Section factor and steel columns embedded in walls

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ABSTRACT: The fire resistance of a steel column is strongly influenced by the conditions in which it is inserted in the building. Beyond other parameters the contact of the column with the building walls and its differential heating are parameters that have a great influence on the column behaviour in fire. The walls, on one hand, have a favourable influence on the fire resistance of the steel sections because they protect a large part of its lateral surface from heating, but on the other hand, they will have an unfavourable influence because they lead to differential heating of the cross-section. The design methods considered in the Eurocode 3 part 1.2 do not take into account this fact and the fire resistance is determined as if the heating was uniform. In this paper, the results of several fire resistance tests performed on steel columns embedded in walls, carried out in the University of Coimbra, will be presented. The evolution of temperatures will be compared with the ones obtained in numeric simulations performed with the computer program SUPER-TEMPCALC, developed by Y. Anderberg of Fire Safety Design, Lund, Sweden. A proposal of modification of the Eurocode 3 part 1.2 method for the evolution of temperatures in steel elements embedded in walls is presented.

KEYWORDS: steel, columns, walls, fire, section, factor

1 INTRODUCTION

The high thermal conductivity of steel leads to the rapid temperature rise in steel elements in fire, and consequently to a reduction in their fire resistance. In order to improve the competitiveness of steel structures, much research has been carried out to provide a better understanding of the performance of steel framed structures in fire.

Most of steel columns in real buildings are embedded in walls and subjected to a differential heating. The effect of the temperature gradient in the steel cross-section is twofold: it is beneficial with a reduction in the average temperature and it is detrimental with the associated thermal bowing leading to large bending moments. The column maximum failure temperature is governed by the net effect of these two factors.

The design methods considered in Eurocode 3 part 1.2 neglect this effect and the fire resistance is assessed considering a uniform distribution of temperatures within the cross section.

2 EVOLUTION OF TEMPERATURES IN STEEL CROSS-SECTIONS ACCORDING TO EUROCODE 3 PART 1.2

The heating rate of a steel element has great effect on its fire resistance. A high mass section will heat up slowly (and thus normally have a higher fire resistance) than a slender section. The influence of the massiveness of the profile is considered in EC3 part 1.2 by the so called 'Section Factor' (fig. 1).

$$SectionFactor = \frac{A_m}{V} \tag{1}$$

where:

A_m is the area of the lateral surface of the steel exposed to fire (m^2)
V is the volume of steel of the element (m^3).

I-section exposed to fire on three sides:

$$\frac{Am}{V} = \frac{\text{perimeter exposed to fire}}{\text{cross-section area}}$$

I-section flange exposed to fire on three sides:

$$A_m/V = (b + 2.tf)/(b.tf)$$

$$\text{If } tf \ll b \quad A_m/V \approx 1/tf$$

Fig. 1 – Section factors according to EC3 part 1.2

For an equivalent uniform temperature distribution in the cross-section, the increase of temperature in an unprotected steel member during a time interval is determined by the following expression:

$$\Delta\theta_{a,t} = k_{sh} . \frac{A_m/V}{c_a . \rho_a} . h_{net,d} . \Delta t \tag{2}$$

where:

K_{sh} - is the correction factor for the shadow effect

A_m/V - is the section factor for unprotected steel members

A_m - is the surface area of the member per unit length (m^2)

V - is the volume of the member per unit length (m^3)

c_a - is the specific heat of steel (J/Kg.K)

$h_{net,d}$ - is the design value of the net heat flux per unit area (W/m^2)

Δt - is the time interval (seconds)

ρ_a - is the unit mass of steel (Kg/m^3)

For unprotected I-sections under nominal fire actions the correction factor for the shadow effect may be determined from:

$$K_{sh} = 0.9\left[\frac{A_m}{V}\right]_b \Big/ \left[\frac{A_m}{V}\right] \quad (3)$$

where $\left[\frac{A_m}{V}\right]_b$ is box value of the section factor.

In all other cases:

$$K_{sh} = \left[\frac{A_m}{V}\right]_b \Big/ \left[\frac{A_m}{V}\right] \quad (4)$$

For cross sections with a convex shape fully engulfed in fire, the shadow effect does not play any role and consequently the correction factor k_{sh} may be considered equals to the unity.

3 EXPERIMENTAL PROGRAM

Two different types of column cross-sections, with two orientations of the web in relation to the fire and two thicknesses of the building walls were tested (Correia *et al.*2007).

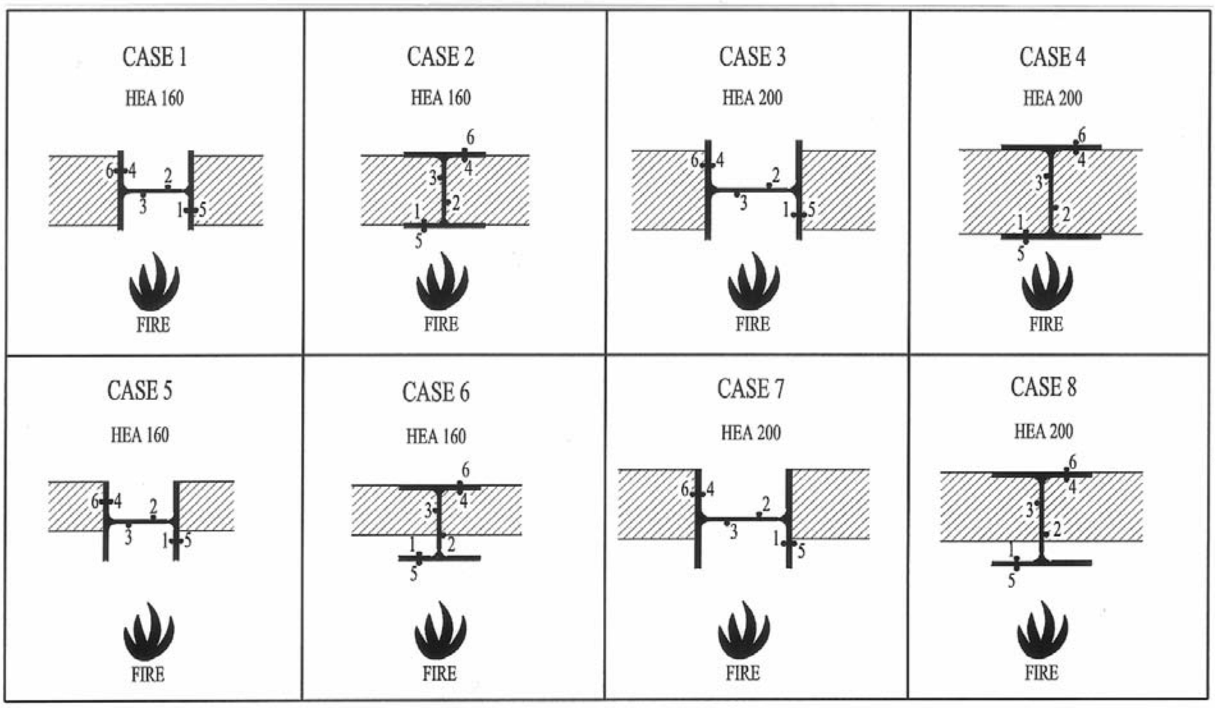


Fig. 2 –Cases studied and location of the thermocouples

The tested columns were HEA160 and HEA200, steel class S355 and the walls made of ceramic bricks of two different thicknesses (fig. 2). The bricks were lasted in place by ordinary cement mortar.

The columns in testing were placed on the center of a 3D restraining frame (fig. 3 a). This frame was composed by four columns HEB200 of 3m tall and four beams HEB200 of 6m span, steel class S355, orthogonally disposed. Two half brick walls were built, one on each side of the column in test (fig. 3 b).

a) **b)** **c)**

Fig. 3 – a) Construction of the test model, b) Column embedded in the wall, c) Column after test.

In order to measure the temperatures in the specimens, type k thermocouples were located in different points of the columns cross-section and walls.

The thermal action was applied by a gas fired furnace on one face of the element, in such a way to permit the analysis of the thermal gradient through the wall and cross-section of the column. The evolution of temperatures in the furnace followed the ISO 834 standard fire curve.

The temperatures inside the furnace were measured by shielded probe type K thermocouples in the first four tests (cases 1 to 4 in fig. 2) and were later changed to plate thermometers in the last four tests (cases 5 to 8 in fig. 2). This changing was decided due to a small delay in the heating of the furnace observed in the first four fire resistance tests.

The differential heating on the columns caused the bending in a plane perpendicular to the wall. Regardless the orientation of the web and flanges in relation to the wall, the curvature of the column was observed to be towards the side of the fire, in all cases.

4 NUMERICAL MODELLING

The computational modelling was performed using the computer program SUPERTEMPCALC (STC) – Temperature Calculation and Design v.5, developed by Y. ANDERBERG (Anderberg, 1997) for two-dimensional thermal analysis of sections exposed to heat.

The thermal properties of the materials adopted in the numerical analysis, were the ones presented in Eurocode 3 for steel and Eurocode 2 for concrete, parts 1.2. For the mortars applied on the bricks, the same properties of the concrete were adopted.

The thermal properties considered for the bricks were the same as the ones adopted in the computer program Ozone, developed in the University of Liège, which are: thermal conductivity = 0,7 W/m°C, specific heat = 840 J/kg°C; mass density = 1600 kg/m^3; specific heat x mass density = 1344000 J/m^3°C.

The emissivity was $\varepsilon = 0.7$, for the steel profile, as well as for the brick and the mortar.

The coefficient of heat transmission by convection in the face exposed to the fire was $\alpha_c = 25$ W/m^2°C and in the non-exposed face was $\alpha_c = 4$ W/m^2°C, as recommended by Eurocode 1 part 1.2.

The models were meshed in finite rectangular elements of 4 mm or 5 mm of side. The computer program STC can draw isothermals, temperature fields, for each instant of time, and punctually, give the value of the temperature in function of time.

5 METHOD FOR CALCULATION OF THE TEMPERATURE EVOLUTION IN STEEL CROSS-SECTIONS EMBEDDED IN WALLS

Four methodologies were developed for the assessment of temperatures in the cross section of steel columns embedded in walls [6]:

- Method 1: web parallel to the fire – wall thickness and flange width similar (comparison between cases 1 and 3)

- Method 2: web perpendicular to the fire – wall thickness and web height similar (comparison between cases 2 and 4);

- Method 3: web parallel to the fire – wall thickness smaller than flange width (comparison between cases 5 and 7);

- Method 4: web perpendicular to the fire – wall thickness smaller than web height (comparison between cases 6 and 8);

The thick wall was used to simulate the cases in real buildings, where the thickness of the wall is nearly the same as the width of the column. Walls of 14cm thickness for HEA 160 columns and 18cm thickness for HEA 200 columns were used. The thin wall was used to simulate cases where the wall is thinner than the column flange width. In these cases, the wall thickness is approximately ¾ of the flange width, and the fire is considered to act on the side where the steel cross section is not embedded in the wall. Walls of 10cm thickness for HEA 160 columns and 14cm thickness for HEA 200 columns were used. These thicknesses were considered depending on the commercial brick thicknesses available in the market.

In methods 1 and 3, the section was considered to be divided in 3 zones, in which the temperature is uniform, being the web, half-flange exposed to fire and the half-flange not exposed to fire. In methods 2 and 4, the section was considered to be composed by 3 zones, the flange exposed to fire, the web and the flange not exposed to fire (fig. 4).

In each zone, two temperature measuring points were used, one at each side of the zone, so that the average value of the temperature was considered at each instant of time.

The numerical analysis was carried out using the temperatures registered in the furnace in each experimental test. To eliminate some deviation of the furnace temperatures from the ISO 834 fire curve the obtained values of temperature with STC were multiplied by a correction factor.

$$f = \frac{T_{ISO834}}{T_{furnace}} \tag{5}$$

The temperatures obtained experimentally were used to calibrate and validate the results of the numerical analyses with STC. The calculations to obtain the reduction coefficients proposed in the following methods were performed using the results of the numerical analysis.

The results of the temperatures calculated with STC in each zone, were then compared with the ones obtained with the simplified calculation method presented in Eurocode3 part 1-2 for the exposed zone of the steel cross-section. This procedure allowed determining reduction factors for the temperatures in each of the 3 zones.

The section factors were calculated dividing the exposure perimeter by the exposed surface (fig. 4). The coefficient K_{shadow} was considered in all cases, except case 2 and 4.

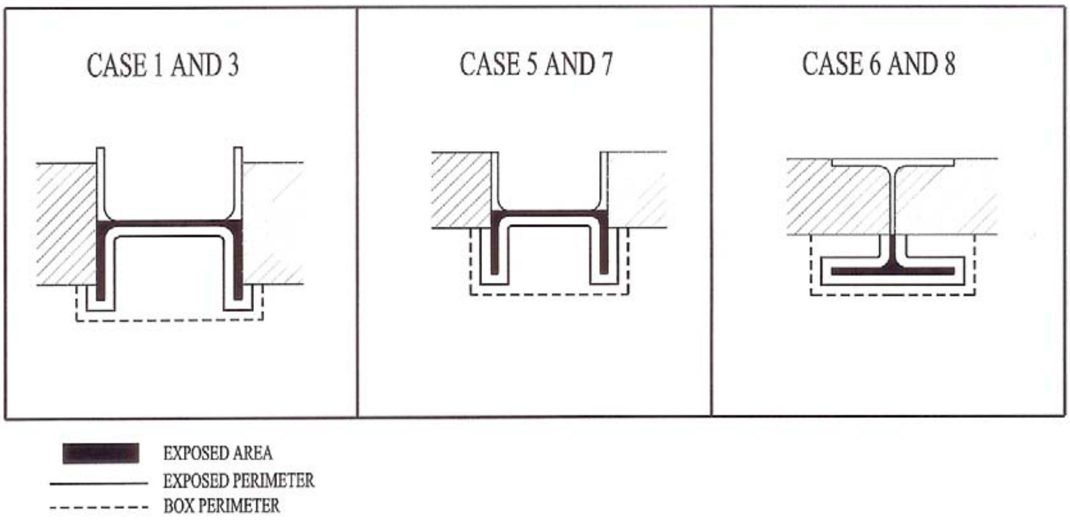


Fig. 4 – Process of calculation of the section factor.

The temperatures in the experimental tests were measured at 6 points on 5 sections of the steel cross-section (fig. 2). These temperatures in the middle height section of the HEA 200 columns were compared with the ones obtained in the numerical simulations (figs. 5 and 6).

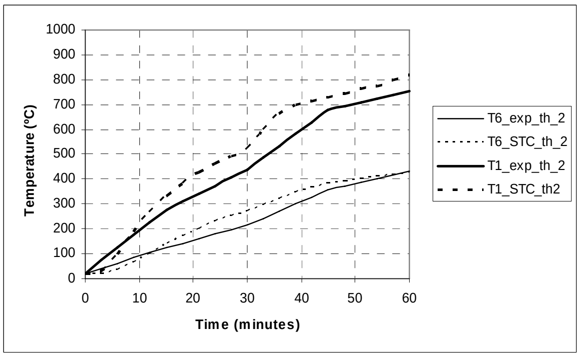


Fig. 5 – Temperatures *vs* time - thermocouple T6 and T1 - HEA200 - web parallel to the wall- case 3

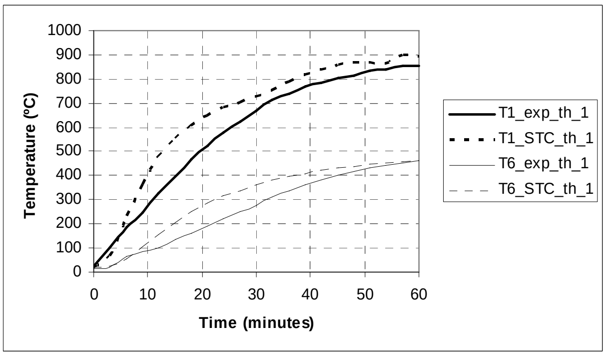
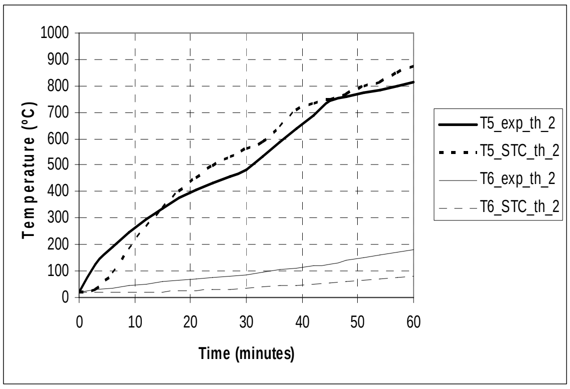


Fig. 6 – Temperatures *vs* time - thermocouple T6 and T1 - HEA200 - web parallel to the wall; - case 7

For the cases of the web perpendicular to the wall, a huge thermal gradient was observed along the height of the steel cross-section (between thermocouple 5 and 6), of about 700ºC for the thinner wall (case 8) and about 600ºC for the thicker wall (case 4), (fig. 5 and 6).

Also for the cases with the web parallel to the wall, a great difference of temperatures between the exposed and unexposed half-flanges was obtained, 400ºC for the thinner wall and 300ºC for the thicker wall (fig. 7 and 8).



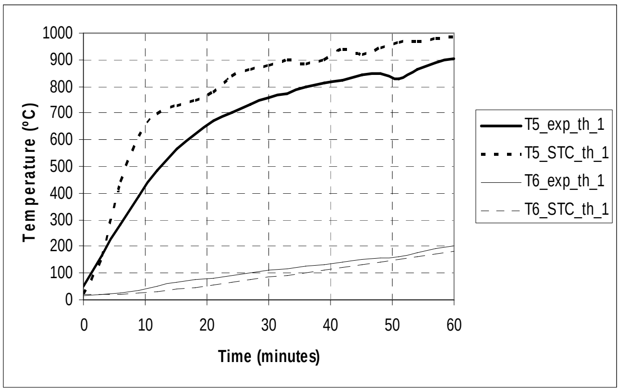


Fig. 7 – Temperatures *vs* time -thermocouple T5 and T6 - HEA200 - web perpendicular to the wall – case 4

Fig. 8 – Temperatures *vs* time -thermocouple T5 and T6 -HEA200 -web perpendicular to the wall - case 8

Tables 1 to 4 present the reduction coefficients that should be multiplied by the temperatures calculated in the exposed zone of the steel cross-section, using the EC3 part 1.2 simplified calculation method, in order to obtain the temperatures in the other zones of the steel cross-section.

Time (minutes)	Half-flange exposed	Web	Half-flange unexposed
10	0.71	0.87	0.27
20	0.80	0.83	0.39
30	0.81	0.76	0.44
40	0.84	0.78	0.46
50	0.87	0.78	0.49
60	0.87	0.77	0.49

Table 1- Method 1- web parallel – thick wall

Time (minutes)	Flange exposed	Web	Half-flange unexposed
10	0.78	0.18	0.07
20	0.82	0.23	0.05
30	0.87	0.30	0.07
40	0.86	0.32	0.09
50	0.90	0.36	0.10
60	0.95	0.39	0.12

Table 2 - Method 2- web perpendicular – thick wall

Time (minutes)	Half-flange exposed	Web	Half-flange unexposed
10	0.98	0.84	0.30
20	0.85	0.73	0.39
30	0.88	0.77	0.44
40	0.93	0.78	0.48
50	0.95	0.78	0.50
60	0.95	0.78	0.50

Table 3 - Method 3- web parallel – thin wall

Time (minutes)	Flange exposed	Web	Half-flange unexposed
10	1.00	0.40	0.06
20	1.00	0.46	0.07
30	1.00	0.50	0.10
40	1.00	0.54	0.13
50	1.00	0.58	0.16
60	1.00	0.60	0.19

Table 4 - Method 4- web perpendicular – thin wall

6 CONCLUSIONS

As expected the flanges of the steel profile directly exposed to fire will be at high temperature than the unexposed ones. This will cause a higher expansion of the heated flange than the cooler one, inducing bending moments in the column cross-section. This effect is called thermal bowing and may be very important in bare steel columns in fire.

The Eurocode 3 part 1.2 formulation for the section factor can be used, although it was proven to be valid only for the exposed flange engulfed in fire (cases of wall thickness smaller than web height – table 4). In all other cases, the temperature in each zone of the cross-section can be calculated in function of the temperature of the exposed area. Several reduction factors were defined in such a way that multiplying the temperature of the exposed area of the steel profile by them, the temperature in the corresponding zone is obtained.

The methods presented in this paper for the calculation of the temperatures in the different parts of the steel cross-section have potential to be used in a future formulation, in Eurocode 3 part 1.2, of the section factor of columns embedded in walls.

The assessment of temperatures in structural elements subjected to differential heating is essential to the development of analytical methods to predict buckling behavior of this type of columns.

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