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The Influence of End Conditions on Numerical Models of Cold Formed Steel and Concrete Composite Beams in Fire

Influência da Vinculação em Modelos Numéricos de Vigas Mistas de Aço e Concreto em Situação de Incêndio





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Abstract

In this paper is discussed the influence of the end conditions in composite cold-formed steel box section and concrete over masonry in fire situation. The software ANSYS was used for numerical simulation of the composite beam. The end conditions are considered as fixed or pinned and axial restrained at the ends. Initially, numerical thermal analysis to determine the field of temperatures in the steel profile and the slab under ISO-fire are carried out. The heat flux between steel, concrete slab and masonry are considered. The structural analysis is carried through for evaluating the performance of the composite beam in fire. Both geometric and materials nonlinearities, as well as the variation of the stress-strain diagram of the materials in function of the temperature are considered. Finally, comparisons between the behavior of beams with fixed ends and pinned ends are shown as well as the reduction factors with the time of exposition to the fire are determined.

Keywords: fire, structural analysis, numerical analysis, composite beams, cold-formed steel..

Resumo

Neste trabalho é discutida a influência da condição de vinculação de extremidade de vigas mistas de aço e concreto, sobre alvenaria, em situação de incêndio. O perfil de aço da viga é formado a frio, com seção transversal do tipo caixão. São consideradas situações de engastamento e rótula ideal para as extremidades da viga de interesse, em modelos numéricos elaborados por meio do código computacional ANSYS. Inicialmente, são realizadas análises numéricas de caráter térmico para a determinação do campo de temperaturas no perfil de aço e na laje, quando submetidos ao incêndio-padrão ISO 834. Em seguida, efetua-se o acoplamento termoestrutural para avaliação do desempenho do elemento em temperaturas elevadas. Por fim, são apresentadas comparações de interesse entre situações de extremidades da viga considerando-as engastadas e rotuladas, bem como são determinados os redutores do esforço resistente em resposta ao tempo de exposição ao fogo.

Palavras-chave: incêndio, análise estrutural, análise numérica, vigas mistas, perfis formados a frio.

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1. Introduction

The scope of this work is to analyze the influence of end supporting in numerical models of steel and concrete composite beams in fire situation. A cold formed steel box section beam and a concrete slab, on a wall, compose the beams under study. The conditions of end supporting are fixed-fixed and pinned-pinned. Within this context, it presents the resultant model mid span deflections as well as the resistance reducers due to fire exposure. ANSYS software was used for performing the thermal and structural analyses.

2. Geometrical characteristics of the beam

The geometry of models is presented in figure 1a. In the model, the following was considered: one steel beam with section dimensions as shown, a 95 cm wide and 8 cm thick concrete slab and a 9 cm thick and 50 cm high masonry (under lower flange, figure 1b). Total length was 3.8 m. Figure 1.c shows the end supports. Condition 1 refers to fixed ends and Condition 2 to pinned ends.

3. Physical-thermal properties of materials

The thermal properties for concrete and steel, variable with temperature and relevant for thermal analysis, are: thermal conductivity, specific heat and elongation. The values for thermal properties of steel in function of temperature are the recommended by ABNT NBR 14323:1999 [1]. The values for thermal properties of concrete in function of temperature are presented by EN 1992-1-2:2004 [2], for 3% humidity. For concrete thermal conductivity, this study adopts the equation referent to the lower limit. It was also considered the light variation of concrete density at high temperature. For masonry, the following parameters, recommended by Ozone v2.0 [3] software, were used: density 1600 kg/m^3, specific heat 840 J/kg°C and thermal conductivity 0.7 W/m°C.

4. Mechanical Properties of steel and concrete

At room temperature, the adopted mechanical properties of steel for computational modeling were: yielding stress 300 MPa and Young`s Modulus 205000 MPa. For structural analysis of steel elements at high temperatures, the thermal action effects were considered by means of reduction coefficients for mechanical properties in function of temperature supplied by ABNT NBR 14323:1999[1] and by EN 1993-1-2:2005 [4]. The stress-strain deformation diagram of steel was the recommended by EN 1993-1-2:2005 [4], presented in figure 2, for temperatures between 20 and 1100 °C.

For concrete, the characteristic compressive cylinder strength at room temperature was 25 MPa. The secant modulus of elasticity was 23800 MPa, obtained from NBR 6118:2003[5]. The characteristic axial tensile strength of concrete was 0.12 of the value corresponding compression strength. It was supposed elastic behavior in tension until rupture.

The stress-strain diagram for concrete was adapted from EN 1992-1-1:2004 [2], where it is considered, as a simplification, perfect plastic behavior after rupture for either tension or compression. The plastic interval has a slope of 1/1000 to avoid numerical instability problems when running Ansys.

The parameters for obtainment of the stress-strain diagram of concrete in function of temperature are presented in table 1, where k_c is the compressive strength reduction factor, k_{Ec} is the modulus of elasticity reduction factor and ε_{c0} is the specific strain of concrete's rupture outset. Having in mind that EN 1992-1-2 does not supply

Figure 1 – (a) Dimensions of beam cross section. (b) General diagram and dimensions of slab and masonry. (c) Support conditions for analyzed cases. Dimensions in mm

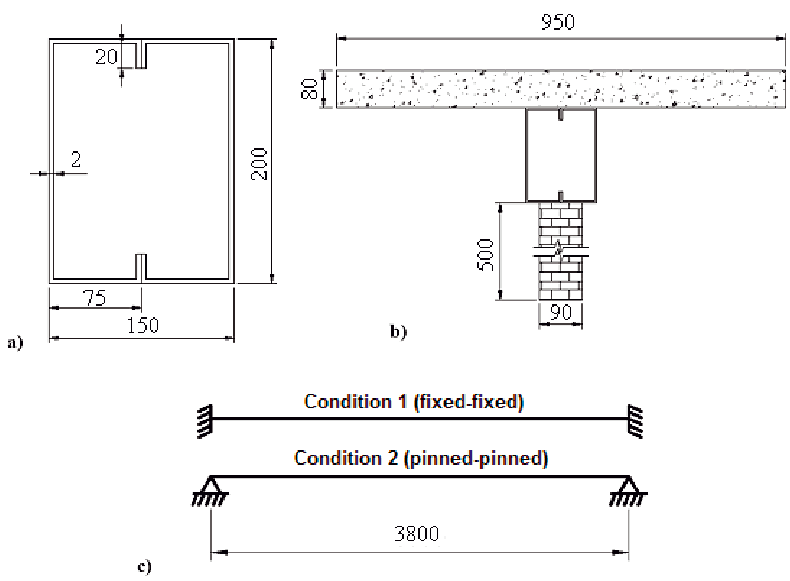
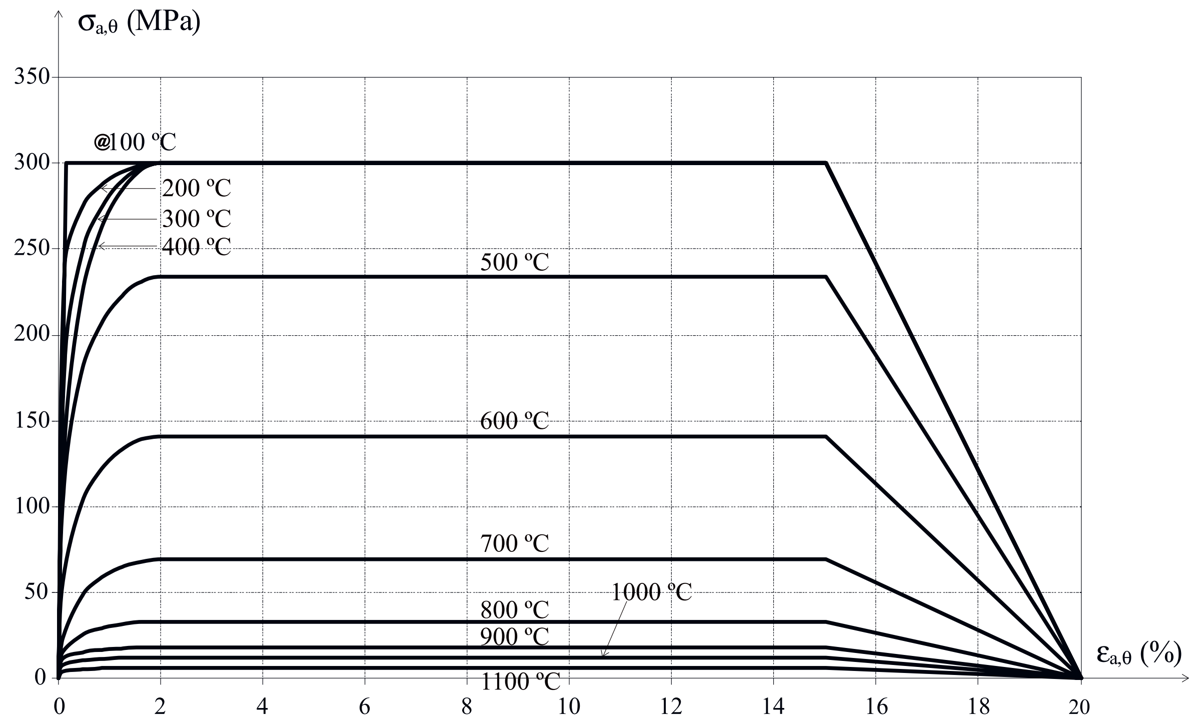


Figure 2 – Stress x strain relations adopted for steel, in function of temperature



the values for the elasticity modulus reducer, k_{Ec}, this work proposes the values that are indicated in table 1, which are based on ANSI/AISC 360-05, with some adjustments. To take into consideration a material with different behaviors in tension and in compression, it was used the HJELM model (cast iron plasticity) available in ANSYS software's library. The stress x strain ratio for concrete in function of temperature is show in figure 3.

5. Considerations related to thermal analysis

The thermal action was considered according to standard fire ISO 834 (eq. 1), where θ_g is the temperature of gases in degrees Celsius and t is the time in minutes.

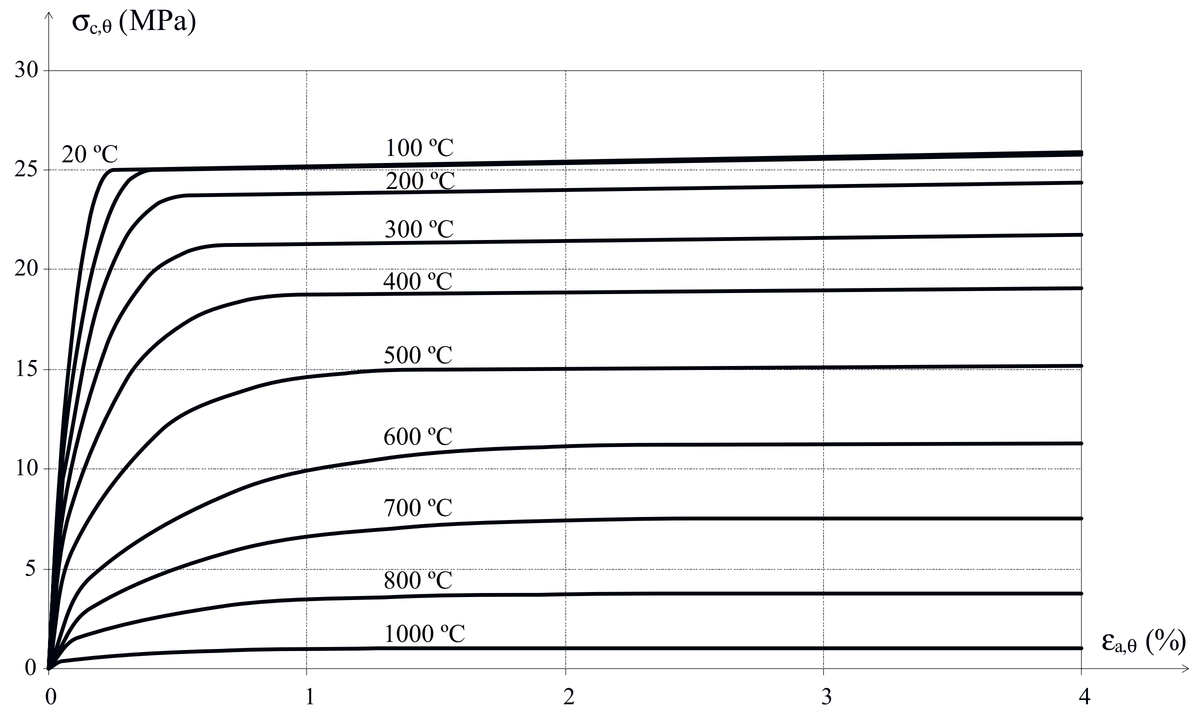
$$\theta_g = 20 + 345 \log_{10}(8t + 1) \quad (1)$$

The resulting flames-material emissivity factor was adopted equal to 0.5 for steel, concrete and masonry. The heat transfer coefficient for convection was adopted equal to 25 W/m²°C.
By means of thermal analysis, it was determined the field of temperatures in the combined section in function of temperature rise of gases along time. In this phase, the concrete slab and masonry actuated as heat absorbers. For numerical representation of the steel beam, concrete slab and masonry in the thermal analysis, the finite element SOLID70 was used. Also, SURF152 element was used for the generation of "convection" and "radiation" surfaces for the faces exposed to fire. Such elements have only temperature as degree of freedom per joint. In figure 4, the conditions of exposure to

Table 1 – Parameters for the determination of the constitutive relation of concrete in function of temperature

θ (°C)	k_c	k_{Ec}	ε_{c0}
20	1	1	0,0025
100	1	0,875	0,004
200	0,95	0,73	0,0055
300	0,85	0,58	0,007
400	0,75	0,42	0,01
500	0,6	0,27	0,015
600	0,45	0,12	0,025
700	0,3	0,08	0,025
800	0,15	0,06	0,025
900	0,08	0,05	0,025
1000	0,04	0,03	0,025
1100	0,01	0,02	0,025
1200	0	0	0

Figure 3 – Stress x strain relations adopted for concrete, in function of temperature



fire and the discretization of the numerical model constructed for thermal analysis purpose, are schematized. For the concrete slab, in the structural analysis, it was considered a uniform temperature variation along the thickness, obtained by means of a simplified procedure from NBR14323:1999[1], with the curve of temperature rise according to figure 5. This is due to the discretization of the slab by shell type elements in structural analysis, having in mind convergence problems when solid elements are used.

6. Considerations related to structural analysis

The steel beam was modeled using SOLID45 finite elements, whose degrees of freedom in each joint correspond to deflections in x, y and z directions.
The concrete slab was modeled using SHELL181 elements whose degrees of freedom in each joint correspond to deflections

Figure 4 – Conditions of exposition to fire and model for thermal analysis

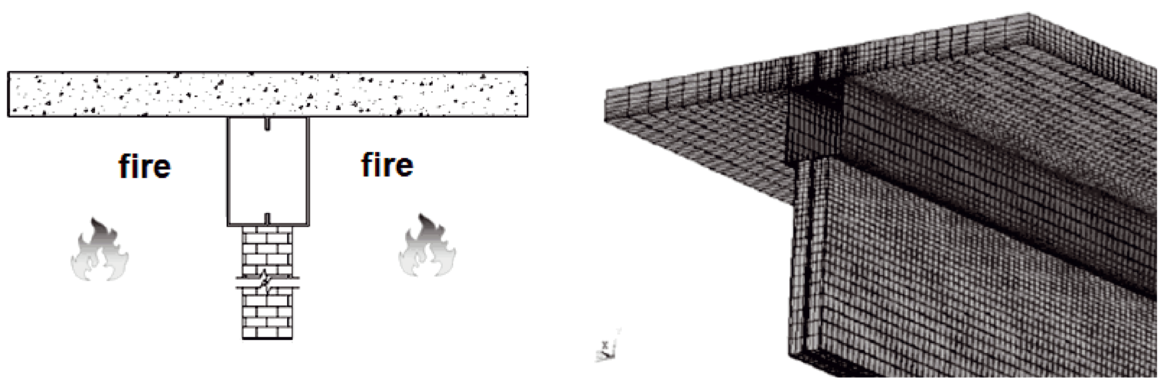
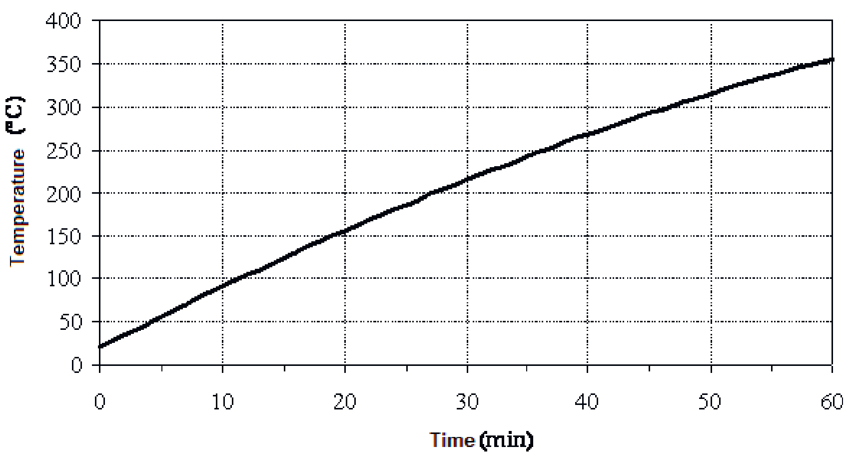


Figure 5 – Temperature rise in the slab, according to ABNT NBR 14323:1999 prescriptions



and rotations in x, y and z directions. The structural analysis was performed applying the load evenly distributed along the beam. Figure 6 presents a general view of the finite element model generated by ANSYS software. Figure 7 presents side and upper views of the model, allowing the visualization of the "connection points" between the beam and the slab. The union between the slab and the beam is obtained by joining the degrees of freedom of the solid and shell type elements to the highlighted joints. The end supporting conditions of the steel/concrete composite beam are displayed by Figure 8. Figure 8a shows the supports corresponding to condition 1, both ends fixed. Figure 8b shows the supports corresponding to condition 2, both ends pinned. For condition 2, figure 8b, it was employed one end plate 2 mm thick (equal to the beam's plate) with constant modulus of elasticity equal to 10 times that of steel (at room temperature). In the case of pinned supports, the vertical deflections of the beam and of the slab are joined at the ends of the composite element.

7. Results and discussions

Initially, the results obtained for the beam at room temperature are presented. Figure 9 shows the deflections at mid-span in function of the load for fixed and pinned ends, figures 9a and 9b, respectively.
In the analysis of figure 9b (pinned-pinned), the great influence of the slab over the determination of element's failure load is verified, given the asymptotic tendency of the load curves versus mid-span deflection. This does not happen for the fixed-fixed model, since in the regions of maximum bending moment (near supports) the concrete is tensioned and, for this reason, contributes not much for the resistance of the composite beam. It suggests the need of beam's continuity study (including upper reinforcements) in future works. Figure 10 shows the obtained deflections for fixed-fixed and pinned-pinned beam, considering one load level and the time of element's exposure to heating according to ISO 834 standard fire curve. By means of analysis of figure 10, one can note that, in general, the deflections of the fixed-fixed beam result smaller if compared to the obtained for pinned-pinned and shorter times (lower temperatures). Next, the deflections become higher and, again, go smaller when closer to the collapse (numerically) of the pinned-pinned beam. In the fixed-fixed model, the smaller deflections, at first, are due to the type of support effect, not yet impaired by the high local strains in the same region in response to the rise of temperature.
The moment in which the deflection of the fixed-fixed beam becomes higher than the pinned-pinned's is possibly due to the occurrence of high local strains (formation of plastic hinges) in the regions of support, in response to the rise of temperature. The imminence of collapse of the pinned-pinned beam, identified by the

Figure 6 – General view of the numerical model

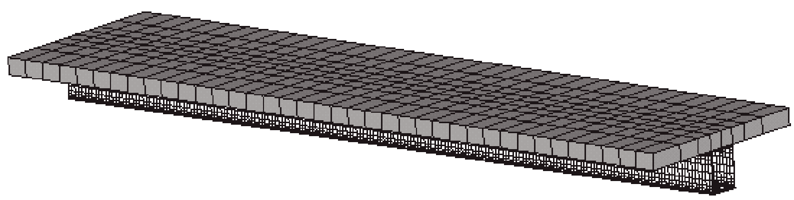
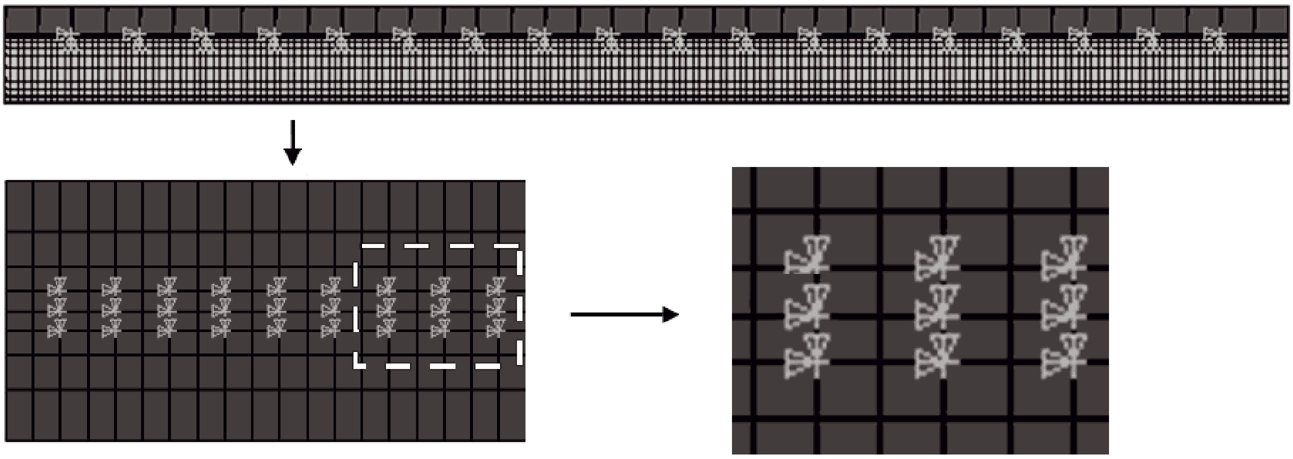


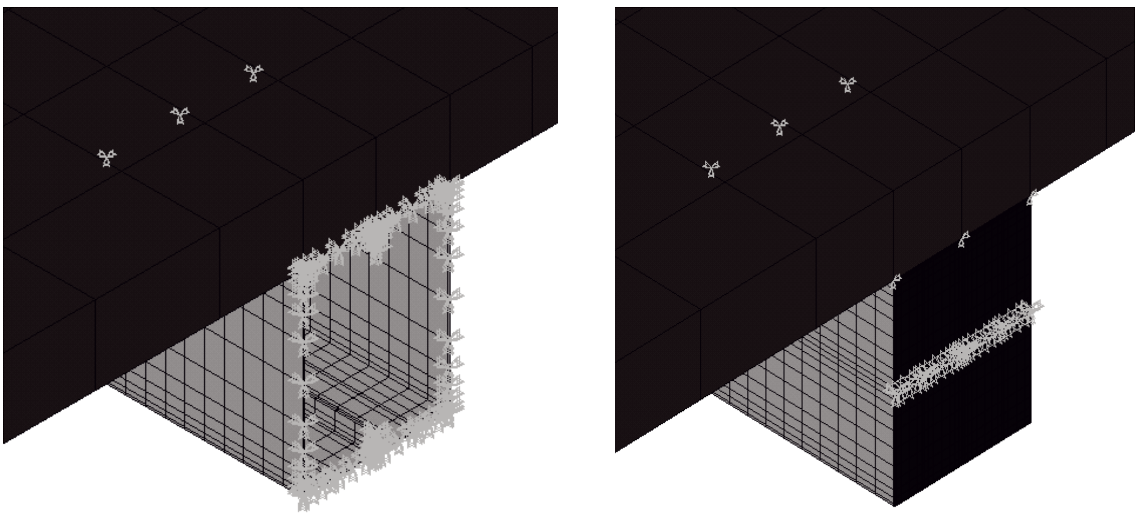
Figure 7 – Beam-slab connection in numerical model: location of joined degrees of freedom to simulate shear connectors



lack of convergence of the software, leads to big deflections, superseding the identified deflections for fixed-fixed, which, possibly, still retains (by the adopted method) a safety margin, leading to a longer time to collapse.
For illustration, figure 11 shows the deformed configuration of the fixed-fixed model for the case of load of 25 kN/m and 26 min (time to collapse). The deflection at mid span is, approximately, 20 cm.
Considering the ultimate load as the load that causes an "asymptotic" tendency in the Time x deflection curve, for one determined load, it is possible, in a preliminary form, to derive one reduction factor for the element's resistance in fire situation. This factor, named "factor k", results from the relation between the maximum load in fire situation and the maximum load at room temperature (eq. 2).

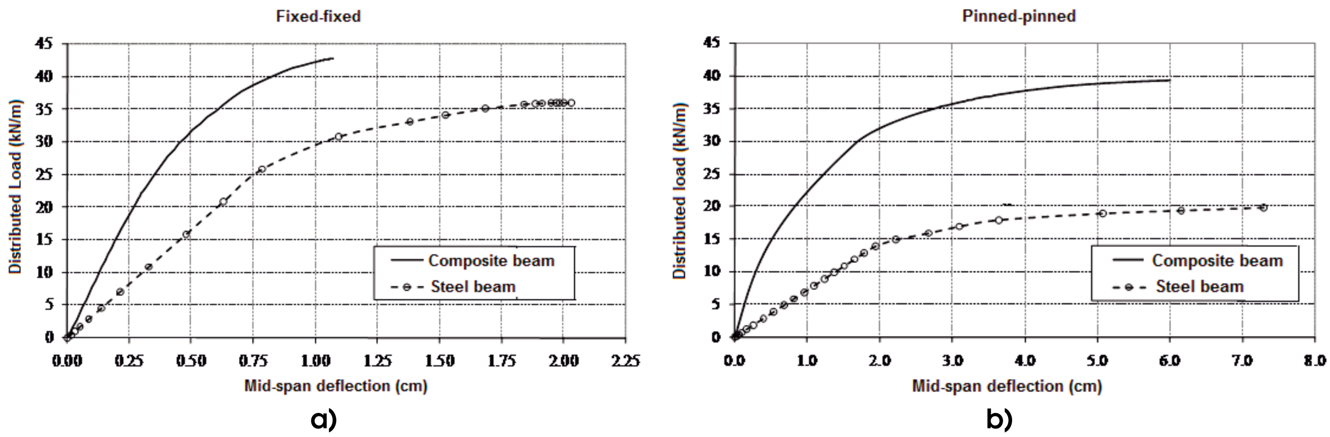
$$k = \frac{p_{Sk,fi}}{p_{Sk}} \quad (2)$$

Figure 8 – Details of the beam's end support. a) fixed b) pinned



a) b)

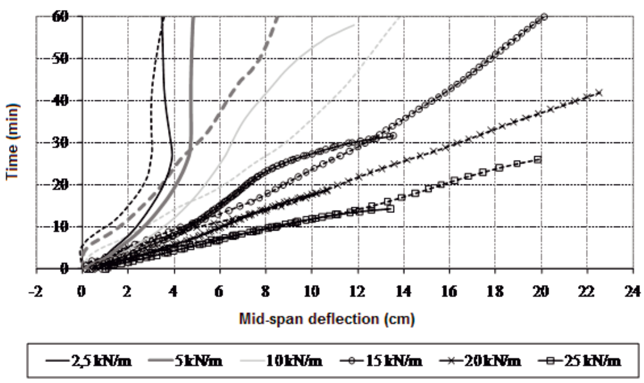
Figure 9 – Mid-span deflection in function of the load. a) Fixed-fixed. b) Pinned-pinned



In equation (2), $p_{Sk,fi}$ is the characteristic value of the maximum load applicable in fire situations and p_{Sk} is the characteristic value of the maximum load applicable at room temperature (kN/m). Figure 12 displays the reduction factors obtained for fixed-fixed and pinned-pinned models.

The analysis of figure 12 shows that the pinned-pinned composite beam model presents reduction factors more severe than the fixed-fixed model along all of the heating process. This conclusion, however, is directly associated to the model adopted for the pinned joint. It is supposed that, in ideal situations, the behavior at high temperatures of both beams, pinned-pinned and fixed-fixed, are similar.

Figure 10 – Mid-span deflection in fire situation. Dotted lines: condition 1 (fixed-fixed) and full lines: condition 2 (pinned-pinned)



8. Conclusions

This work presented a study of the influences of the support conditions on a system formed by a composite steel + concrete beam in fire situation where the steel beam is in contact with the masonry.

For the beams` analyses at room temperature, it is verified the great influence of the slab in the obtainment of the collapse load for the pinned-pinned model. The same does not occur with the fixed-fixed model, since in the maximum moment regions (near to supports) the concrete is tensioned e, for this reason, has not much influence on the resistance of the composite beam. This suggests the necessity of a study on the beam's continuity (including the upper reinforcements) in future works.

Figure 11 – Deformed configuration of fixed-fixed beam, corresponding to load 25 kN/m and time 26 min of fire exposure

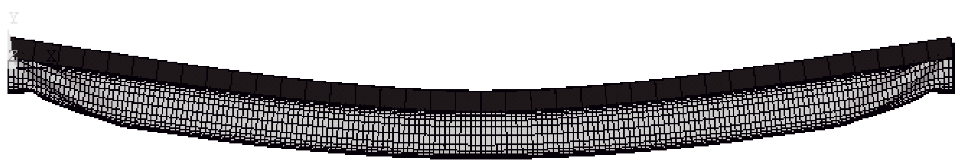
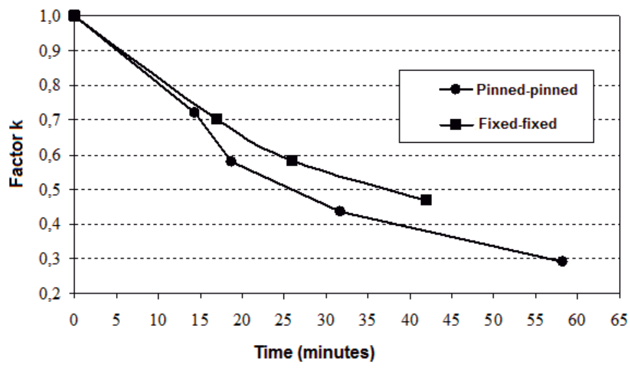


Figure 12 – Resistance reduction factor in fire situation for pinned-pinned and fixed-fixed models



In the fixed-fixed model, the point of application of the resultant of horizontal reaction at the support, varies along the beam`s height in function of the thermal gradient.
With the adopted modeling strategy, it was verified that, for the same level of load, the collapse time obtained for the fixed-fixed model was greater than the obtained for the pinned-pinned model. Having in sight that this observation depends decisively on the model used for the supports, there is a need of studying new models and, when feasible, analyze them experimentally.

9. Acknowledgements

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