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APPLICATION OF THE FINITE ELEMENT METHOD FOR TWO-DIMENSIONAL THERMAL ANALYSIS OF STEEL-CONCRETE COMPOSITE STRUCTURES IN FIRE

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Abstract. *In the area of structures in fire, the structural elements under the action of high thermal gradients, the thermo-physical properties of the materials degrade, and, consequently, the strength of the element is reduced. In this context, the temperature field in the cross-section becomes important for analysis and design verifications. This article applied a computational tool developed in MATLAB environment,called NASEN, to perform two-dimensional thermal analysis of the nonlinear nature of structural elements under fire condition. The basic theory of the program is based on Galerkin finite element procedures, making it possible to simulate varied geometries with different physical properties as a function of temperature. Also, different fire curves, such as ISO 834, parametric or experimental, can be inserted into the program. The test cases are based on composite steel-concrete structures. To evaluate the performance of the program, numerical solutions, and experimental data available in the literature are used. In summary, the results show a good correlation with the reference solutions, directing a good calibration of the program developed to solve the proposed problems.*

Keywords: *Finite element method, Fire, Thermal analysis, Composite steel-concrete*

1. INTRODUCTION

In projects of concrete and/or steel structures in fire, simplified methods of analysis are considered, which are usually intended for systems with simple and restricted configurations. However, there are practical problems that do not apply the simplified premises and considerations of the standard, requiring advanced methods of analysis. For example, structural parts with unconventional sections, composite elements with different materials, advanced mechanical behavior of the elements at high temperatures, large structures, and others. Thus, regardless of the analysis carried out, knowledge of the temperature field inside the structures is an inevitable and important step in the design of structures under fire condition.

Numerical models are applied widely in academic research as well as in practical industry projects, due to their versatility and solution performance. Several researches were developed in this area, the work of Yin *et al.* (2006), Ribeiro (2009), Pierin *et al.* (2015) and Pires *et al.* (2018), developed computer programs for thermal analysis in fire based on the finite element or finite difference method. In this scenario, the present work aims to present a specific computational module for thermal analysis of structures under fire situations, developed in MATLAB environment and denoted as NASEN/TA-FIRE (Numerical Analysis System for Engineering/Thermal Analysis - Fire). In Neves (2019) details about the implementation and specific characteristics of the computational code are presented.

2. PHYSIC THEORY E NUMERICAL PROCEDIMENTS

The first step in the formulation of finite elements is prior knowledge of the model differential of the physical phenomenon. This article analyzes a problem of heat conduction in a solid body. Thus, based on the principle of energy conservation and considering the heat flow described by Fourie law, the governing equation is presented in Eq. (1).

$$\nabla^T \mathbf{D}(T)\nabla T + f = \rho(T)c(T)\frac{\partial T}{\partial t} \tag{1}$$

Where T is the temperature, f is the internal heat generation, ρ is the specific mass of the material, c is the specific heat, **D** is the thermal conductivity matrix of the material, for the case of a two-dimensional isotropic material, the matrix is given by the following.

$$\mathbf{D} = \begin{bmatrix} k & 0 \\ 0 & k \end{bmatrix} = k(T)\mathbf{I} \tag{2}$$

In fire condition, the properties of the materials are a function of temperature, making the problem nonlinear. The mathematical expressions of the thermophysical properties of steel and concrete are based on EN 1993-1-2 (2005) and EN 1992-1-2 (2004) respectively, as shown in Fig. 1. The thermal conductivity curves of the concrete for the upper and lower limits are presented, as well as the specific heat behavior as a function of the temperature and the moisture content $u(\%)$ of the concrete weight.

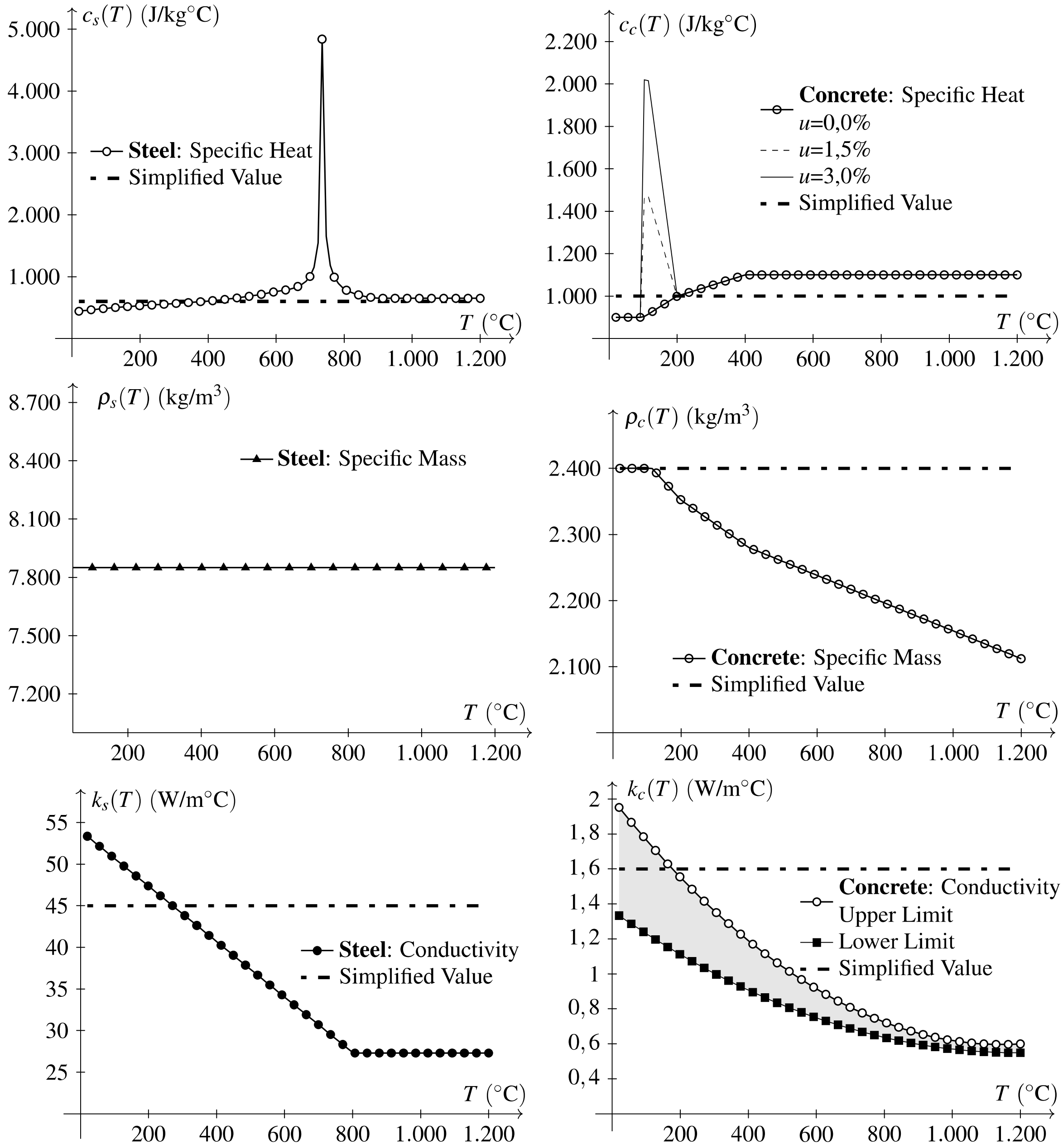

Figure 1: Thermal properties of steel (left) and concrete (right) as function of temperature

Regarding the boundary conditions, using the convection and radiation heat transmission models, the equation of the total heat transfer rate, expressed in linear form, can be written by Eq. (3)

$$\mathbf{q}_n = \alpha_c(T - T_g) + \alpha_r(T - T_g) = \left\{\alpha_c + \left[\epsilon\sigma(T - T_g)(T^2 - {T_g}^2)\right]\right\}(T - T_g) \tag{3}$$

Where T_g is the gas temperature in the vicinity of the fire exposed element, σ is the Stephan Boltzmann constant, ϵ is the emissivity, α_c is the convection heat transfer coefficient and α_r is the radiation coefficient. According to ISO 834 (1999), the temperature of the gases is described by Eq. (4).

$$T_g = 20 + 345\log_{10}(8t + 1) \tag{4}$$

The second step in formulating the finite element method for heat diffusion problems is to write Eq. (1) as an integral sentence associated with a weight function, w. Then, applying relations of the differential-integral calculus and with some algebraic manipulations, resulting in Eq. (5).

$$\int_{\Omega} \nabla^T w(\mathbf{D}\nabla T)d\Omega + \int_{\Omega} \rho c \frac{\partial T}{\partial t} w d\Omega = \int_{\Omega} f w d\Omega - \int_{\Gamma} \mathbf{q}_n w d\Gamma \tag{5}$$

Equation (5) is known as a weak variational formulation, which has no numerical approximation. Writing the approximate response function as a combination of coefficients and N interpolation functions, as given by Eq. (6).

$$T \approx \sum_{i=1}^{N} N_i T_i = \mathbf{N}^{\mathrm{T}} \tilde{T} \tag{6}$$

The problem of heat conduction in a fire condition is characterized by the transient nature, the temperature field varies with time. The finite difference method is applied to approximate the differential temporal operator (Neves *et al.*, 2019). Thus, it is possible to write the temperature at $n+1$, as shown in Eq. (7).

$$\hat{\mathbf{A}} \tilde{T}_{n+1} = \hat{\mathbf{B}} \tag{7}$$

$$\hat{\mathbf{A}} = \left[\frac{\mathbf{C}}{\Delta t} + \theta \mathbf{K} \right] \quad \hat{\mathbf{B}} = \left[\frac{\mathbf{C}}{\Delta t} - (1-\theta)\mathbf{K} \right] \tilde{T}_n + (1-\theta)\mathbf{F}_n + \theta \mathbf{F}_{n+1} \tag{8}$$

Where Δt is the time interval and the θ parameter ranges from 0 to 1, which represents the time integration scheme. In the present work, 2/3 is adopted, which characterizes the Galerkin scheme, being unconditionally stable.

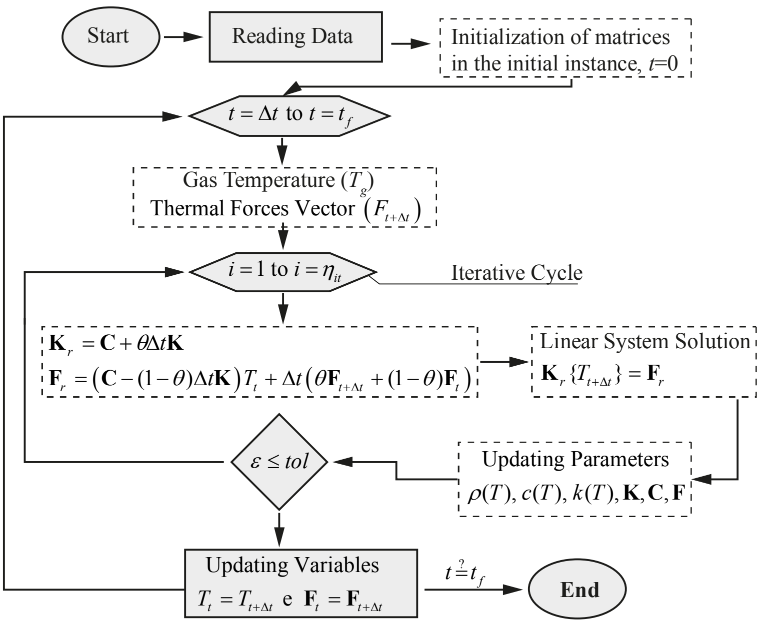

Figure 2: General numerical finite element procedures for solving the nonlinear heat conduction problem

The general numerical solution process adopted in the computational development of the specific module of the NASEN program for nonlinear analysis of heat conduction of structures in fire conditions is shown in Fig. 2. Due to the non-linear nature of the physical problem, an iterative routine for converging the temperature field is implemented in the program at each time step.

3. NUMERICAL EXPERIMENTATION

3.1 Concrete-filled steel square tubular under fire

The first example is a concrete-filled steel square tubular in fire condition. In this case, the domain is subject to the standard fire curve ISO 834 (1999). Due to the physical and geometric symmetry of the problem, it is possible to analyze only a quarter of the problem, as shown in Fig. 3.

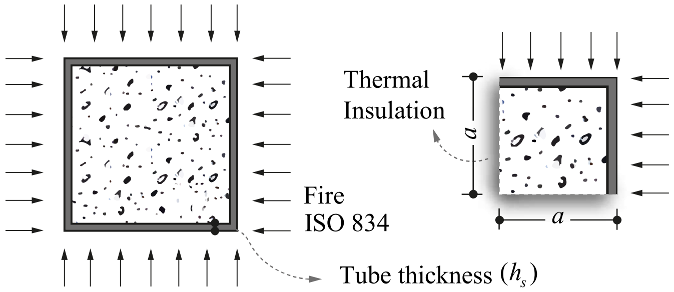

Figure 3: Thermal conditions and characteristics of the concrete-filled steel square tubular under fire

The width and height dimensions of the cross section are equal and taken as $2a = \sqrt{\pi}R$, where $R = 500$mm, the thickness of the tube is given by the expression $h_s = 0.5\sqrt{\pi}h_c$, where $h_c = 20$ mm. On the faces exposed to the fire, a convection coefficient and emissivity resulting from 25 W/m^2°C and 0,7 respectively. The results of the NASEN program are compared with the numerical data extracted from Yin *et al.* (2006).

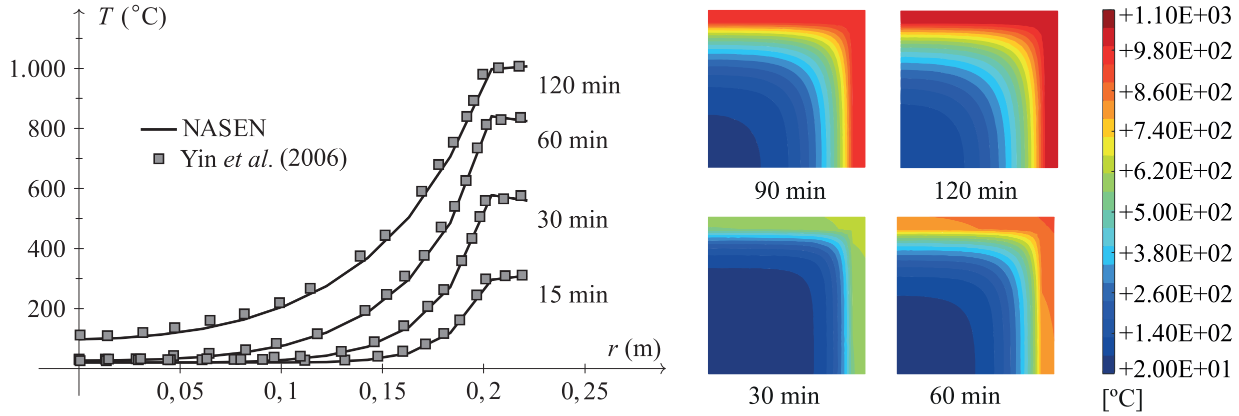

Figure 4: Temperature profile in the center line of the square steel tube for 15, 60, 60 and 120 min of exposure to fire and two-dimensional thermal field in the cross-section

Figure 4 shows the centre temperature profile. Analyzing the results, a similar behavior is observed between the curves, confirming the good performance of the code. In addition, due to the high thermal conductivity of the steel, the temperatures in the steel tube do not show significant variations, it remains almost constant. On the other hand, the temperature profile in the concrete increases as it approaches the boundary of the tube, as this region is close to the fire.

3.2 Steel profile totally encased in concrete

Consider an steel profile completely encased in concrete, acting as a protection for the steel profile. A profile equal to UC 152 ×152×37 mm is adopted, encased by concrete whose dimensions of the sides are equal and with a value of 300 mm, totaling a cross-sectional area of 300×300mm^2. Such a structure is exposed to fire by all four faces of the element. Also is considered a concrete with a moisture content of 8 %, a value adopted in the numerical simulation of Huang *et al.* (2007).

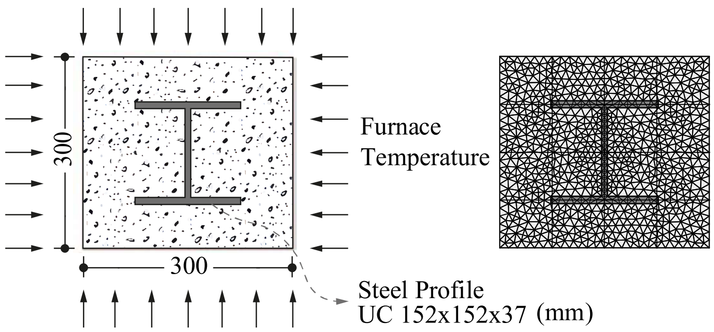

Figure 5: Composite steel-concrete column totally filled (in mm) and numerical mesh

Figure 5 shows the model of the cross-section with the dimensions and boundary conditions, and also represents the mesh of linear triangular elements with 3 nodes used in the computer simulation, where we have a mesh of 817 nodes with 1728 elements. The results are compared with numerical and experimental results, both are extracted from the work of (Huang *et al.*, 2007).

The fire temperature-time curve is estimated based on measurements in experimental furnaces, these data are shown in Table 1 and graphically in Fig. 6. The computational code performs a linear interpolation between the values obtained in the test, allowing the formation of a temperature curve as a function of time. The tests were performed up to 420 min of exposure to fire.

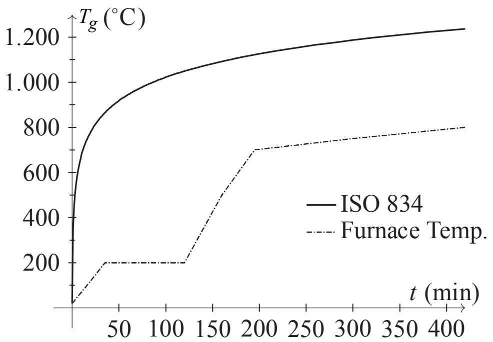

Figure 6: Temperature-time fire curves.

Table 1: Temperature values extracted from the test furnace.

Time (min)	Furnace temperature (°C)
0	20
20	120
35	200
120	200
160	500
195	700
300	750
420	800

Three tests were carried out with different physical properties of the concrete, in order to evaluate the importance of the parameters and how the results behave in each configuration. Simulation I, II and III, being respectively characterized by a dry concrete, with moisture content of 4% and 8% respectively. In addition to the experimental results obtained via experimental tests, the results of this research are also compared with numerical data using the SAFIR program.

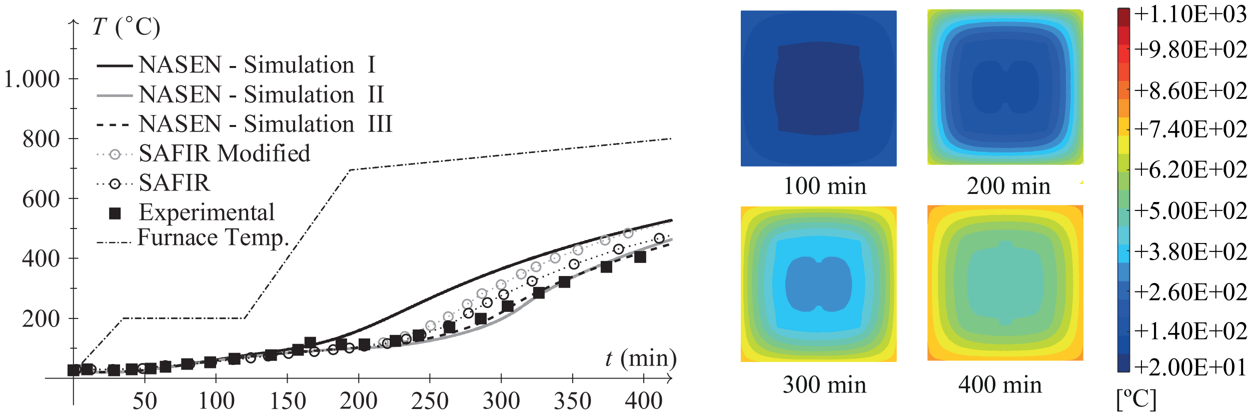

Figure 7: Fire temperature-time curve, results of the NASEN program and the temperature through numerical simulation via SAFIR and experimental by Huang *et al.* (2007) and two-dimensional thermal field for 100, 200, 300 and 400 min of exposure to fire

Figure 7 shows the results obtained by the NASEN program. All curves are measured at a point located in the center of the profile. It is observed that simulation I does not provide satisfactory results. On the other hand, when considering moisture content of the concrete, simulation II provides better results and a behavior consistent with experimental data. However, considering a moisture content of 4 % there is a small difference between the solutions. Adopting a moisture content of 8 %, simulation III provides the best results compared to experimental results. When compared with results obtained with the SAFIR program, simulations II and III present a better behavior. It can be noted that for non-linear problems the functions of describing the behavior of physical properties have a significant influence on the results.

4. CONCLUSION

The current work carried out a two-dimensional thermal analysis on structures under fire conditions based on the NASEN/TA-FIRE program. Two cases are tested, in each case the performance of the program is checked against the results obtained by numerical simulations or experimental data. The work focused on the analysis of structures composed of steel-concrete.

The results obtained in the cases analyzed by the developed computer program are consistent with the reference solutions, presenting a good performance of the module for the nonlinear transient two-dimensional thermal analysis. In addition, it is noted with this study that the physical properties of the thermal model have a significant influence on the results. Concrete moisture is an important parameter to be considered in simulations.

5. ACKNOWLEDGEMENTS

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