Thermal analysis of steel-concrete composite cross sections via CS-ASA/FA

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Abstract

When exposed to high temperatures, such as in a fire situation, the physical and resistance characteristics of the materials employed in the structure deteriorate as the temperature increases. This fact promotes a considerable loss in the bearing capacity and stiffness of the structural system. The verification of a structure exposed to fire depends primarily and principally on the thermal analysis of the cross section of the structural element. This analysis permits determination of the temperature variation or temperature range in the element from the boundary conditions provided by the fire model adopted. As such, this study had the objective of performing a thermal analysis in a transient regime by means of a finite element method on steel-concrete composite cross sections that are employed in civil construction through use of the Computational System for Advanced Structural Analysis/Fire Analysis (CS-ASA/FA). Two cross sections are analyzed and the results obtained were satisfactory. In addition, different iterative solution processes were adopted in the analysis. Parametric studies were also performed related to the mesh variation of the finite elements and time increase. From the results, it was possible to conclude that CS-ASA/FA can supply the necessary information when a thermo-structural analysis is performed for the evaluation of strength and stiffness losses of the structural material when exposed to fire.

Keywords: thermal analysis, fire, temperature, composite cross section, FEM.

1. Introduction

The structure integrity under a fire condition involves the knowledge of the temperature influence in the structural behavior. Such an understanding has been achieved through increasingly sophisticated numerical models. It is known that the high temperature, which is common in a fire situation, causes changes in the physical characteristics and mechanical strength of the materials. The characteristics of both steel and concrete deteriorate during exposure to fire, and the loss of strength and stiffness increases significantly with the rising temperature. Thus, in the analysis of structures exposed to high temperatures, one important control parameter is fire exposure time. Fire resistance is defined as the ability of a material or structural element to continue carrying out, for a certain time, the functions for which it was designed, while being exposed to the action of fire. This time is called Required Fire Resistance Time (RFRT).

Through RFRT, it is possible to obtain the fictitious temperature of the ambient gases at the curve of standard fire (among other curves available in existing

standards). By means of this temperature, it is possible to obtain the temperature of the structural element to be used in the project calculations. The temperature range of the cross section of the structural element is determined through a thermal analysis. In structural problems where fire exposure is considered, the thermal analysis basically consists of two parts: (i) determining the heat transfer by convection and radiation from the fire along the boundary of the element of interest, and (ii) determining the heat transfer by conduction in the interior of the structural elements.

Taking into consideration that the structure is exposed to fire, a consecutive resolution of the two systems of equations within each time interval can be performed.

The first equation system results from the integration of the heat conduction equation (thermal analysis) and the second system corresponds to the incremental equilibrium equations (structural analysis) according to Figure 1. Therefore, the information from the thermal analysis is essential for the correct evaluation of the structure under high temperatures.
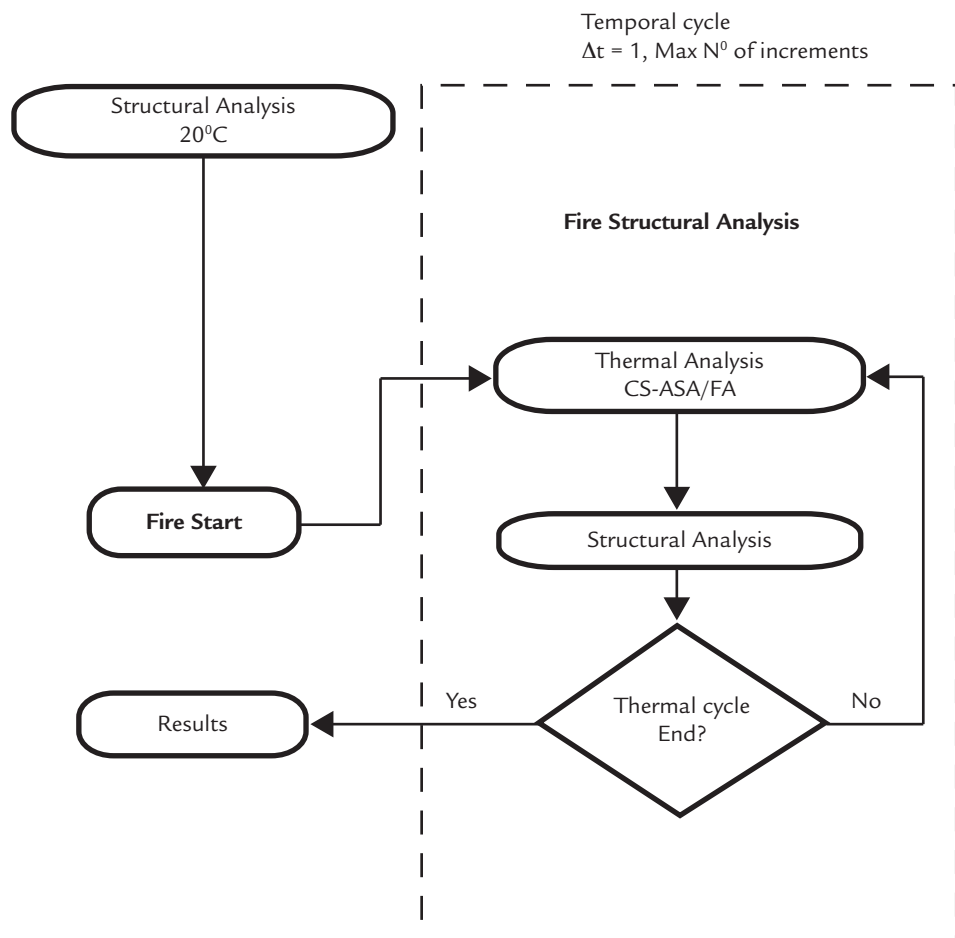

Figure 1
Solution of the thermo-structural problem.

Herein, the computational module CS-ASA/FA (Computational System for Advanced Structural Analysis/Fire Analysis; Pires *et al*., 2015) is used to perform a thermal analysis in transient regime of steel-concrete composite cross sections of structural elements. This module was developed based on the Finite Element Method (FEM) (Cook *et al*., 1989) and is part of an ample computation system denominated CS-ASA (Computational System for Advanced Structural Analysis; Silva, 2009). Within the CS-ASA, the CS-ASA/FA is able to perform a thermal analysis of the cross section in both permanent and transient regimes, as well as a thermo-structural analysis of steel structures when coupled to the module CS-ASA/FSA (Computational System for Advanced Structural Analysis/Fire Structural Analysis; Barros *et al.,* 2016). Therefore, the objective of this

study was to perform a thermal analysis of the steel-concrete composite cross sections, exploring the features of CS-ASA/FA and in the future, make it possible to thermo-structurally analyze the composite structures. Within the principal characteristics of the CS-ASA/FA module, the following are worth highlighting:

- its total integration with the GID graphic pre-processor elaborated by CIMNE (2004);

- the possibility of using isoparametric triangular finite elements with 3 and 6 nodal points and isoparametric rectangles with 4 and 8 nodal points;

- the possibility of employing different strategies for the non-linear solution of thermal problems;

- its total integration with the CS-ASA/FSA module which already performs well for thermo-structural analysis

of steel structures.

It should be noted that a large part of the research in Brazil related to the analysis of structures in fire situations has been essentially numerical, with intensive developments and advances in recent years, such as the works of: Caldas (2008); Rigobello (2011); Landesmann (2012); Pierin and Silva (2014); Pierin *et al*. (2015); Pires *et al*. (2015); Barros *et al*. (2016) and Barros (2016). In the international context, works by Othuman and Wang (2011), Zandi *et al*. (2012), Zang and Usmani (2015), and Wong (2017) can be highlighted.

The next section details the methodology used to obtain the equilibrium equation of the heat transfer problem while also explaining the nonlinear solution, which is characterized by a simple incremental or incremental-iterative scheme solution.

2. Equilibrium equation by FEM

The heat conduction problem consists of solving the following partial differential equation (Peréz, 2001; Halliday *et al.*, 2009):

$$\left(k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} \right) + Q = \rho c \frac{\partial T}{\partial t}, \qquad (1)$$

considering the constitutive relationship of the material (Fourier's law) and satisfying the boundary conditions. In (1), k_x and k_y are the thermal conductivities in the x and y directions, respectively, T is the temperature, Q is the heat generated inside the element per unit volume and time, ρ is the unit material mass, c is the specific heat of the material, and t is the fire exposure time.

For solids, the heat transfer within the body volume (domain) occurs only by conduction. Being a solid body surrounded by a fluid, as shown in Figure 2, the convection and radiation boundary condition can be used for the solution of the solid domain problem (radiative convective bound-

ary), besides a prescribed heat flux.

Many engineering problems are governed by a valid differential equation in a domain and are subject to boundary conditions on the surface. In general, however, analytical solutions for these differential equations are known only for some simple cases. Nevertheless, the values of an unknown function (problem solution) for some predetermined points can be obtained through numerical methods. It is possible to obtain approximate solutions to differential equations using the Weighted Residual Methods (WRM). Among these methods, Galerkin stands out for its generalizability and accuracy of numerical results. This

approach, together with the Finite Element Method (FEM), is applicable to a wide variety of engineering problems. FEM is a widespread numerical procedure used in the analysis of structures and continuous media. It is based on the concept of the discretization of structure and continuous media and, from there, obtaining approximate numerical solutions. Thus, FEM attempts to divide a continuous medium into subdomains, such as elements, which are interconnected through nodal points where the degrees of freedom to be determined are defined. The basic idea is to transform a complex problem into a sum of several simple problems.
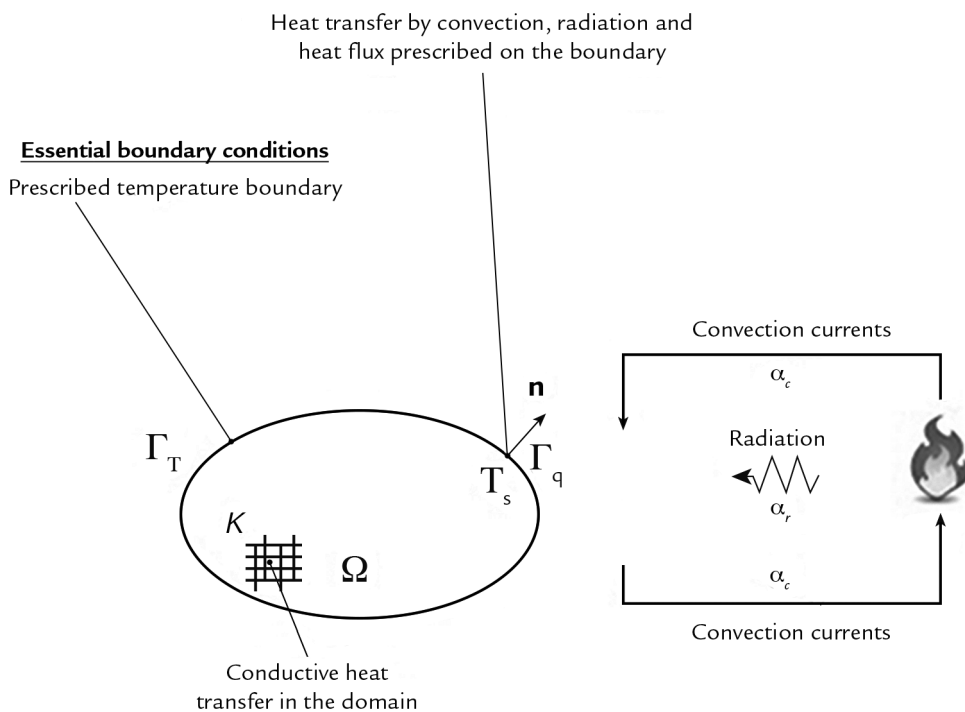

Figure 2
Boundary conditions
in a solid domain problem.

Galerkin's method is used to minimize the error when approaching the problem solution. From its weak formu-

lation, and in the FEM context of considering the contribution of all elements of the mesh, it arrives at the equilibrium

equation governing the transient problem of heat conduction, described below in matrix form:

$$C \left\{ \frac{\partial \mathbf{T}}{\partial t} \right\} + \mathbf{K} \left\{ \mathbf{T} \right\} = \mathbf{R} \qquad (2)$$

in which, $\mathbf{C} = \int_{\Omega} \rho c \mathbf{N}^T \mathbf{N} d\Omega$ is the capacitance matrix (thermal capacity);

$\mathbf{K} = \int_{\Omega} \mathbf{B}^T \mathbf{D} \mathbf{B} \, d\Omega + h \int_{\Gamma} \mathbf{N}^T \mathbf{N} \, d\Gamma$ is the thermal conductivity matrix;

$\mathbf{R} = Q \int_{\Omega} \mathbf{N}^T d\Omega + h T_{\infty} \int_{\Gamma} \mathbf{N}^T d\Gamma - q_0 \int_{\Gamma} \mathbf{N}^T d\Gamma$ is the nodal heat flux vector; and $\mathbf{T}$ is the nodal temperatures vector meant to be determined.

The matrices **N, B,** and **D** in the above equations are the matrix of interpolation functions; the matrix that contains the derivatives with respect to x and y of the interpolation functions; and the matrix containing the thermal conductivities, k_x and k_y.

For thermal analysis in module CS-ASA/FA, there are available: the two triangular elements T3 and T6, with 3 and 6 nodes, respectively; and two quadrilateral elements Q4 and Q8, with 4 and 8 nodes, respectively.

To solve Equation (2), this study adopts a numerical integration strategy in time based on the Finite Difference Method (FDM; Bathe, 1996; Burden and Faires, 2008). Therefore, the equilibrium equation of the transient heat conduction problem (2) can be rewritten as:

$$C_{n+\theta} \left\{ \frac{\partial \mathbf{T}}{\partial t} \right\}_{n+\theta} + \mathbf{K} \left\{ \mathbf{T} \right\}_{n+\theta} = \mathbf{R}_{n+\theta} \tag{3}$$

The temperature variation $t_{n+\theta}$ can be written by a Taylor series expansion and, after algebraic manipulations, the equation adopted to calculate the temperatures at each time step is given by:

$$C_{n+\theta} \left\{ \frac{T_{n+1} - T_n}{\Delta t} \right\} + \mathbf{K}_{n+\theta} \left\{ \theta T_{n+1} + (1-\theta) T_n \right\} = \mathbf{R}_{n+\theta} \tag{4}$$

The equation above can be rearranged as follows:

$$\left\{ T_{n+1} \right\} = \left(C_{n+\theta} + \theta \Delta t \mathbf{K}_{n+\theta} \right)^{-1} \left[C_{n+\theta} - (1-\theta) \Delta t \mathbf{K}_{n+\theta} \right] T_n + \mathbf{R}_{n+\theta} \tag{5}$$

or even more compactly as:

$$\hat{\mathbf{K}} \left\{ \mathbf{T} \right\}_{n+1} = \hat{\mathbf{R}} \tag{6}$$

with

$$\hat{\mathbf{K}}_{n+\theta} = \left(C_{n+\theta} + \theta \Delta t \mathbf{K}_{n+\theta} \right)$$

$$\hat{\mathbf{R}}_{n+\theta} = \left[C_{n+\theta} - (1-\theta) \Delta t \mathbf{K}_{n+\theta} \right] T_n + \mathbf{R}_{n+\theta}$$

The temperature values in the current time step, n+1, are found using the temperatures calculated in the previous time step (n) and using the nodal heat flows in the current and previous time steps. Inside each time interval, the parameter θ defines the instant at which Equations (5) or (6) are satisfied. It is possible to obtain different integration schemes in time by varying the parameter θ. Herein, θ is adopted as being equal to 0.9 in the analysis, in accordance with SAFIR software (Franssen, 2005). More information about integration schemes in time and a detailed problem solution of transient heat conduction can be found in Bathe (1996), Lewis *et al.* (2004), Rigobello (2011), Nunes (2014) and, more recently, in Barros (2016).

As can be observed, Equation (6) is strongly non-linear due to its dependency on the material's thermal properties. It is worth emphasizing that there is not a general method to resolve such a non-linear system of equations. The CS-ASA/FA module contains two implemented procedures that deal with the resolution of the system of equations described in (6): simple incremental and incremental-iterative. For the latter, the iterations can be performed through the use of the Picard algorithms, also known as a successive approximation method, and Newton-Raphson (Cook *et al.*, 1989). The methodology described in this section is detailed in Table 1, as well as the solution algorithms available in CS-ASA/FA.

It should be noted here that, for a thermal analysis that describes the dynamics of fire, there exist several options of models. These models are usually represented by heating curves that are standardized and provided by current standards, or by specific curves defined for cases of nonconventional heating. In prescriptive procedures for design and laboratory testing in furnaces to determine the fire resistance of structural elements, the gas temperature is calculated using the standard fire curve (ISO 834-1). Thus, this study adopts this heating curve, which is given by:

$$\theta_g = 20 + 345 \log(8t+1) \tag{7}$$

where θ_g is the temperature (°C) of the gases and *t* is the time in minutes of fire exposure.

Table 1
Solution algorithms: heat transfer transient problem

A. SOLUTION OF THE HEAT TRANSFER TRANSIENT PROBLEM:
  A1. Sets input data, initial and boundary conditions
  A2. Do: $T_n = T_{n+1} = T_{n+\theta} = T_0 = 20°C$
B. SOLUTION PROCEDURE : *Incremental simple* or *Incremental-iterative (Picard or Newton-Raphson)*
C. GIVE A NEW TIME INCREMENT AND GO TO STEP B

INCREMENTAL SIMPLE

1. INCREMENTAL PROCESS : *inc* = 1, 2, 3,..., *nmáx*

  1a. Calculate the capacitance matrix: $\mathbf{C}_{n+\theta} = \int_\Omega \rho c \mathbf{N}^\mathsf{T}\mathbf{N}d\Omega$

  1b. Calculate thermal conductivity matrix: $\mathbf{K}_{n+\theta} = \int_\Omega \mathbf{B}^\mathsf{T}\mathbf{DB}d\Omega + h\int_\Gamma \mathbf{N}^\mathsf{T}\mathbf{N}d\Gamma$

  1c. Calculates the heat flux vector: $\mathbf{R}_{n+\theta} = Q\int_\Omega \mathbf{N}^\mathsf{T}d\Omega + hT_\infty \int_\Gamma \mathbf{N}^\mathsf{T}d\Gamma - q_0\int_\Gamma \mathbf{N}^\mathsf{T}d\Gamma$

  1d. Get: $\hat{\mathbf{K}}_{n+\theta} = \left(\mathbf{C}_{n+\theta} + \theta\Delta t\mathbf{K}_{n+\theta}\right)$

  1e. Get: $\hat{\mathbf{R}}_{n+\theta} = \left[\mathbf{C}_{n+\theta} -\left(1-\theta\right)\Delta t\mathbf{K}_{n+\theta}\right]\mathbf{T}_n + \mathbf{R}_{n+\theta}$

  1f. Solve the system of equations: $\{\mathbf{T}\}_{n+1} = \hat{\mathbf{K}}_{n+\theta}^{-1}\hat{\mathbf{R}}_{n+\theta}$

INCREMENTAL-ITERATIVE (PICARD)	INCREMENTAL-ITERATIVE (NEWTON-RAPHSON)
1. INCREMENTAL PROCESS : *inc* = 1, 2,..., *nmax*	**1. INCREMENTAL PROCESS** : *inc* = 1, 2,..., *nmax*
2. ITERATIVE PROCESS (PICARD) : *k* = 1, 2,..., *nmax*	**1a.** Calculate the capacitance matrix:
2a. Do: $\hat{\mathbf{R}}_{n+\theta} = \mathbf{T}_{n+\theta}^1 = \mathbf{T}_{n+\theta}^2 = 0.0$	$\mathbf{C}_{n+\theta} = \int_\Omega \rho c \mathbf{N}^\mathsf{T}\mathbf{N}d\Omega$
2b. Calculate the capacitance matrix:	**1b.** Calculate thermal conductivity matrix:
$\mathbf{C}_{n+\theta} = \int_\Omega \rho c \mathbf{N}^\mathsf{T}\mathbf{N}d\Omega$	$\mathbf{K}_{n+\theta} = \int_\Omega \mathbf{B}^\mathsf{T}\mathbf{DB}d\Omega + h\int_\Gamma \mathbf{N}^\mathsf{T}\mathbf{N}d\Gamma$
2c. Calculate thermal conductivity matrix:	**1c.** Calculate the heat flux vector:
$\mathbf{K}_{n+\theta} = \int_\Omega \mathbf{B}^\mathsf{T}\mathbf{DB}d\Omega + h\int_\Gamma \mathbf{N}^\mathsf{T}\mathbf{N}d\Gamma$	$\mathbf{R}_{n+\theta} = Q\int_\Omega \mathbf{N}^\mathsf{T}d\Omega + hT_\infty \int_\Gamma \mathbf{N}^\mathsf{T}d\Gamma - q_0\int_\Gamma \mathbf{N}^\mathsf{T}d\Gamma$
2d. Calculate the heat flux vector:	**1d.** Get: $\hat{\mathbf{K}}_{n+\theta} = \left(\mathbf{C}_{n+\theta} + \theta\Delta t\mathbf{K}_{n+\theta}\right)$
$\mathbf{R}_{n+\theta} = Q\int_\Omega \mathbf{N}^\mathsf{T}d\Omega + hT_\infty \int_\Gamma \mathbf{N}^\mathsf{T}d\Gamma - q_0\int_\Gamma \mathbf{N}^\mathsf{T}d\Gamma$	**1e.** Get: $\hat{\mathbf{R}}_{n+\theta} = \left[\mathbf{C}_{n+\theta} -\left(1-\theta\right)\Delta t\mathbf{K}_{n+\theta}\right]\mathbf{T}_n + \mathbf{R}_{n+\theta}$
2e. Get: $\hat{\mathbf{K}}_{n+\theta} = \left(\mathbf{C}_{n+\theta} + \theta\Delta t\mathbf{K}_{n+\theta}\right)$	**1f.** Solve the system of equations: $\{\mathbf{T}\}_{n+1} = \hat{\mathbf{K}}_{n+\theta}^{-1}\hat{\mathbf{R}}_{n+\theta}$
2f. Get: $\hat{\mathbf{R}}_{n+\theta} = \left[\mathbf{C}_{n+\theta} -\left(1-\theta\right)\Delta t\mathbf{K}_{n+\theta}\right]\mathbf{T}_n + \mathbf{R}_{n+\theta}$	**2. ITERATIVE PROCESS (N-R)**: *k* = 1, 2,..., *nmax*
2g. Determines the 1st approximation:	**2a.** Update $\hat{\mathbf{K}}_{n+\theta}$ and $\hat{\mathbf{R}}_{n+\theta}$ for $\mathbf{T}_{n+1}$
$\mathbf{T}_{n+\theta}^1 = \hat{\mathbf{K}}_{n+\theta}^{-1}\hat{\mathbf{R}}_{n+\theta}$	**2b.** Solve the system defined in 1f to obtain $\mathbf{T}_{n+1}^k$
2h. Determines the 2nd approximation:	**2c.** Calculates the unbalance vector:
$\mathbf{T}_{n+\theta}^2 = \mathbf{T}_0 + 2\left(\mathbf{T}_{n+\theta} -\mathbf{T}_0\right)$	$\mathbf{g} = \hat{\mathbf{R}}_{n+\theta} - \hat{\mathbf{K}}_{n+\theta}\{\mathbf{T}\}_{n+1}$
	2d. Get the correction of the nodal temperatures:
2i. Checks for convergence: $\dfrac{\left\|\mathbf{T}_{n+\theta}^1 - \mathbf{T}_{n+\theta}^2\right\|}{\left\|\mathbf{T}_{n+\theta}^1\right\|} <$ tolerance	$\delta\mathbf{T}^k = \left[\hat{\mathbf{K}}_{n+\theta}\right]^{-1}\mathbf{g}\left(\mathbf{T}^{(k-1)}\right)$
	2e. Updates nodal temperatures:
YES :	$\mathbf{T}_{n+1}^k = \mathbf{T}_{n+1}^{(k-1)} + \delta\mathbf{T}_{n+1}^k$
Calculate the vector $\mathbf{T}_{n+\theta} = \mathbf{T}_{n+\theta}^1 + 0.5\left(\mathbf{T}_{n+\theta}^1 -\mathbf{T}_0\right)$	
Update vector $\mathbf{T}_0 = \mathbf{T}_{n+\theta}^1$ *and go to item C*	**2f.** Checks for convergence: $\dfrac{\left\|\mathbf{T}_{n+1}^k - \mathbf{T}_{n+1}^{(k-1)}\right\|}{\left\|\mathbf{T}_{n+1}^k\right\|} <$ tolerance
<u>**NO**</u>:	
If k < nmax, calculate	
$\mathbf{T}_{n+\theta} = 0.5\left(\mathbf{T}_{n+\theta} + 0.5\left(\mathbf{T}_{n+\theta}^1 +\mathbf{T}_0\right)\right)$ *and returns to*	**YES** : *Stop and proceed to item C*
step2	<u>**NO**</u>: *If k < nmax, returns to step 2*
If k = nmax, stop and try another strategy	*If k = nmax, stop and try another strategy*

The other heating curves, although they have been implemented in the CS-ASA/FA, are not addressed in this study. However, more information on them can be obtained from Franssen *et al.* (2009), Bailey (2011) and Barros (2016).

3. Numerical examples

This section aims to determine, by transient thermal analysis, the structural behavior of composite cross sections subjected to high temperatures, using the CS-ASA/FA (Pires *et al.*, 2015). As already mentioned, this module is part of the CS-ASA program (Silva, 2009) and was developed for the analysis of structures exposed to fire. Therefore, it is indispensable that the thermal analysis be performed in a correct manner so as not to compromise the response of the thermo-structural analysis. The CS-ASA/FA module was used with success by Barros (2016) in the first step of the thermo-structural analysis of steel structures. Herein, two steel-concrete composite cross sections having different geometric and physical characteristics are analyzed to evaluate the capacity of CS-ASA/FA to supply the necessary information from the thermal analysis for the composite structures. Besides this, results are obtained for two types of solution processes: simple incremental and incremental-iterative (Picard or Newton-Raphson). The objective is to demonstrate the influence of these processes on the response of the problem. The thermal properties of steel are those given by EN 1993-1-2: 2005 and of concrete are those given by EN 1992-1-2: 2004, considered to be varying with the temperature. The adopted parameters are highlighted in each example below.

3.1 Concrete-filled steel tubular section

The first example, shown in Figure 3a, concerns a rectangular, steel concrete-filled tubular section. Yang *et al.* (2013) pointed out that, in recent decades, researchers have studied in depth the behavior of this cross section's structural elements subjected to uniform fire. Where knowledge is limited, however, is on the performance of the structural components when exposed to fire on three sides, a common real-world scenario. Hence, these authors analyzed such an example, experimentally, using a ceramic fiber blanket to simulate the side not exposed to fire.

Figure 3 shows the temperature distribution within the cross section being studied: in (a) the points on the steel profile, and (b) the points in the concrete region. For the discretization of the cross section, the study adopted a mesh structured with 308 quadrilateral finite elements, linear. A time increment, Δt, of 10s was used. It can be seen that the obtained responses in this study show good agreement with the experimental results.

To verify the influence of the time increment, Δt, in obtaining the temperature distribution in the section, the study adopted point 6 in the concrete region (Figure 3b) and Δt was varied by the following values: 1s, 10s, 30s, 60s, 90s, and 120s. The results are shown in Figure 4. See that with a larger increment of time, the temperature tends to be higher in the first few minutes of exposure to fire (between 5 to 20 min). A maximum difference was observed of about 4°C between curves where Δt was equal to 1s and 120s. As the fire exposure time increases, the curves practically coincide.
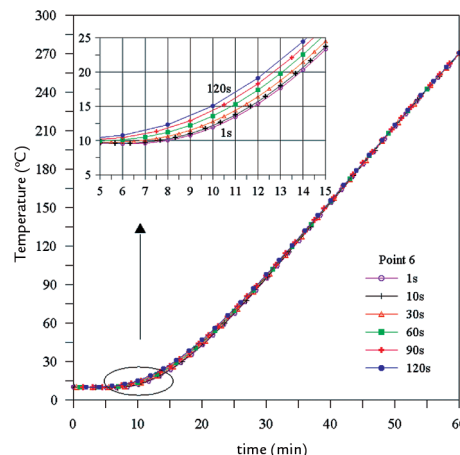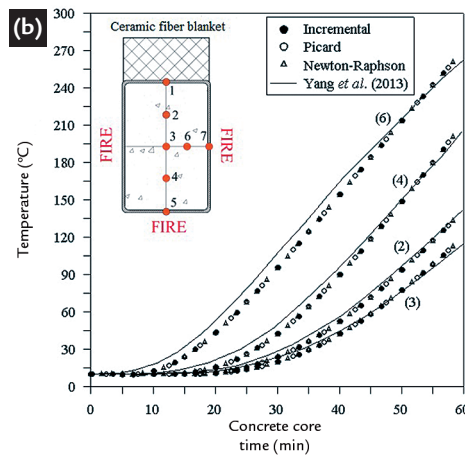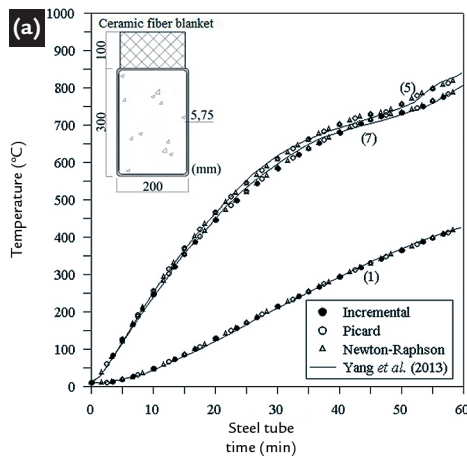

Figure 3
Temperature versus time curves: concrete-filled steel tubular section.

Figure 4
Variation of the time increment to point 6.

3.2 Steel-concrete composite beam section

The other section chosen to evaluate its behavior under the action of fire was the cross section of a composite beam of steel and concrete, illustrated in Figure 5a.

The composite beam was made by the IPE 500 profile. It is part of a seven-story structure studied by Behnam and Rezvani (2014). Using SAFIR software, these authors investigated the structure being subjected to the action of fire spreading (Franssen, 2005). The study also considered the uniform action of fire represented by the curve described by Equation (7). The results presented by the

authors, considering the ISO-834 curve, are used for comparison.

Figure 5b shows the temperature-versus-time curve for five points of the cross-section. It is noteworthy that for the discretization of the section this study used a mesh structured with 530 quadrilateral finite elements and 4 triangular finite elements, both linear, which is shown in Figure 6a. Again, you can see there is good agreement between the results obtained in this study and those provided by Behnam and Rezvani (2014).

In obtaining the temperature distri-

bution in the section, point 4 was chosen to check the influence of discretization of the finite element mesh. The adopted meshes are illustrated in Figure 6a, where the number of finite elements used in each is highlighted. Two meshes were adopted (MESH 1 and 2) that were less refined than the mesh initially adopted for the study of the section (MESH 3). The results are shown in Figure 6b, where it can be clearly seen that the more refined the mesh produced, the better the result; that is, the values converge more with those found in literature.
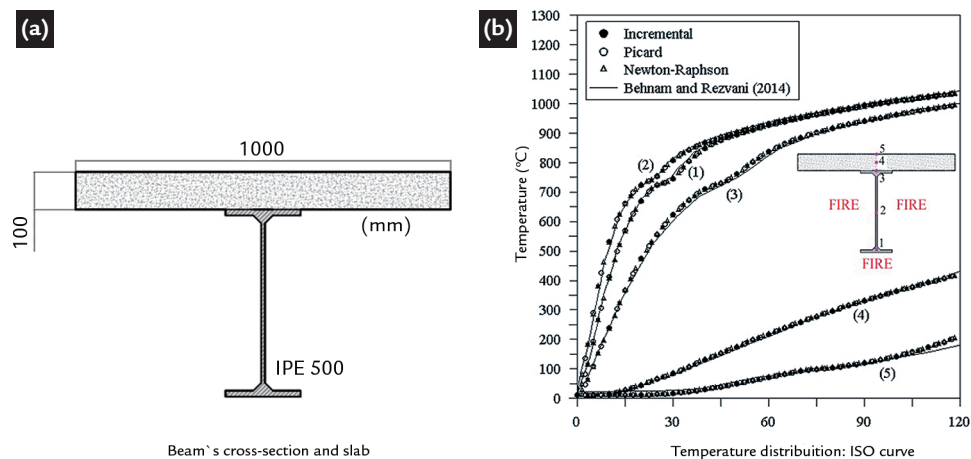

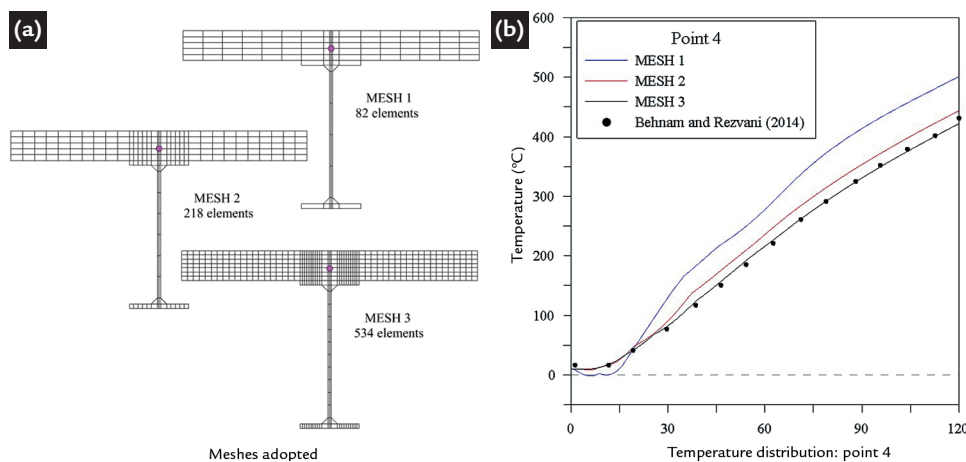**Figure 5**
Distribution of temperature inside beam.

Figure 6
Variation of the cross-section's finite element mesh.

4. Final remarks

In numerical contexts, the analysis of structural elements at high temperatures is made possible by two fundamental phases: thermal analysis and structural analysis, which are interconnected. It is important to consider how the inelastic behavior of the material is affected by temperature as well as to consider the second-order effects that arise due to changes in geometry. After all, it is known that the structural elements bearing capacity is significantly reduced as temperatures rise. In addition to changing the characteristics of the cross

section, a temperature increase also causes the appearance of thermal strains in the stretching behavior of materials. Thus, the information from the thermal analysis is key to achieving, in a satisfactory way, the thermo-structural behavior.

This article presents the thermal analysis of cross sections of structural elements commonly used in construction. The results were compared with the experimental and numerical solutions found in literature.

From the examples analyzed in the

previous section, we can conclude that the CS-ASA/FA computation module can satisfactorily simulate the effect of high temperatures on the cross sections of structural elements. These results have agreed with those found in literature. Both experimental (Yang *et al.*, 2013) and numerical (Behnam and Rezvani, 2014) results found in literature were used for comparison.

In addition, it was possible to verify the influence of two solution procedures: simple incremental and incremental-

iterative (Picard and Newton-Raphson), as well as the length of the incremental time and the mesh of the finite elements; all of which influence temperature distribution. It has also been observed that the two solution procedures are efficient in obtaining the thermal response of the two sections and almost no difference was verified in the response between them. The simple incremental procedure is more efficient regarding the processing time in function of the solution algorithm shown in Table 1, where the volume of operations needed to be performed is less. However, a deeper study involving more samples and analysis situations is necessary to define a better option for the solution in this case. Regarding the time incremental variation adopted in this analysis, an insignificant influence was encountered, or in other words, there occurred a maximum difference of 4°C between the values of 1s and 120s. This difference between the curves (temperature versus time) may be related to the standard fire curve, Equation (7), since it varies logarithmically. Adopting time increment values equal to 1s and 120s, the gas temperature is equal to 38.75°C and 444.50°C, respectively, at the end of the first time increment. However, there can be seen in Figure 4 a small variation of structural element temperature (cross section), about 4°C. This small influence of the time increment allows larger values to be used without compromised response, since smaller incremental values lead to a higher processing time. A greater sensibility was observed in relation to the finite element mesh discretization. Depending on the cross section, too coarse a mesh would not accurately represent the physical problem (MESH 1), being necessary a certain refinement for better results, as verified in the second example presented. It is worth mentioning that more detailed studies about the finite element mesh discretization and the time increment were presented in Barros *et al.* (2016), for steel cross sections, who also used the CS-ASA/FA computational module.

Finally, we can affirm the CS-ASA/FA module is also efficient in the thermal analysis of steel-concrete composite cross sections, being able to supply data for a future thermo-structural analysis of composite structures exposed to fire.

Acknowledgments

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