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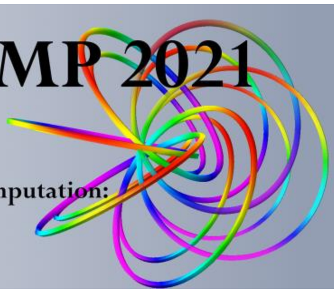

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ANALYTICAL AND NUMERICAL METHODOLOGIES TO STUDY FOUR DIFFERENT HOT-ROLLED STEEL PROFILES UNDER FIRE

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Abstract *The main goal of this paper is to calculate the temperature distribution in four different hot-rolled steel profiles (IPE, HEM, L and UAP), during a thermal and transient process due an accidental fire situation. This work presents the lumped capacitance method, according to the section factors effect, and compares all results with the finite element method, using Ansys® numerical program. The basis of the lumped capacitance method is that temperature of the solid body is uniform at any given time instant during heat transient process. This methodology is compared with the numerical results and allows the calculation of the temperature evolution in steel profiles under fire, like an easy way to follow. The results comparison allows to verify an agreement between the used methodologies. This find enabled to conclude that the lumped capacitance method is accurate and could be easily applied. This method allows to calculate a constant temperature distribution for any profile, at any time instant. It was also intended to understand the relationship between the increase in the cross-section and the temperature difference in the profiles. In the studied profiles ranges with the larger cross-section, a lower temperature field was obtained. As conclusion, members with low section factors will heat up more slowly.*

1. INTRODUCTION

The study of elements submitted to fire is a topic that has been extensively studied by several authors in recent years. However, it still has a significant number of aspects to be known and developed, requiring some research work.

Simple developments to analyse steel profiles submitted to fire could help engineers in their building design. In comparison with other materials, steel elements have a critical behaviour due to the very high thermal conductivity.

Fire is a very complex phenomena and can cause severe structural damages. Transient conduction is a process of heat transfer by conduction in a non-stationary regime that depends on the elapsed time. Metals with high thermal conductivity, have an almost uniform temperature distribution in the cross-section during a heat transfer process, for any time. Any thermal analysis that uses this idealization can be performed using the lumped capacitance method [1-5]. The presented simplified models are depending on a given number of thermal parameters, boundary conditions and cross-section shape parameters [6]. Some numerical techniques with high performance are also available for this type of analyses, with major contributions being given in references [7-9].

The main objective of this paper is to calculate the temperature distribution in the cross-section of a solid profile, in relation to time, during a transient process. Different ranges of hot-rolled steel profiles have been studied (IPE, HEM, L and UAP), submitted to fire at all four sides, to verify the temperature distribution and the influence of the profile size in their thermal behaviour, using the lumped capacitance method and the numerical method with ANSYS®. Those methodologies are in accordance and appear as a clear and alternative tool to calculate the temperature evolution in steel profiles submitted to fire.

2. THERMAL ANALYSIS USING THE FINITE ELEMENT METHOD

The governing equation for transient heat conduction is represented in Equation 1, and as referred by [1-3].

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial\theta}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial\theta}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial\theta}{\partial z}\right)+\dot{Q}=\rho C\frac{\partial\theta}{\partial t} \tag{1}$$

λ is the thermal conductivity, $\dot{Q}$ the heat generated by unit volume ρ the material density, C the specific heat, θ the temperature and t the time.

Figure 1 shows the typical boundary conditions used in a thermal analysis problem.

The convection global effect is calculated by the following equation on Γ_c:

$$q_c = h_c(\theta - \theta_\propto) \tag{2}$$

q_c is the heat transfer coefficient due the convection.

The heat radiation flux through a part Γ_r of the boundary at the Temperature θ and the environment at the absolute Temperature θ_a is represented by Equation (3).

$$q_r = \beta\varepsilon\,(\theta^4 - \theta_a^4) = \underbrace{\beta\varepsilon\,(\theta^2 + \theta_a^4)(\theta + \theta_a)}_{h_r}(\theta - \theta_a) = h_r(\theta - \theta_a) \tag{3}$$

β is the Stefan-Boltzmann constant, ε is the emissivity and h_r is the heat transfer coefficient by radiation.

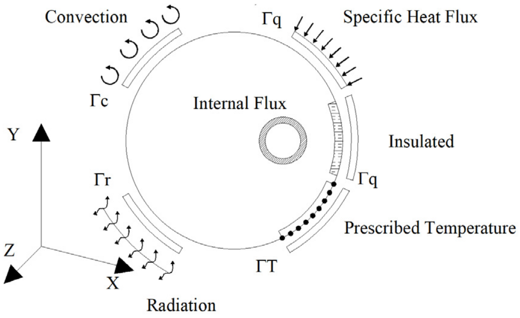

Figure 1. Boundary conditions used in heat transfer.

Using finite elements to discretize the domain, a weak formulation with weight functions based on the Galerkin Method is used, giving rise to a system of differential-algebraic equations generally be written as the following condensed form:

$$\mathrm{K}\,\theta+\mathrm{C}\,\dot{\theta}=\mathrm{F} \tag{4}$$

where C is the global capacitance matrix, K the global conductance matrix, θ the vector of nodal temperature and F the vector of thermal loads. Or written in the following form, where all terms are representative of the different parameters:

$$\sum_{j=1}^{m}\left[\int_{\Omega e}\left(\frac{\partial N_i}{\partial x}\lambda\frac{\partial N_j}{\partial x}+\frac{\partial N_i}{\partial y}\lambda\frac{\partial N_j}{\partial y}+\frac{\partial N_i}{\partial z}\lambda\frac{\partial N_j}{\partial z}\right)d\Omega^e+\int_{\Gamma h^e}h_{cr}N_iN_jd\Gamma^e-\int_{\Gamma\theta^e}N_i\lambda\frac{\partial N_i}{\partial n}\quad d\Gamma_\theta^e\right]\theta_j++\sum_{j=1}^{m}\left[\int_{\Omega^e}\rho CN_iN_jd\Omega^e\right]\dot{\theta}_j=\int_{\Omega^e}N_i\,\dot{Q}d\Omega^e-\int_{\Gamma q^e}N_i\bar{q}\,d\Gamma_q^e+\int_{\Gamma h^e}N_i\,h_{cr}\theta_\infty d\Gamma_h^e \tag{5}$$

m is the total number of elements, N_i and N_j represent element shape functions of the problem. Using a finite difference technique to time discretization, the system of ordinary differential equations (5) results in the recurrence formula represented in:

$$\left(\mathrm{K}_{n+\alpha}+\frac{\mathrm{C}_{n+\alpha}}{\alpha\,\Delta\theta}\right)\theta_{n+\alpha}=\mathrm{F}_{n+\alpha}+\frac{\mathrm{C}_{n+\alpha}}{\alpha\Delta t}\theta_n \tag{6}$$

Solving the system of equations for $\theta_{n+\alpha}$ at time $\mathrm{t}_{n+\alpha}$, the value of θ at the end of the time interval $\Delta\theta$, at time t_{n+1}, is given by the following equation:

$$\theta_{n+1}=\frac{1}{\alpha}\theta_{n+\alpha}+\left(1-\frac{1}{\alpha}\right)\theta_n \tag{7}$$

α is a constant parameter used for several time integration schemes.

To fully satisfy the conditions from equation 4 as a nonlinear problem, it is necessary to use an iterative procedure in each time step. In this algorithm a modified Newton-Raphson method is adopted.

This procedure is also used in ANSYS® program to solve the thermal and transient nonlinear problem, due the thermal material dependent of the temperature. The time interval considered for each step was equal to 5 seconds, where the minimum increment is 0.1 seconds, and the maximum is 5 seconds. A temperature-based convergence criterion with an accept tolerance of 0.1 was used. Its verification was performed by the L2 vector standard proposed by the program itself. This standard verifies convergence using the sum of the square root of the sum of the squares value of the terms, also called the Euclidean norm.

3. NUMERICAL METHODOLOGY: FINITE ELEMENT METHOD

Ansys® program was used to obtain numerical results about the temperature field in all studied hot-rolled steel profiles. Each model was meshed with a 2D thermal plane element (Plane77) with 8 nodes and a single degree of freedom, temperature, at each node. A dimension for the element edge equal to 2 mm was used, automatically generated by the program. The dimension of the element edge was chosen considering the need to have at least 2 or 3 elements dependent of the smallest thickness of the cross-section profile. Figure 2 shows different used meshes of the hot-rolled steel profiles.

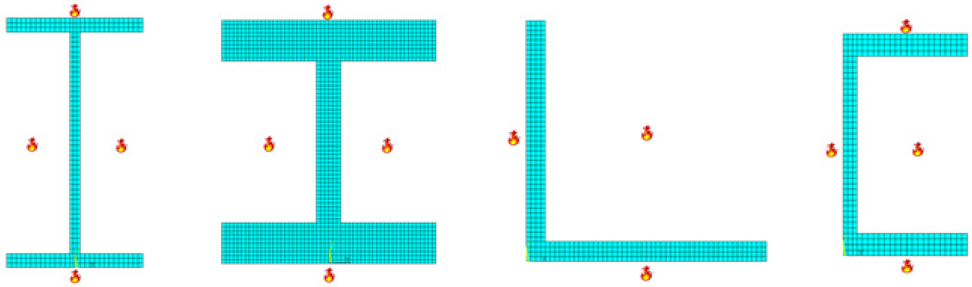

Figure 2. Cross-sections of hot-rolled steel profiles meshes.

Each profile cross-section was exposed to fire, at all four sides, during 1800 s. At the exposed face, the environment temperature follows the ISO curve [10]. The convection coefficient is taken equal to 25 W/m^{2}K [11] in the exposed face. The surface emissivity is taken constant and equal to 1 for exposed side [11]. The non-linearity due to thermal properties dependence was considered in the numerical simulation [12].

4. ANALYTICAL METHODOLOGY: LUMPED CAPACITANCE METHOD

The lumped capacitance method is a simplest analysis transient heat conduction approach, which allows to analyse the temperature of the steel members, only as a function of the time. For application of this method, the temperature of a solid is assumed uniform. A perfect spatially uniform transient temperature field does not exist, and a relatively uniform temperature distribution within the solid should be assumed when compared to the distribution between the body and its surroundings. This assumption can be made if the resistance to the heat conduction within the solid is small in comparison to the heat transfer resistance between the solid and ambient. This assumption is in accordance with the calculated Biot number (Bi) [2, 3, 5].

The Biot number is a dimensionless heat transfer coefficient and is defined as the ratio of the convection resistance and the conduction thermal resistance, according to equation 8 [13].

$$B_i = \frac{L_c \, \alpha_{cr}}{\lambda_s} \tag{8}$$

L_c is the characteristic length of the solid, in [m^{-1}], defined as the ratio between the solid volume and the cross-section area exposed to fire, and equal to the inverse of the section factor $\frac{A_m}{V}$. The characteristic length can be simplified according to the expression 9, function of the cross-section area of the steel profile A, the perimeter cross-section P and the profile length L.

$$L_c = \left(\frac{A_m}{V}\right)^{-1} = \frac{V}{A} = \frac{A \times L}{P \times L} = \frac{A}{P} \tag{9}$$

In the equation 8, λ_s is the thermal conductivity of steel, in [W/mK], and should be determined according Eurocode 3 as a function of temperature [12], and α_{cr} is the coefficient of heat transfer by convection and radiation [W/m^{2}K], which is given by the sum of the coefficient of heat transfer by convection and the coefficient of heat transfer by radiation, α_r, which must be calculated according the equation 10.

$$\alpha_r = \varepsilon\sigma(\theta + \theta_\infty)(\theta^2 + \theta_\infty^2) \tag{10}$$

To apply this method to solids submitted to fire, it is necessary to consider the heat transfer by radiation since a large part of the heat flow transferred to the steel members is through radiation [14].

The use of this method is generally accepted, if the Biot number is smaller than unity [13]. This means that the assumption of a uniform temperature distribution is acceptable [2]. Therefore, solid bodies with high thermal conductivity, as in case of steel, are good candidates for the use of this method. If the temperature in the solid cross-section is uniform, that is $\theta_{x,t} \cong \theta_t$, the solution of equation 11 allows to obtain the temperature as a function of time.

$$\theta_t = (\theta_i - \theta_\infty)e^{(-Bi.Fo)} + \theta_\infty \tag{11}$$

θ_t is the temperature for a time t , $(\theta_i - \theta_\infty)$ is the temperature difference at time $t = 0$ and Fo is the Fourier number.

The Fourier number is a dimensionless ratio between the heat conducted through the solid and the heat retained by the solid. A high Fourier number indicates a faster heat spread through a solid body, and it is calculated for a time after step change in ambient temperature, according to the following equation:

$$Fo = \frac{\lambda_a . t}{\rho \, C_a \, L_c^2} \tag{12}$$

The results obtained from the lumped capacitance method will be presented and compared with the results from the numerical results. In the present work, for lumped capacitance method, the Biot number was below the unit in all studies.

5. RESULTS AND DISCUSSION

Using the numerical method, it was possible to obtain the temperature evolution at different nodal points, which will be compared with the temperature evolution calculated using the lumped capacitance method (LC). To verify the numerical results, for each cross-section in study, three nodal points were chosen, to understand the evolution of the temperature and to verify the point that reaches the highest temperatures.

Figure 3 shows the comparison of results between the two methodologies, the lumped capacitance method (LC) and the numerical method using Ansys®. It is possible to analyse the temperature-time history for all different types and sizes of the studied hot-rolled steel profiles.

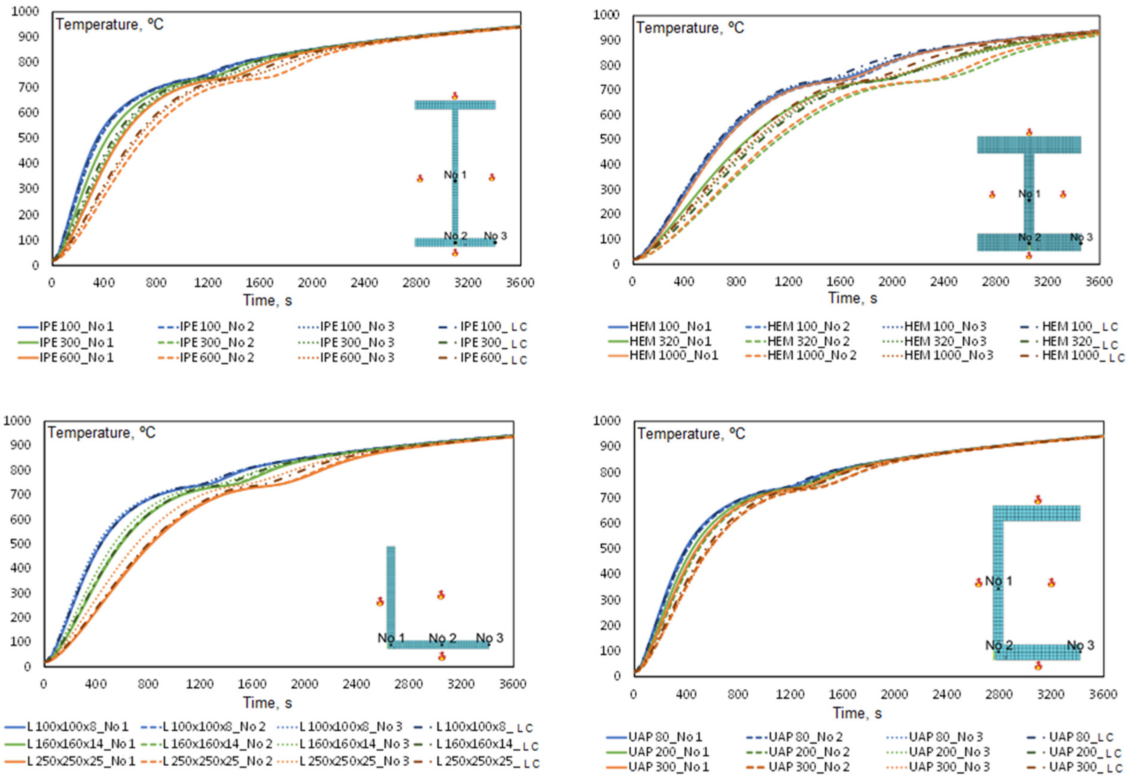

Figure 3. Temperature-time history of different types of steel profiles. Comparison between the lumped capacitance method (LC) and the numerical model in different nodal points (N0 1, N0 2 and N0 3).

The temperature variation in the cross-section in all three different nodal points (N0 1, N0 2 and N0 3) agrees with the results from lumped capacitance method. In general, the temperature obtained in N0 1 is closer with the LC. N0 3 is the point that reaches higher temperatures.

The numerical results demonstrate that there is a small temperature variation in the cross-section and this variation increases with the increase of the profile cross-section and over the time of fire exposure. But in general, the temperature distribution for any time instant is considered as constant. In transient analysis, it is possible to verify that for IPE, L and UAP steel profiles, when the cross-section size increases the temperature distribution decreases, except for HEM profile. This fact is related with the values of the section factor. However, it is possible to verify that when an hour of exposure to fire is reached, the thermal gradients in the cross-section are not significant, for any type of profile exposed to fire.

Thus, it can be said that, for any time, there is a constant temperature distribution in the cross-section, as represent in Figure 4 for different time instants.

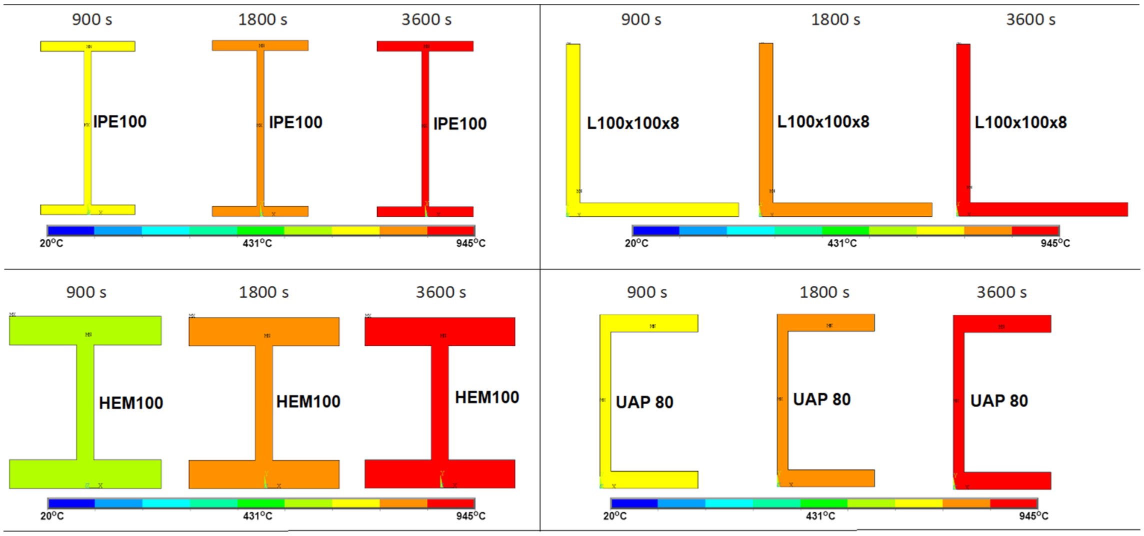

Figure 4. Temperature distribution in some of the studied hot-rolled steel profiles.

5. CONCLUSIONS

The results obtained from the lumped capacitance method were compared with the results obtained from the finite element method. It was found that the results from the lumped capacitance method present values close to those obtained from the numerical results. This find enabled to conclude that the lumped capacitance method is trustworthy and could be applied to these type of steel profiles. Although the analytical methods consider a constant temperature distribution along the cross-section, the results obtained by the numerical simulations demonstrated the existence of small thermal gradients in the section and that these increase with the increase in the size of the profile section. However, for greater fire exposure, the temperature distribution in the cross-section is considered constant.

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