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DISTRIBUTION OF TEMPERATURE IN STEEL AND COMPOSITE BEAMS AND JOINTS UNDER NATURAL FIRE

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INTRODUCTION

Until recently [ECS, 1995], 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 objective of this article is to describe new developments aimed at improving the predictions of temperature in steel and composite beams and joints and to compare the results obtained by use of the new proposed analytical methods to those given by use of FE models built in the specially-purposed software SAFIR developed at the University of Liège [Franssen, 2005].

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 [Incropea et al., 2005], with some adaptations for steel beams that support a concrete slab on the upper flange and for joints. An interpolation profile is also given for beam-to-column and beam-to-beam steel joints with beams supporting any type of concrete floor, based on the temperature of the bottom flange at mid-span.

Comparisons recently realized with experimental measurements have shown that the temperatures calculated with interpolation profile of the Eurocode, 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 [Anderson et al., 2009]. 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. Numerical simulations performed with the finite element package Abaqus [Abaqus, 2009] 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 a too sophisticated tool to be used in practical applications. The software SAFIR has been used here as the numerical tool for predicting 2-D or 3-D temperature distributions in composite joints and beams.

NEW METHOD

A new method is proposed here where the heat exchanged between the top flange and the gas, ΔQ_{gas}, the heat exchanged between the top flange and the concrete slab, $\Delta Q_{top\text{-}bottom,}$ and the heat transferred between the top flange and the rest of the steel section, $\Delta Q_{concrete,}$ are all considered in the energy equilibrium equation (*Eq. 1*).

$$\Delta Q_{gas} + \Delta Q_{top-bottom} + \Delta Q_{concrete} = c_a \ \rho_a \ V \ \Delta\theta_{a,t} \qquad (1)$$

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

2) Results of numerical simulations show that the distribution of temperature in a composite beam is approximately uniform in the web and in the bottom flange (Fig. 1). A gradient of temperature is observed at the junction between the web and the top flange and heat is transferred by conduction in that zone. It is proposed to evaluate the heat transfer between the top flange and the rest of the steel section, $\Delta Q_{top-bottom}$, by *Eq. 2*. This energy can be positive (heat received by the top flange) or negative (heat lost by the top flange). In *Eq. 2*, λ 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, following the recommendations of the EN 1994-1-2.

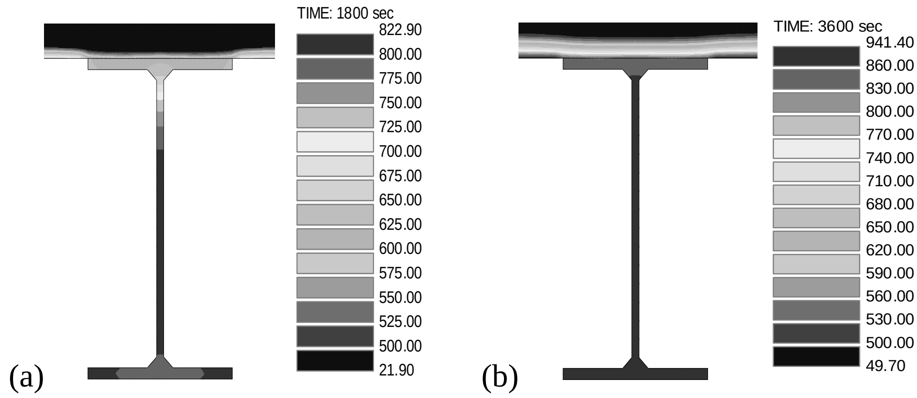


Fig. 1 Thermal distribution in a composite beam under ISO fire – (a) 30 min – (b) 60 min

$$\Delta Q_{top-bottom} = \lambda \frac{(T_2 - T_1)}{x} t_w \, \Delta t \tag{2}$$

In beam-to-column joints, the expression of the heat flux $\Delta Q_{top-bottom}$ is an adaptation of *Eq. 2* to 3-D zones (*Eq. 3*). Heat is transferred through the cross-section area $A_{top-bottom}$ (*Eq. 4*), 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.

$$\Delta Q_{top-bottom} = \lambda \frac{(T_2 - T_1)}{x} A_{top-bottom} \, \Delta t \tag{3}$$

$$A_{top-bottom} = l_b \, t_{wb} + t_p \, b_p + A_c/2 \tag{4}$$

3) The quantity of heat transferred from the flange to the concrete slab, $\Delta Q_{concrete}$, 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 T_1 of the top flange and the parameter Γ used to determine the shape of the parametrical fire curves in Annex A of EN 1991-1-2. Numerical simulations of an isolated steel flange covered by a slab and submitted to parametrical fires have been performed. The flux transferred from the top flange to the slab has been obtained from the difference between the quantity of heat received by the flange from the gases and the quantity of heat consumed to increase its temperature. During the cooling phase, the distribution of temperature in the slab depends on the history of the thermal loading because the

evolution of the heat exchange is not reversible. Numerical simulations have been performed for heating and cooling phases of several parametric curves (Γ varying between 0.4 and 2) and simple analytical expressions have been defined in order to approach the results obtained from the numerical simulations (*Eqs 5a to 5d*). The parameters ϕ_{150} and ϕ_{475} are given in Tab. 1. $T_{1,heating}$ 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 Fig. 2. The strong discontinuities observed around 735°C are due to the peak value of the specific heat of steel at this temperature.

$$\phi_{heating}(T_1) = \phi_{150}\,\frac{(T_1 - 20)}{(150 - 20)} \quad ; \quad T_1 \leq 150°C \tag{5a}$$

$$\phi_{heating}(T_1) = \phi_{475} - (\phi_{475} - \phi_{150})\left(\frac{475 - T_1}{325}\right)^2 \quad ; \quad 150°C \leq T_1 \leq 730°C \tag{5b}$$

$$\phi_{heating}(T_1) = \phi_{475} - 0.616*(\phi_{475} - \phi_{150}) - 0.035*(T - 730) \;\; ; \;\; T_1 \geq 730°C \tag{5c}$$

$$\phi_{cooling}(T_1) = \phi_{heating} - (\phi_{heating} + 5)\sqrt{1 - \left(\frac{T_1}{T_{1,heating}}\right)^2} \;\; ; \;\; 20°C \leq T_1 \leq T_{1,\max,heating} \tag{5d}$$

Tab. 1 Tabulated data of ϕ_{150} and ϕ_{475} in function of the parametrical fire curve

	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)**
ϕ_{150}	**17**	**20**	**23**	**26**	**28**
ϕ_{475}	**24**	**28**	**31**	**34**	**36**

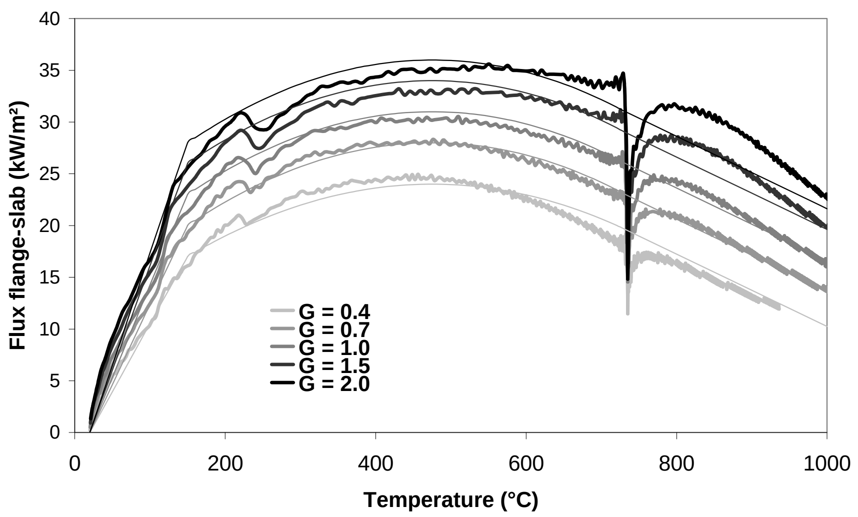


Fig. 2a Heat flux from top flange to concrete slab during heating phase of parametrical fire curves

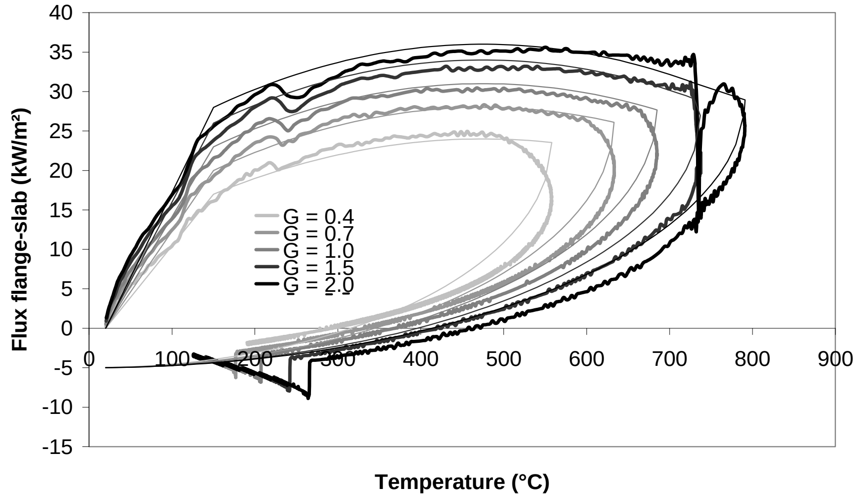


Fig. 3b Heat flux from top flange to concrete slab during cooling phase ($t_{heating}$ = 30 min) of parametrical fire curves

$\Delta Q_{concrete}$ is given by *Eq. 6* for 2-D beam sections (in which b_b is the width of the beam flange) and by *Eq. 7* and for 3-D joint zones. The transfer area $A_{transfer}$ is given in *Eq. 8*, 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.

$$\Delta Q_{concrete} = b_b \, \phi \, \Delta t \tag{6}$$

$$\Delta Q_{concrete} = \phi \, A_{transfer} \, \Delta t \tag{7}$$

$$A_{transfer} = l_b \, b_b + t_p \, b_p + \left(\min\left(h_{slab}\,; l_c\right) * \left(h_c + 2b_c\right)\right) \tag{8}$$

This method gives a very good agreement with the temperatures obtained by use of the 2-D (Fig. 3) and 3-D models (Fig. 4) built in SAFIR software during the complete parametrical fire curve.

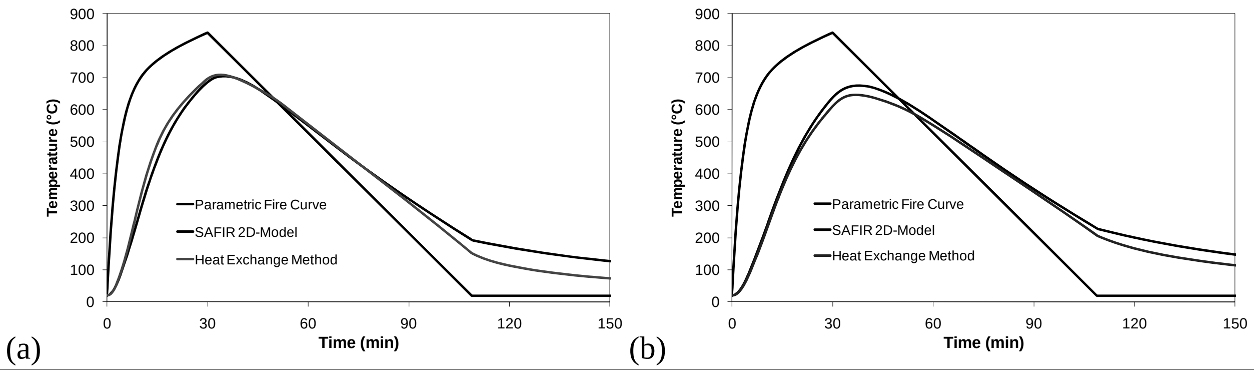
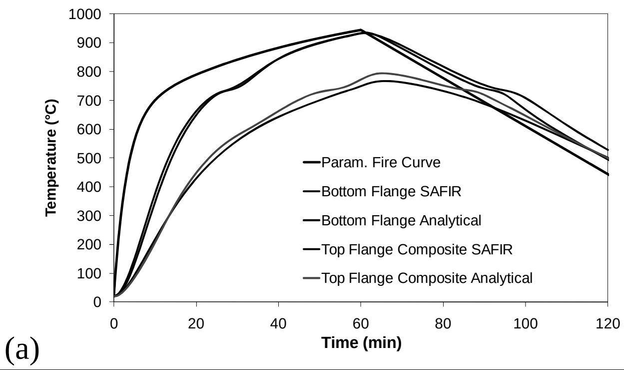


Fig. 4 Temperature of the top flange obtained numerically and analytically - $t_{heating}$ = 30 min
(a) IPE 300 (b) IPE 550



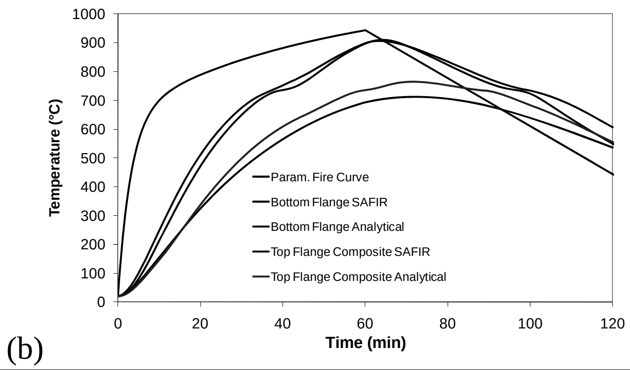


Fig. 5 : Comparison between temperatures of the top and bottom flanges obtained numerically and analytically - $t_{heating}$ = 60 min (a) IPE 300 (b) IPE 550

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. A method has 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 (Fig. 5), where b_b is the width of the beam flange. In usual joints, bolts are situated close to this reference line. The present simple method is based on a bilinear profile, as described on Fig. 6. Fig. 7 and 8 show comparisons between the temperatures interpolated from analytical results and numerical results.

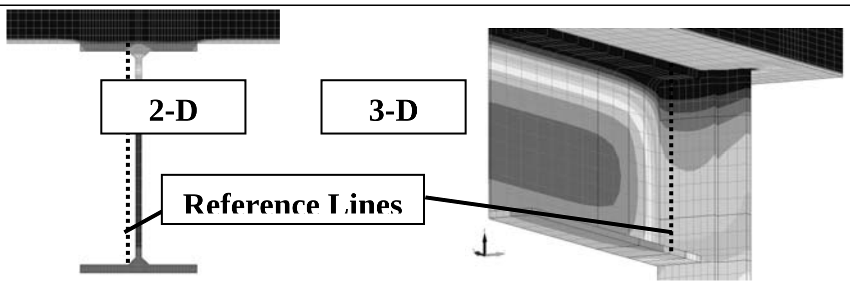


Fig. 6 Reference lines for temperature interpolation between the levels of top and bottom flanges

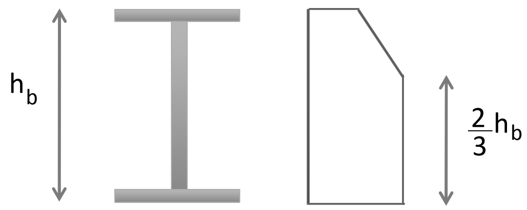


Fig. 7 Simple temperature profile between the levels of top and bottom flanges

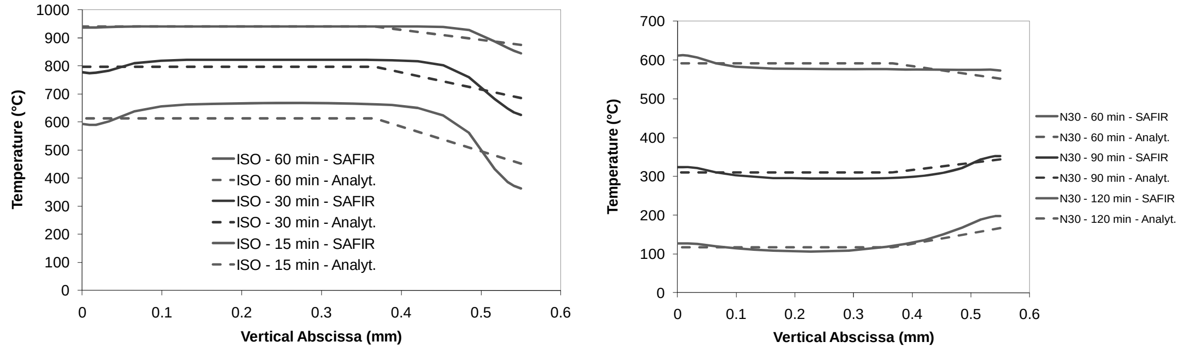


Fig. 8 Temperature profiles in the IPE 550 beam under ISO and parametrical fire curves

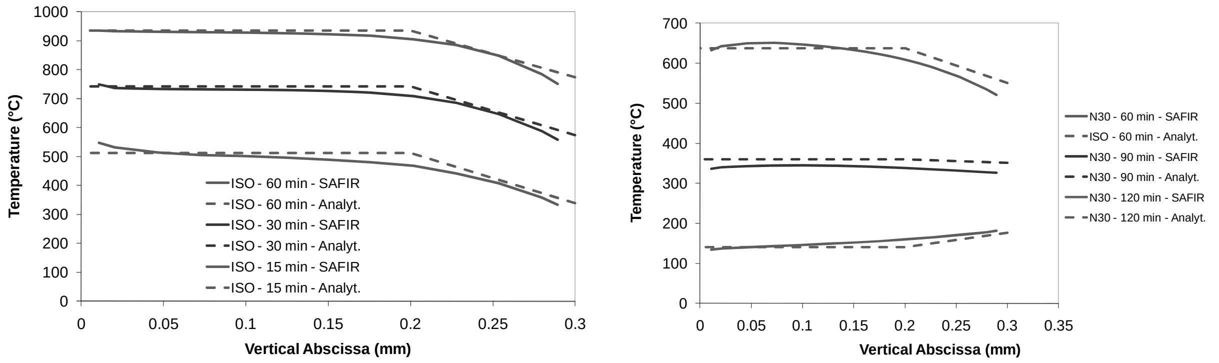


Fig. 9 Temperature profiles in the IPE 300 joint under ISO and parametrical fire curves

CONCLUSIONS

A method is proposed where the heat fluxes are calculated between, on one hand, the top flange of a steel beam covered by a concrete slab and, on the other hand, the gases of the compartment, the rest of the steel section and the concrete slab. The temperatures given by this 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 it gives a much better estimation of the temperature in the top flange than the current method of EN 1993-1-2. It is yet limited to a certain type of fire curves (ISO curve and parametrical fire curves defined in the Annex A of the EN 1991-1-2).

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.

REFERENCES

[1] ENV 1993-1-2 – Eurocode 3 “Design of steel structures” – Part 1-2: Structural fire design, European Committee for Standardization, Brussels, 1995.

[2] “SAFIR A Thermal/Structural Program Modelling Structures under Fire”, J.-M. Franssen, Engineering Journal, A.I.S.C., Vol. 42, No. 3, pp. 143-158, 2005.

[3] “Fundamentals of Heat and Mass Transfer”, F.P. Incropea, D.P. DeWitt, T.L. Bergma,, A.S. Lavine, John & Wiley Sons, Hoboken, USA, Sixth Edition, 2005.

[4] “Investigation into Methods for Predicting Connection Temperatures”, K. Anderson, M. Gillie, Czech Technical University Publishing House, Acta Polytechnica Vol. 49 No. 1, 2009.

[5] “Abaqus User’s Manual, version 6.6”, Providence, RI, USA, 2009.