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Proposal of new expressions for the calculation of section factor on structural steel columns in contact with walls

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Abstract

The fire resistance of a steel column is highly affected by the contact between the columns and the walls, leading in general to a favorable effect due to the reduction of temperatures. However, it leads to the *Thermal Bowing* effect, which is not more than a differential heating in the steel cross sections, causing an inversion of bending moments and an inversion of the deflections of the column. Thus, it is necessary to accurately assess the evolution of the temperature field in the cross section of the steel elements in contact with walls. In Eurocode 3 part 1-2, the structural design of steel elements in fire situation is performed with expressions for the calculation of the section factor of steel profiles, but different cases of positioning the columns and the surrounding walls could be considered as causing extremely high thermal gradients. In this paper, a new approach for the calculation of section factors for cases not included in table 4.2 of Eurocode 3, part 1-2 are presented. This was achieved using numerical models with finite element modelling with the ABAQUS program, varying the cross-section of the columns, orientation of the web in relation to the walls, and the position and thickness of the walls, to achieve the desired section factors.

Introduction

Most generally, it has been considered that in case of fire, a steel column experiments a uniform temperature distribution along the cross-section, due to the great thermal conductivity of the steel.[1,2]

However, this assumption is not accurate, and in recent years several studies have been conducted to obtain a better understanding of this phenomenon. In 1988, Cooke[3] developed a study about the gradients in the cross-sections of building elements, and observed that important deflections occur on steel elements, because of this uneven heating of the elements. Valdir Silva[4] has carried out studies with the aim of calculating the temperature of thermally unprotected steel members under fire situations, with particular focus on the Section Factor parameter. In the University of Coimbra, a great amount of studies has been conducted, regarding these topics such as thermal gradients in cross-sections embedded on walls,[5-7] section factor,[8] determination of temperatures in cases of columns partially embedded in walls,[9] and thermal bowing.[10] In 2016, Lopes presented some proposals for Section Factor calculation, for columns in contact with walls.[11] Moreover EN 1993-1-2[1] considers a uniform temperature evolution in these elements, in case of fire, and does not contemplate all cases of embedment of steel columns in the partition walls.

Thus, based on many laboratory and numerical studies, it was found that this phenomenon should be considered in the fire design of buildings, even because it may create unfavorable situations in the structure due to the degradation of the material properties of steel, and the inversion of bending moments that create a marked curvilinear deformation in the element, best known as the phenomenon of *thermal bowing*.

The purpose of this paper is based on the introduction of reduction coefficients in the formulae of the aforementioned Eurocode for calculating the correct evolution of temperatures, providing data for the calculation of the real temperatures in different parts of the steel sections embedded on walls.

Materials and Methods

Methods of modelling the temperature evolutions in steel profiles and determination of section factors

This work presents a study based on a geometric and nonlinear material finite element analysis of 26 different steel profiles, with two different brick wall thicknesses of 7 cm and 15 cm and with two orientations of the web in relation to the walls, giving a total of 94 cases. In each of these cases, four methodologies were adopted to calculate the section factors. For each case, it was identified which method most closely approximates the temperatures obtained by the numerical models.

Case studies

For each profile studied, temperature values are presented in four different methods, which consist no more than different ways of calculating the section factor, that is, different methodologies to obtain the temperatures in the profile.

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Figure 1 intends to show the four different approaches used to calculate the temperatures, in the steel cross sections. In this Figure, we considered P_{exp} represented with a red line, A_{exp} with orange diagonal line, P_{box} with green line, the unexposed area is dark gray as well as the total area of the profile.

A list of the simulations program is shown in Appendix Table A1. For each combination of wall thickness and orientation of the web profile to the wall, the list of steel profiles adopted in the study is presented.

For each of these profiles, the four approaches used to calculate the temperatures according the Eurocode 3 part 1-2,[1] are described:

Case 1, $\frac{Am}{V} = \frac{Pexp}{Aexp}$,

is shown in Figure 1A. Case 1 is related to the quotient between the exposed perimeter, which is in red and the exposed area, which is illustrated with orange dashes. The exposed perimeter corresponds to the profile boundary that is in contact with fire, while the exposed area reflects which surface is exposed to it.

In Case 2, $\frac{Am}{V} = \frac{Pexp}{Atot.profile}$,

the quotient between the exposed perimeter and the total profile area, shown in full and gray, representing the entire surface of the profile, is determined.

Case 3, $\frac{Am}{V} = \frac{Pbox}{Aexp}$,

is obtained dividing the perimeter of the box, represented by a green line, by the exposed area designating the surface in contact with fire.

The box designation refers to a box that surrounds the profile only from the exposed side. This box concept is intended to consider the perimeter that will be heated in the profile by entering the flame into a concave surface.

Case 4, $\frac{Am}{V} = \frac{Pbox}{Atot.perfil}$,

refers to the division between the perimeter of the box, already mentioned, and the total profile area.

The parameters $A_{tot.profile}$, P_{box}, A_{exp}, and P_{exp} were calculated, in such a way to obtain for each case, the section factor calculated by different approaches.

With the above approaches, temperatures were estimated according to Eurocode 3 - part 1-2[1] for 15 min, 60 min and 120 min.

With the ABAQUS finite element program,[2] the temperatures were then calculated in the various cross-section zones of the profiles at different instants of time (15, 60 and 120 minutes). Temperatures were taken in different finite elements at half height, in the heated flange (HF) or heated half-flange (HHF), web (W), and unheated flange (UF) or unheated half-flange (UHF). An average value was adopted, considering the total finite elements in each of the mentioned zones.

Subsequently, the reduction coefficients were determined by dividing the temperatures calculated by the Eurocode, and the temperatures obtained by the ABAQUS finite element analysis.

The cases mentioned above are:

- Case 1: $\frac{Am}{V} = \frac{Pexp}{Aexp}$ (1)

- Case 2: $\frac{Am}{V} = \frac{Pexp}{Atot.perfil}$ (2)

- Case 3: $\frac{Am}{V} = \frac{Pbox}{Aexp}$ (3)

- Case 4: $\frac{Am}{V} = \frac{Pbox}{Atot.perfil}$ (4)

Modelling with the ABAQUS program

Figure 2A and B represents the construction of the 3D models of the HE 160A profile with the web parallel to the wall and another with the web perpendicular to the wall, respectively.

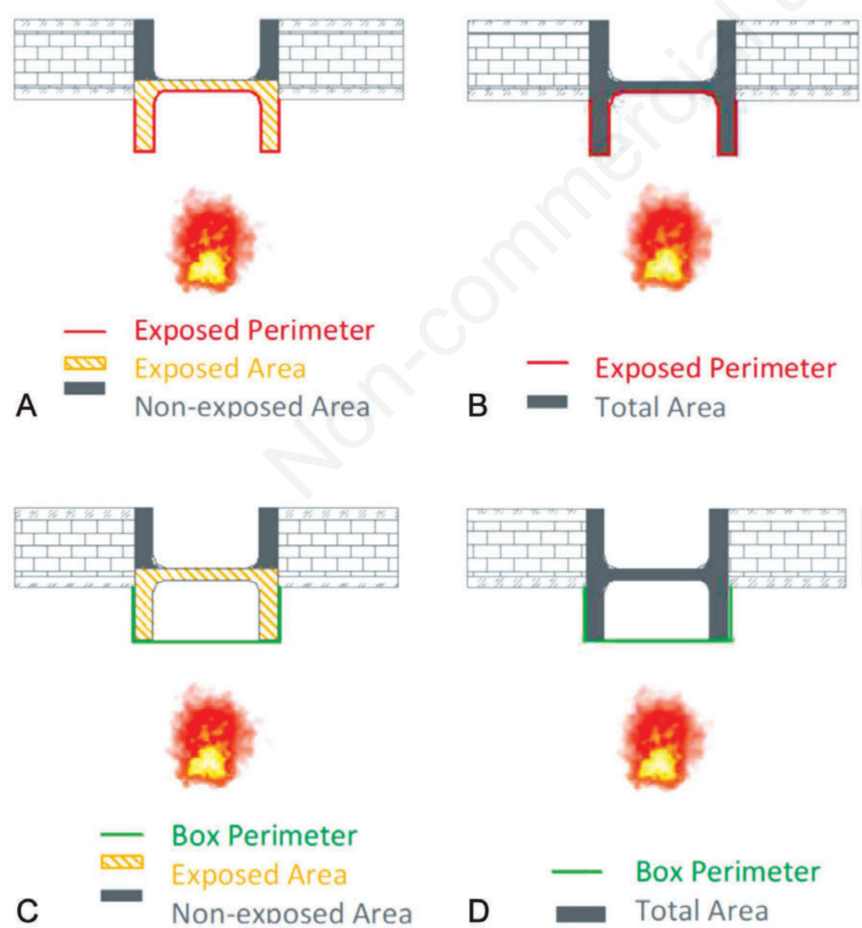

Figure 1. Different approaches to the calculation of temperatures in the steel profiles. A) Case 1. B) Case 2. C) Case 3. D) Case 4.

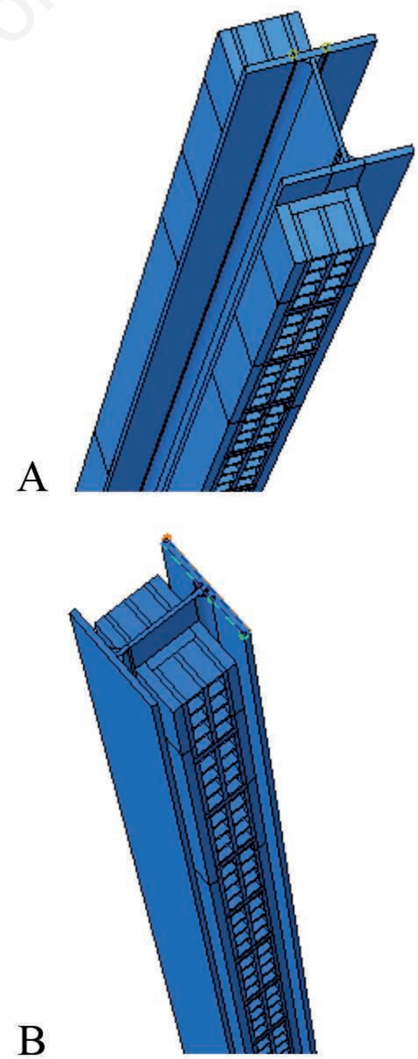

Figure 2. A) HE 160 A Assembly with web parallel to the wall. B) HE 160 A Assembly with web perpendicular to the wall.

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Figure 3 represents the assembly or assembly steps of the model and relate to the definition of the master and slave surfaces. The master face is represented in red and the slave face in pink.

Figure 4A and B shows examples of numerical models used in the finite element analysis of the thermal behavior of steel columns embedded in walls. It also shows how the surfaces that were analyzed to obtain the temperatures of the finite elements were selected, that is, the results on the web and half-flanges of the profile. For the representation, we used the HE 160A profile, 7cm wall with the web parallel to the wall. In this case, as in the others where the web is parallel to the wall, the wall creates a kind of fire protection and divides the flanges by their *half*. So, we refer to heated half-flanges and unheated half-flanges. The same does not apply to situations where the web is perpendicular to the wall.

Results

From the numerical simulations, temperature fields in the web and heated and unheated flanges were obtained, in the case of the columns with the web perpendicular to the walls, and in the heated and unheated half-flanges and web, in case of profiles with the web parallel to the walls. Appendix Tables A2-A5 are related to the HE 160M profile with a web positioned perpendicular to the wall of 7 cm thickness.

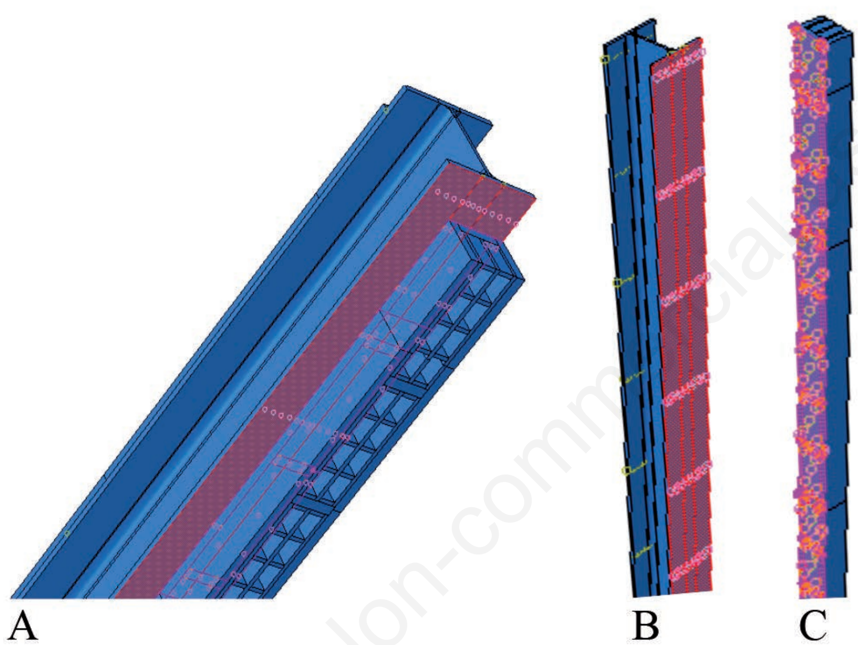

Figure 3. Surface definition demonstration. A) Master; B) master; C) slave.

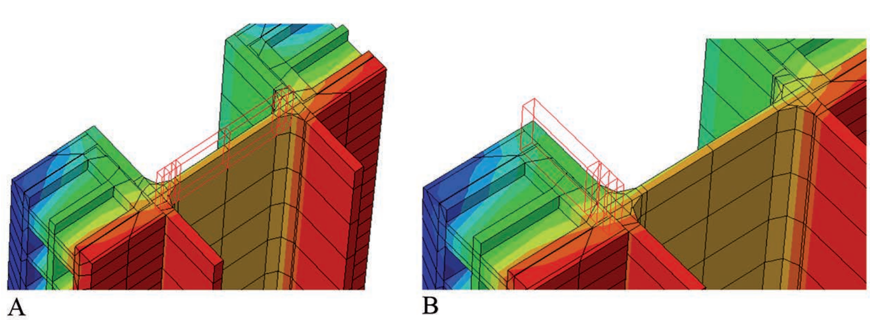

Figure 4. Visualization of the method to obtain the temperatures in the different zones. A) Web; B) unheated flange.

For different time instants, 15, 60 and 120 seconds, the relationship between the temperatures estimated by the Eurocode and the temperatures obtained by the finite element numerical models was calculated.

Discussion

Proposal of new expressions for calculating the Section Factor

In this chapter, calculation methods have been developed to obtain new expressions for the calculation of the section factor. This factor, although present in EN 1993-1-2,[1] is not adapted to some real situations, as it assumes that the temperature distribution occurs evenly along the steel profile cross section.

Parametric studies were used in 94 different cases, in steel profiles inserted, either in 7 cm wall or 15 cm wall, and with the position of parallel or perpendicular web to the wall. They were modeled in the ABAQUS program,[2] as already mentioned previously, applying a thermal finite element analysis, in which the temperatures for each situation were obtained.

The problem was subdivided into four distinct cases where the perimeter of the box, the exposed perimeter, the exposed area and the total area of the profile under study were considered. The obtained temperatures were compared with those provided by the EN 1993-1-2,[1] thermal reduction coefficients were obtained for three time periods, being 15, 60 and 120 min for the heated flange, web and unheated flange (in the case of the web perpendicular to the wall), or heated half-flange, web and unheated half-flange (in case of the profile with web parallel to the wall).

After calculating the coefficients, we used the least squares method, performed for each case and situation studied, so that it was possible to verify which of the studied cases has the lowest error. For this evaluation, we used the cases where the box perimeter was considered *vs* cases where it was not considered. Thus, we analyzed case I *vs* case II and case III *vs* case IV.

The situations were further distributed in four new cases. They concern the dimensions of the wall and the dimensions of the profile as well as the position of the profile relative to the wall, subdivided into cases A, B, C and D which will be detailed next. Thus, for each case two tables were constructed where the situations described in the previous paragraph are verified.

In cases with lower errors, which suggest to be the most accurate, coefficients k_1, k_2 and k_3 were taken, which represent the heated flange, web and unheated flange, respectively (in the case of the web perpendicular to the wall) and heated half-flange, web and half unheated half-flange (in the case of the web parallel to the wall). These represent the correction coefficients to be applied in EN 1993-1-2[1] formulae to obtain the most accurate approximation of temperatures during the occurrence of a fire.

The EN 1993-1-2[1] formula to be used is:

$$\Delta\theta_{a,t} = k_{sh} \frac{A_m/_V}{c_a \rho_a} \dot{h}_{net,d} \Delta t \quad (5)$$

Where:

$\Delta\theta_{a,t}$ is the variation of temperature, for instant t [ºC]; k_{sh} is the correction of the shadow effect factor; A_m/V is the section factor for unprotected steel members; A_m is the surface area of the member per unit length [m2]; V is the member volume per unit length [m3]; c_a is the specific heat of steel [J/kgK]; $\dot{h}_{net,d}$ is the effective flow calculation value per unit area [W/m2]; Δt is the time interval [seconds]; ρ_a is the unit of mass of steel [kg/m3].

The proposal consists on implementing a correction coefficient, k_c, in the previous formula, so that it provides non-uniform temperatures throughout the section, and consequently, more realistic in the different zones of the section.

$$\Delta\theta_{a,t} = k_{sh} \frac{k_c \, A_m/_V}{c_a \rho_a} \dot{h}_{net,d} \Delta t \quad (6)$$

The parameters involved in this new expression are the same as previously described with the introduction of k_c which corresponds to the correction coefficients obtained.

Reduction coefficients for Case A: p>0.5×b

This subsection leads us to situations where the profile web is parallel to the wall (p) and the wall thickness is greater than half the flange dimension (b), meaning p> 0.5×b (Figure 5).

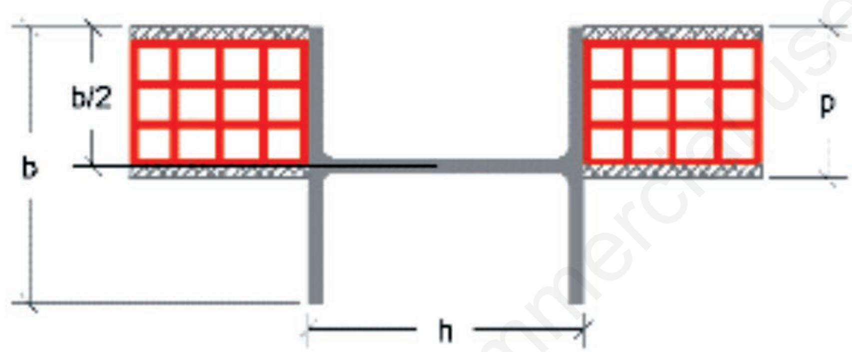

Figure 5. Profile subject to case A: p>0.5×b. p is the thickness of the wall and b is the length of the flange.

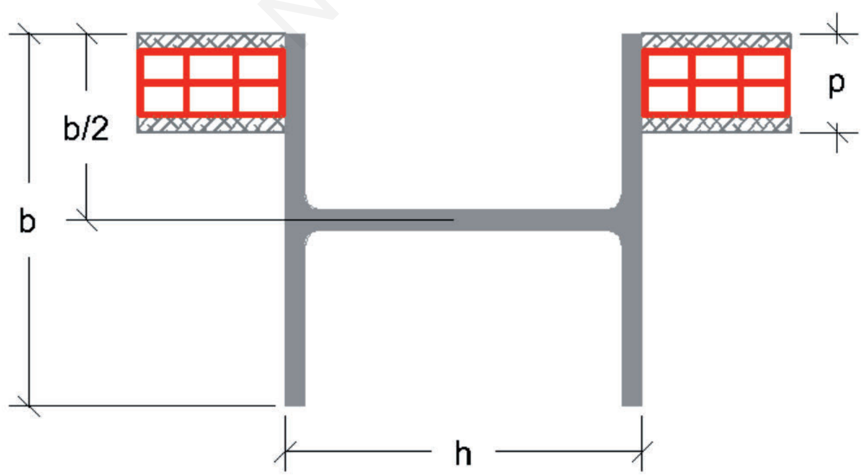

Figure 6. Profile subject to case B: p<0.5×b. p is the thickness of the wall and b is the length of the flange.

Appendix Table A6 presents the best fit performing the calculation with the exposed perimeter, and Appendix Table A7 presents the best fit with the calculation based on the box perimeter. Both approaches are possible, and the results are pretty similar. It is possible to conclude that, after 120 seconds, the temperatures in the unexposed zone of the profile are about 63% of the temperature estimated by the EN 1993-1-2.[1]

Reduction coefficients for Case B: p<0.5×b

This sub-chapter is intended for situations where the web of the steel profiles is parallel to the wall (p) and the wall width, in turn, is less than half the flange dimension (b), p<0.5×b (Figure 6).

Appendix Table A8 presents the best fit performing the calculation with the exposed perimeter, and Appendix Table A9 presents the best fit with the calculation based on the box perimeter. Again, the best calculation procedure is using the total area of the profile (cases 2 and 4). It may be observed that the differences are not so relevant.

Reduction coefficients for Case C: p>0.5×h

For situations where the profile web is perpendicular to the wall and the wall (p) is greater than half of the total profile height (h), p>0.5×h (Figure 7).

Again, Appendix Tables A10 and A11 present the results for cases 2 and 4. It is worth mentioning that on the unheated part of the column, the temperatures are now about 21% of the values estimated by the EN 1993-1-2,[1] after 120 seconds of heating.

Reduction coefficients for Case D: p<0.5×h

The methodology presented in Case D, is used when the profile web is perpendicular to the wall and the wall dimension (p) is less than half of the total profile height (h), p<0.5×h (Figure 8).

The same conclusions are applicable to this case D: both approaches 2 and 4 are more suitable for calculating the temperatures, *i.e.* using the total area of the profile. Another conclusion worth of notice is that the unheated flanges are much cold than the heated flange and web (Appendix Tables A12 and A13).

Conclusions

In this study, we presented proposals for a new approach for the calculation of the section factor, for cases not included in table 4.2 of the referred EN 1993-1-2.[1]

These proposals were obtained using finite element numerical models with the ABAQUS program,[2] varying the cross section of the steel profiles, the orientation of the web of the profiles in relation to the walls, and the position and thickness of the brick walls, in relation to the columns, to allow obtaining a correction of the section factor, with the largest possible field of validity. The proposed methodology makes the determination of real temperatures in unevenly heated steel profiles in contact with walls very easy. It simply consists of introducing reduction factors to the section factor, to obtain more realistic temperatures in the different parts of the steel profile, according to the position of the walls.

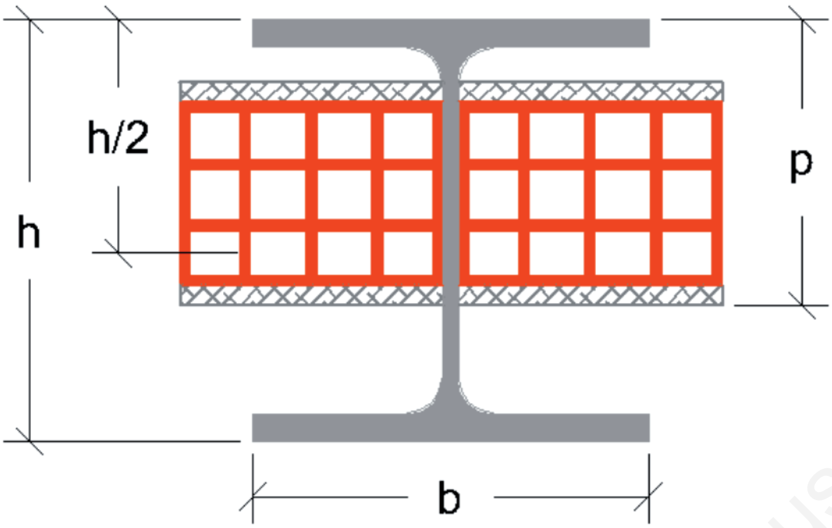

Figure 7. Profile subject to case C: p>0.5×h. p is the distance of the heated surface of the wall and the outer surface of the unheated flange and h is the height of the profile cross section.

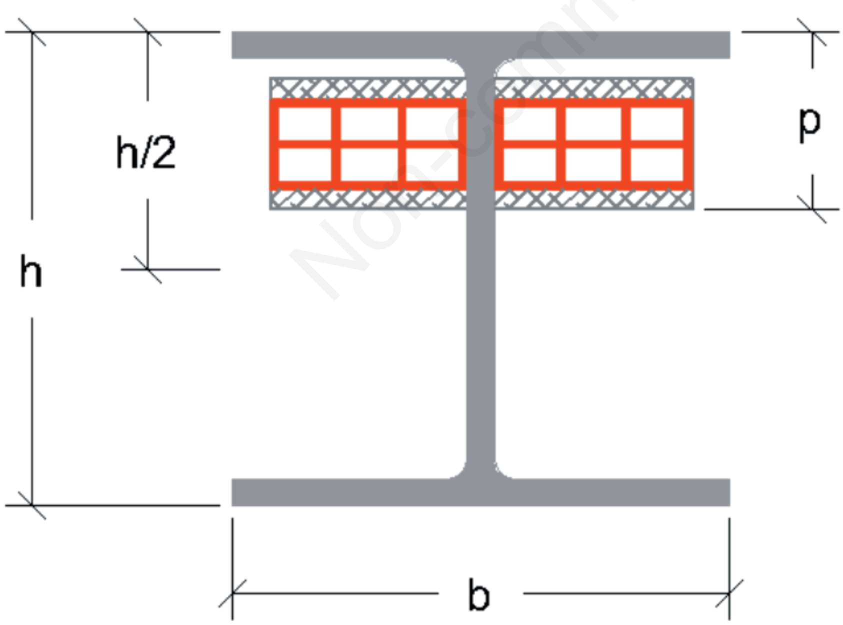

Figure 8. Profile subject to case D: p<0.5×h. p is the distance of the heated surface of the wall and the outer surface of the unheated flange and h is the height of the profile cross section.

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