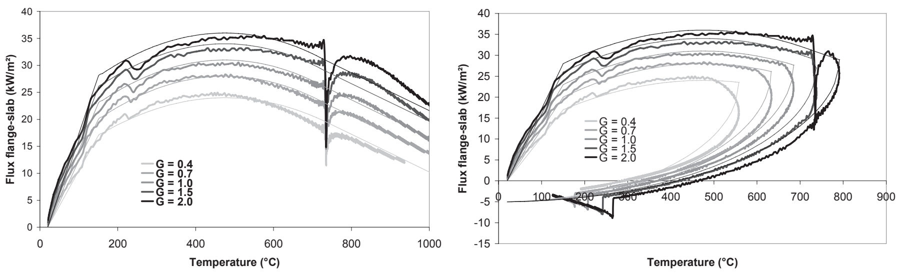



Figure 10_Heat flux from top flange to concrete slab during the heating phase (left) and the cooling phase (right : $t_{heating}$ = 30 min) of parametrical fire curves

The quantity of heat $\Delta Q_{slab}$ exchanged between the top flange and the concrete slab during a time step $\Delta t$ is respectively given by Eqs 10 and 11 for 2-D beam sections (in which $b_b$ is the width of the beam flange) and for 3-D joint zones. The transfer area $A_{transfer}$ is given in Eq. 12, where $t_p$, $b_p$, $b_c$ and $h_c$ are the thickness of the end-plate, the width of the end-plate, the width of the column flange and the height of the column. The lengths $l_b$ and $l_c$ are taken as equal to the half of the beam height and the half of the column height.

$$\Delta Q_{slab} = b_b \, \phi \, \Delta t \qquad \text{(Eq. 10)}$$

$$\Delta Q_{slab} = \phi \, A_{transfer} \, \Delta t \qquad \text{(Eq. 11)}$$

$$A_{transfer} = l_b \, b_b + t_p \, b_p + (\min(h_{slab}; l_c) * (h_c + 2b_c))$$

(Eq. 12)

The Heat Exchange Method for the prediction of temperature at the level of the beam top flange gives a very good agreement with the temperatures obtained by use of the 2-D (Figure 11) and 3-D models (Figure 12) built in SAFIR software. The delay observed at the beginning of the cooling phase with the Composite Section Method has disappeared and the correlation with FE results remains good during the complete parametrical fire curve.

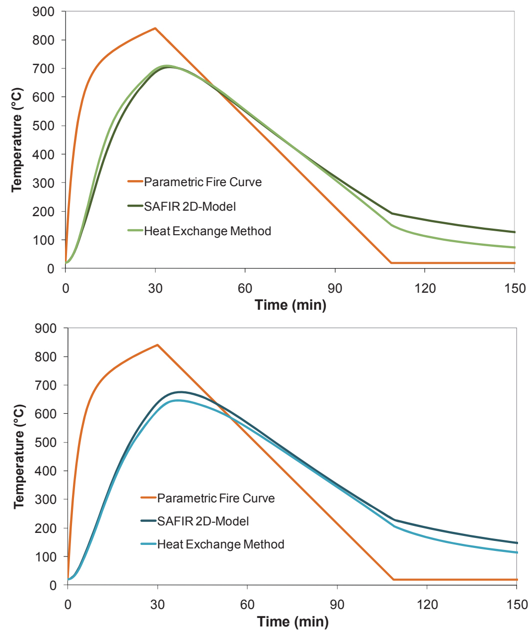



Figure 11_Temperature of the top flange obtained numerically and analytically - $t_{heating}$ = 30 min (a) IPE 300 (b) IPE 550

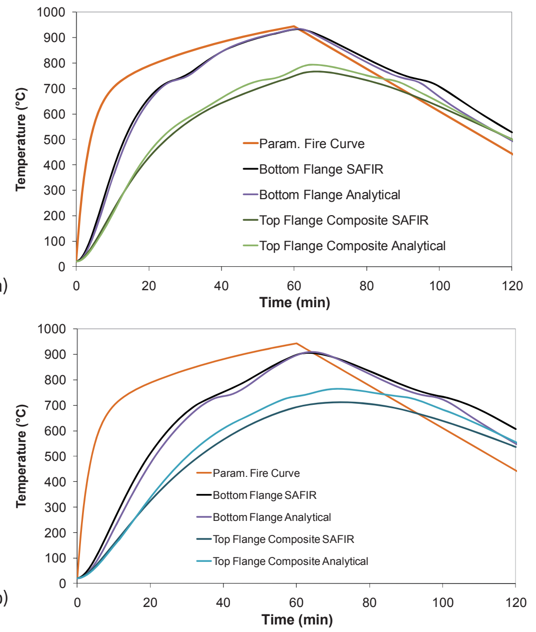



Figure 12_Comparison between temperatures of the top and bottom flanges obtained numerically and analytically - $t_{heating}$ = 60 min (a) IPE 300 (b) IPE 550

## INTERPOLATION PROFILES

Existing methods give a sufficient degree of precision for the prediction of temperature at the level of bottom flange in 2-D beam sections and 3-D joint zones. Two methods have been presented in order to predict the evolution of temperature in the top flange for these cases. A simple method is proposed to interpolate on the height of the steel beam and is compared to the thermal profiles obtained in simulations realized with SAFIR software. For 2-D beam sections, the reference temperatures of the finite element model are taken on the vertical axis of symmetry of the steel profile. For 3-D joints zones, the reference temperatures of the model are read on the external surface of the end-plate at a distance $b_b/4$ of the vertical plane of symmetry of the beam (Figure 13), where bb is the width of the beam flange. In usual joints, bolts are situated close to this reference line. The present simple method consists in the assumption of a bilinear profile, as described on Figure 14. Figures 15 and 16 show comparisons between the temperatures interpolated from analytical results and numerical results.

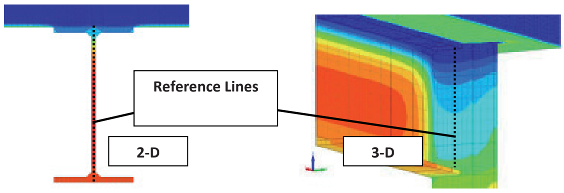



Figure 13_Reference lines for temperature interpolation between the levels of top and bottom flanges

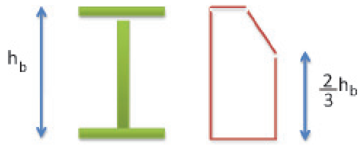



Figure 14_Simple temperature profile between the levels of top and bottom flanges

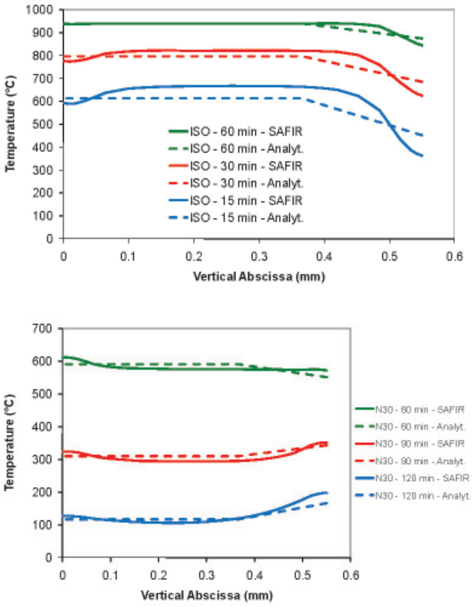



Figure 15_Temperature profiles in the IPE 300 beam under ISO and parametrical fire curves

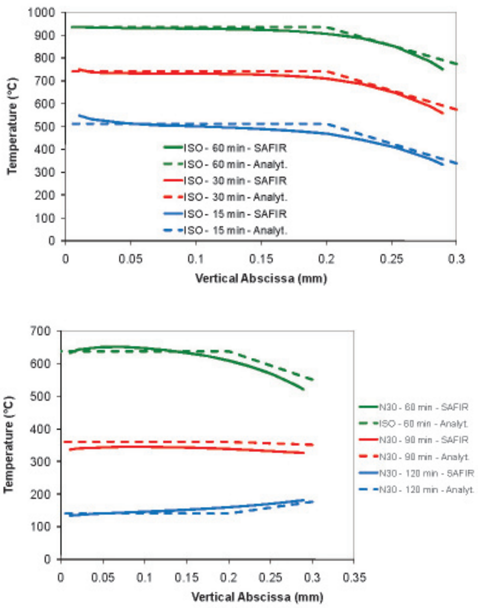



Figure 16_Temperature profiles in the IPE 300 joint under ISO and parametrical fire curves

## SUMMARY AND CONCLUSIONS

The present article describes the existing methods and recommendations for the evaluation of temperature profiles in steel beams and joints covered by a concrete slab. Then, modifications and improvements to the existing methods are proposed in order to predict more accurately temperatures at the level of the top flange of the beam by accounting for heat fluxes between the steel elements and the concrete slab. The two methods presented in this article differ by the degree of simplicity, the field of applicability and the accuracy of the predicted results. Comparisons with numerical simulations performed in the finite element program SAFIR have been described for the validation of these new methods. It is assumed in these numerical models that the contact between the steel profile and the concrete slab is perfect.

The "original" Lumped Capacity Method gives globally good predictions of temperature in steel and composite beams and joints but does not integrate heat fluxes between the steel elements and the concrete slab. This leads to an over-estimation of temperature in the steel elements during the heating phase and to an under-estimation of temperature during the cooling phase. In order to take these fluxes into consideration in the evaluation of the top flange temperature, it is suggested in the first proposed method to integrate a part of the concrete slab into the heated surface or volume considered in the Lumped Capacitance Method. The Composite Section Method correctly predicts temperature at the level of the top flange under ISO fire or during the heating phase of parametrical fire curves but a delay is observed between these analytical results and those obtained from numerical simulations performed in SAFIR software. In a second method, called Heat Exchange Method, it is proposed to calculate separately the heat fluxes between, on one side, the top flange and, on the other side, the gases of the compartment, the rest of the steel section and the concrete slab. The temperatures given by this latter method are in very good agreement with those obtained from FE models. The use of this method is really less fastidious than the use of FE models, especially for joints, but is limited to a certain type of fire curves (parametrical fire curves defined in the Annex A of the EN 1991-1-2).

Finally, a bilinear temperature profile has been proposed to interpolate the analytically-calculated temperatures at the level of the top and bottom flanges on the total height. This procedure is simple and shows a good agreement with the numerical results in 2-D beam sections and 3-D joint zones during the heating and cooling phases of parametric fire curves.

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