IBRACON Structures and Materials Journal
Revista IBRACON de Estruturas e Materiais
ISSN 1983-4195 ismj.org

ORIGINAL ARTICLE

Parametric analysis related to dimensioning of tubular steel columns filled with concrete in a fire situation

Análise paramétrica do dimensionamento de pilares tubulares de aço preenchidos com concreto em situação de incêndio.

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Received 10 April 2021
Accepted 02 September 2021

Abstract: For the dimensioning of structural elements in fire situation, simplified equations and parameters are commonly used in analytical equations or numerical models. More complex equations or simplified values can be chosen by the designer for determine materials properties in high temperature in numerical models, however, numerical modeling can be quite sensitive to the variation of some of the physical and mechanical properties. In this paper, the sensitivity of the numerical model in relation to the values according to the level of simplification chosen was evaluated, presenting an analysis in relation to the results found to contribute to the choice of these parameters and presenting the indications found in the literature. In this sense, this work presents a study of sensitivity to the variation of the values of steel and concrete properties, presented in the Eurocode and Brazilian standards, in addition to the moisture content and emissivity of the surface exposed to fire, for the dimensioning, in a fire situation, of steel tube columns, of circular and square section, filled with concrete. The studies were carried out via numerical modeling developed in the software ABAQUS. It was verified that the resulting emissivity values equal to 0.7 or 0.8, recommended in the literature, are conservative, and the choice of either does not bring significant changes in the temperature field obtained for the structural elements under analysis. It was also verified that the concrete moisture content is a relevant aspect for the formation of its temperature field, also affecting, but to a lesser extent, the steel temperature. Regarding the physical and mechanical properties of the materials, this sensitivity study suggests the adoption of the values from the equations presented in Eurocodes, without simplifications, and with the specific heat and thermal conductivity of the concrete, adopted in accordance with the Eurocode 4.

Keywords: fire situation, column, steel, concrete, numerical models.

Resumo: Na verificação de elementos estruturais em situação de incêndio por meio de equações analíticas, e mesmo via modelagem numérica, normalmente são empregados parâmetros e propriedades dos materiais simplificados. Entretanto, os resultados obtidos podem ser bastante sensíveis ao grau de simplificação adotado pelo projetista ou mesmo conforme à escolha de uma ou outra opção de propriedade dos materiais envolvidos. No presente artigo foi apresentado um estudo de sensibilidade considerando a variação das propriedades dos materiais; visando auxiliar a escolha desses parâmetros dentre as diversas opções descritas na literatura. O estudo de sensibilidade foi elaborado para pilares compostos por tubos de aço de seção circular e quadrada, vazio e preenchidos com concreto, e com as propriedades do aço e concreto indicadas pelo Eurocode ou por normas brasileiras para o dimensionamento de estruturas em situação de incêndio. Também foi analisado o comportamento do modelo conforme variações no teor de umidade do concreto e variações da emissividade da superfície de aço exposta ao fogo. O estudo foi realizado em modelo numérico desenvolvido no software ABAQUS e os resultados obtidos demonstram que os valores de 0,7 e 0,8, recomendados na literatura para a emissividade resultante, são conservadores e a alternância entre esses dois

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Financial support: None.
Conflict of interest: Nothing to declare.
Data Availability: The data that support the findings of this study are available from the corresponding author, [FMR], upon reasonable request.

valores não altera, significativamente, o campo de temperaturas na seção transversal do elemento estrutural. Já com relação ao teor de umidade do concreto foram verificadas alterações significativas no campo de temperaturas, inclusive na temperatura do tubo de aço, com a alternância deste parâmetro. Com relação às propriedades físicas e mecânicas dos materiais, o estudo de sensibilidade sugere a adoção dos valores obtidos a partir das equações sem simplificações apresentadas no Eurocode e com o valor do calor específico do concreto determinado conforme Eurocode 4.

Palavras-chave: situação de incêndio, pilares, aço, concreto, modelos numéricos.

How to cite: F. M. Rodrigues, A. L. Moreno Júnior, and J. Munaiar Neto, "Parametric analysis related to dimensioning of tubular steel columns filled with concrete in a fire situation", *IBRACON Struct. Mater. J.*, vol. 15, no. 2, e15210, 2022, https://doi.org/10.1590/S1983-41952022000200010

1. INTRODUCTION

The columns made of steel tube, of circular and square section, filled with concrete, are usually dimensioned for a fire situation by simplified equations of practical application, presented in the literature [1], [2] and in normative codes, such as EN 1994-1-2 [3] and ABNT NBR 14323: 2013 [4]. However, simplified processes do not always provide satisfactory results and are often used very comprehensively.

In the case of steel tubes filled with concrete, the interaction between both materials increases the complexity of the problem, so that the temperatures usually obtained from graphs and tables presented in the literature [2] are not suitable for any type of situation.

Numerical modeling can be a solution for situations not contemplated by simplified processes. However, whatever the sizing method for a fire situation, whether simplified or advanced, it is essential to evaluate correctly and choose the values for the physical and mechanical properties of the materials.

The normative codes indicate complex and simplified formulations to determine the values of the thermal and mechanical properties of steel and concrete, as well as constant values allowing their assessment in simple design methods. However, there are often no specific rules for when to consider such simplifications. The absence of accurate information on the material property can result in remarkable discrepancies among numerical models and reference experimental models result. The validation of numerical modeling is always conditioned by the values considered for the thermal or mechanical properties of the material, which may not necessarily be the real value, but the ones that yields a better adjustment of the numerical model to the validation data. Hence, it is evident the importance of knowing the influence of each property on the response of the model and, consequently, on the strength capacity of the structural element when in a fire situation.

The moisture content in the concrete and the resulting emissivity factor are two important parameters for numerical modeling, but uncertainties remain in the literature.

This work presents a study on the sensitivity of the steel and the concrete properties applied to circular and square steel tubes filled with concrete and in a fire situation. In addition, this paper reports studies on the usual values adopted for the concrete moisture content, concrete density and emissivity of the surface exposed to fire. The analyses take into consideration the complete and simplified equations presented in EN 1992-1-2 [5], EN1993-1-2 [6] and EN1994-1-2 [3] and ABNT NBR 14323:2013 [4].

The parametric sensitivity evaluation was conducted via numerical modeling, using the software ABAQUS (Dassault Systems SIMULIA Corp., 2014), considering initial studies for model adjustments and including the effect of air-gap, as presented in Rodrigues [7].

2. NUMERICAL MODEL

A three-dimensional model and another two-dimensional model were developed in ABAQUS [8], as described below.

2.1. Three-dimensional model

The three-dimensional model (Figure 1) was developed to allow the analyses of transient and mechanical heat transfer, both developed in the same model (joint analysis). The dynamic-explicit solver was used to reduce computational effort and convergence problems [7]. The finite element was the C3D8 (hexahedron).

The fire temperature was applied evenly around all the specimen, considering the initial temperature equal to 20 °C, with the hot gases heating its exposed face by convection and radiation, with a convection coefficient equal to 25 W/m^2°C, and considering the ISO-834 standard fire curve [9]. In the tube-concrete interface a mechanical contact was defined in the normal direction, allowing the separation between the tube and the concrete. Another mechanical contact was defined in the tangential direction, with a coefficient of friction equal to 0.3, as [1].

The concrete behavior was defined by the CDP model (Concrete Damage Plasticity), with the parameter values indicated in the literature [8]. It is worth highlight that, regarding the three-dimensional model (Figure 1), a pinned support was considered at the base of the column, and at its top considered as a weightless adiabatic rigid block.

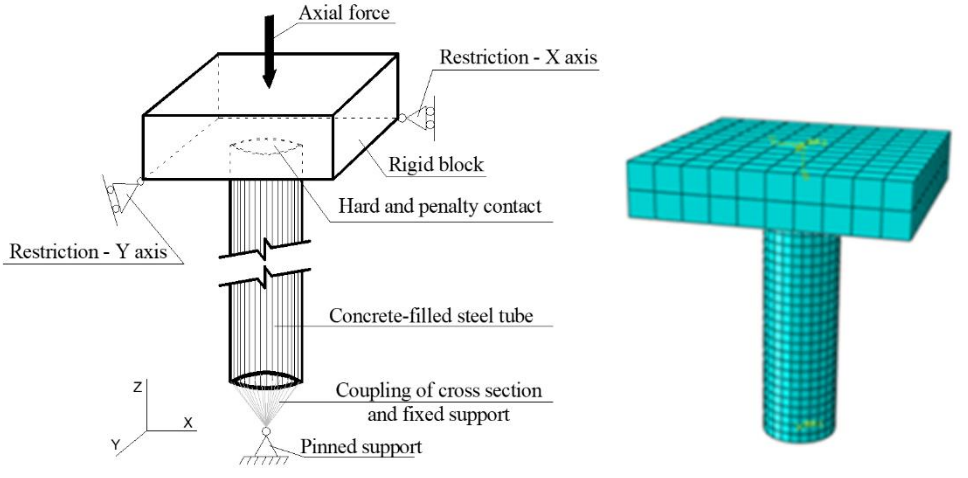


Figure 1. Boundary conditions and connections considered in the model.

2.2. Two-dimensional model

A two-dimensional model was used for the transient heat transfer analyses, resolved with the static-implicit solver, adopting the finite element D2D3 (tetrahedral) for circular section columns and the DC2D4 (quadrilateral) element for the square-section columns (Figure 2).

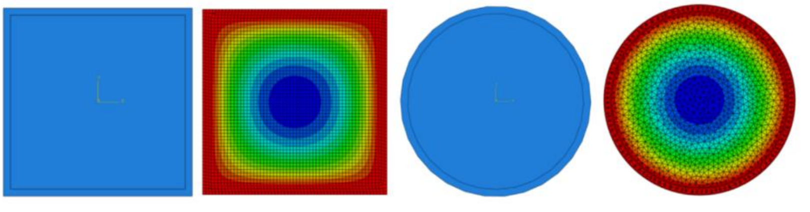


Figure 2. Two-dimensional models with tetrahedral and quadrilateral mesh.

The thermal load was applied directly to the exposed face, according to the standard fire curve, considering a perfect thermal contact in the tube-concrete interface. The intent to building this two-dimensional model was to evaluate the emissivity values of the exposed face, in addition to complementing the studies on the concrete moisture content.

2.3. Materials properties at high temperature

The thermal properties of steel and concrete considered in the numerical models were from EN 1992-1-2 [5], EN 1993-1-2 [6], EN 1994-1-2 [3] and ABNT NBR 14323: 2013 [4], aiming to compare the results considering the properties specification from European or Brazilian standards.

With respect to the steel elastic modulus at high temperature $\left(E_{a,}\right)$ its value is determined by Equation 1, whose respective reduction factors are indicated in EN 1993-1-2 [6], EN1994-1-2 [3] and ABNT NBR 14323 [4], as Table 1.

$$E_{a,} = kE_{a,\theta} \cdot E_a \tag{1}$$

where: $KE_{a,\theta}$ is the reduction factor of the steel elastic modulus at high temperature; E_a is the steel elastic modulus at room temperature equal to 210,000 MPa.

Table 1. Steel yield strength and elastic modulus reduction factor.

Steel temperature θ_a (°C)	Steel yielding strength reduction factor ($Ky_{a,\theta}$)	Steel elastic modulus reduction factor ($KE_{a,\theta}$)
	*1 / 2 / 3	*1 / /2 / 3
20	1.000	1.000
100	1.000	1.000
200	1.000	0.900
300	1.000	0.800
400	1.000	0.700
500	0.780	0.600
600	0.470	0.310
700	0.230	0.130
800	0.110	0.090
900	0.060	0.0675
1000	0.040	0.045
1100	0.020	0.0225
1200	0.000	0.000

* 1- EN 1994-1-2 [3]; 2- ABNT NBR14323:2013 [4] (steel not subject to local buckling); 3-EN 1993-1-2 [6]

The steel constitutive law specified in EN1994-1-2 [3] and ABNT NBR 14323:2013 [4] are the same as EN1993-1-2 [6].

The concrete force is reduced with the temperature increase as shown in Figure 3.

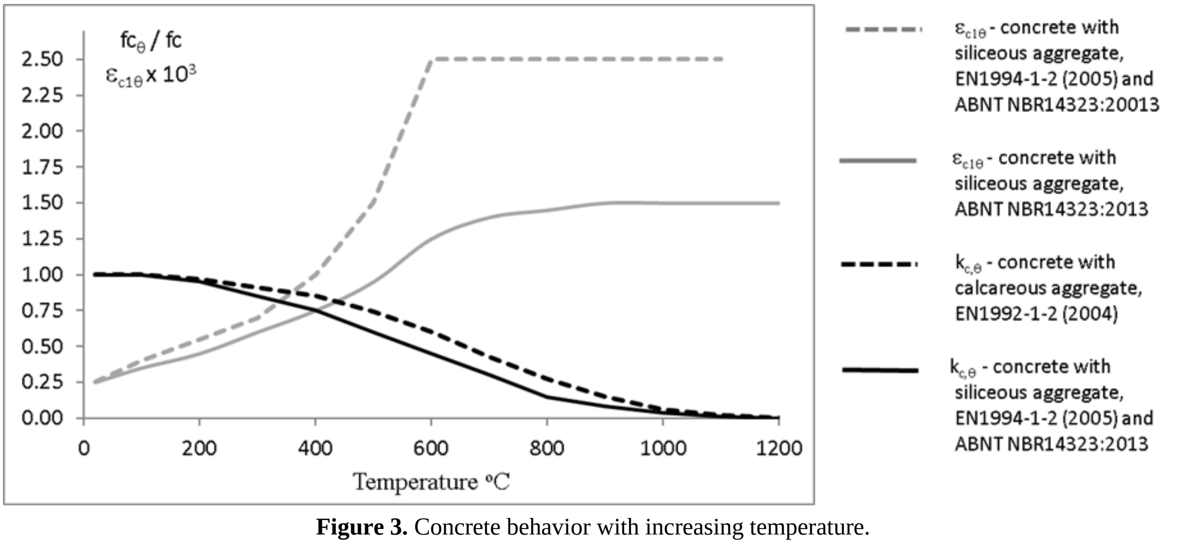


Figure 3. Concrete behavior with increasing temperature.

Equation 2 represents the concrete strength to compression at high temperature, presented in EN 1994-1-1 [3] and ABNT NBR 14323:2013 [4].

$$\sigma_{c,\theta} = \frac{3\varepsilon_{c,\theta} \cdot f_{c,\theta}}{\varepsilon_{c1,\theta}\left[2+\left(\frac{\varepsilon_{c,\theta}}{\varepsilon_{c1,\theta}}\right)^3\right]} \text{ with, } f_{c,\theta} = K_{c,\theta} \cdot f_c \tag{2}$$

In Equation 2, $K_{c,\theta}$ is a factor of concrete strength reduction (Table 2); f_c is the concrete strength to compression at room temperature; $f_{c,\theta}$ is the concrete strength to high temperature (θ) expressed in MPa; $\varepsilon_{c,\theta}$, is the concrete specific strain to high temperature (θ); $\varepsilon_{c1,\theta}$ is the specific strain corresponding to the stress of the concrete maximum strength at high temperature (θ). It is worth mentioning that the term $\varepsilon_{c1,\theta}$ is so called in EN1992-1-2 [5], and in EN1994-1-2 [3] the term is called $\varepsilon_{cu,\theta}$.

The codes EN1994-1-2 [3] and EN1992-1-2 [5] indicate Equation 3 to determine the concrete strength to traction at high temperature.

$$fck,t(\theta) = kc,t(\theta) \cdot fck,t \tag{3}$$

Where: $Kt,_{\theta}$ = 1.0 for 20 °C ≤θ≤ 100 °C; $Kt_{\theta}1-1(\theta-100)/500$ for 100 °C ≤θ≤ 600 °C; Kt_{θ} = 0 for θ> 600 °C.

The reduction factor of the elastic modulus of concrete at high temperature can be determined by Equation 4, based on the constitutive relations presented, for example, in EN1992-1-2 [5].

$$\mathrm{K}_{\mathrm{Ec},\theta} = \mathrm{Kc}_{,\theta} \cdot \frac{\varepsilon_{\mathrm{c1}}}{\varepsilon_{\mathrm{c1},\theta}} \tag{4}$$

Where: ε_{C1}, corresponding specific strain of concrete at room temperature.

Figure 4 shows the factors of reduction determined from the strain corresponding to the stress of the concrete maximum strength to compression, according to Eurocode and to Brazilian standards.

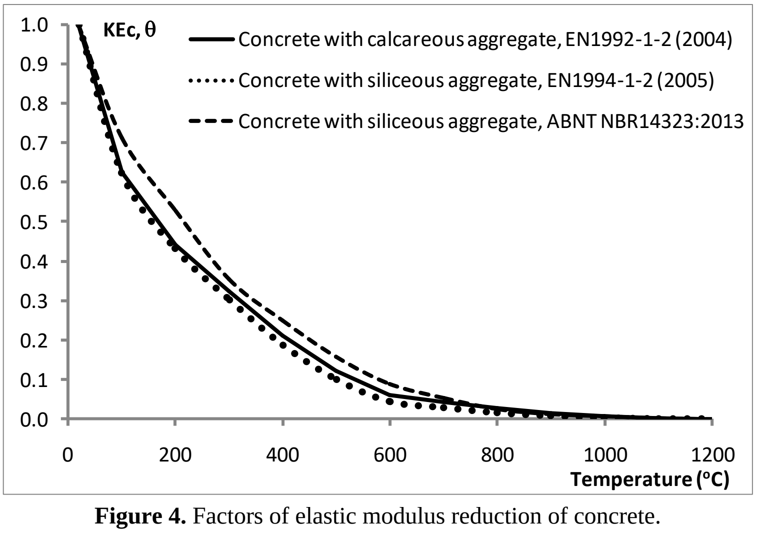


Figure 4. Factors of elastic modulus reduction of concrete.

The Poisson coefficient of steel and concrete is indicated respective as equal to 0.3 and 0.2, regardless of temperature.

4. PARAMETERS AND CONCEPTS FOR NUMERICAL MODELING PURPOSES

4.1. Moisture content in concrete

The moisture content in some materials causes changes in the specific heat; for example, in concrete, there is a considerable increase in specific heat for temperatures about 100 °C. This increase is the result of the latent heat of evaporation of the moisture incorporated into the pores, which is added to the specific heat of the dry material. After evaporation of all the water contained in the material, the specific heat suddenly decreases to remain at the specific heat levels of the dry material. The peak value of the specific heat depends on the moisture content and on the time needed for the water to vaporize [13].

The effect of the moisture content in the concrete is usually considered in the numerical models by values of the specific heat obtained by Equation 7 or 8, considering Cc, peak as a peak value, which occurs between 100 °C and 115 °C, decreasing linearly between 115 °C and 200 °C. From this temperature, the concrete specific heat again follows the values obtained by Equations 5 or 6. The peak value is indicated with values equal to 2020 and 5600 J/kgK for 3% and 10% moisture, respectively, and linear interpolation is valid for intermediate moisture contents.

Equation 7, specified in EN1992-1-2 [5], allows us to determine the specific heat of dry concrete with 0% moisture content (J/kgK).

$$
\begin{aligned}
&C_c = 900 \quad 20\ °C \leq \theta c \leq 100\ °C \\
&C_c = 900 + (\theta c - 100) \quad 100\ °C < \theta c \leq 200\ °C \\
&C_c = 1000 + (\theta c - 200)/2 \quad 200\ °C < \theta c \leq 400\ °C \\
&C_c = 1100 \quad 400\ °C < \theta c \leq 1200\ °C
\end{aligned}
\tag{5}
$$

On the other hand, EN 1994-1-2 [3] indicates Equation 8.

$$C_c(\theta) = 890 + 56.2\left(\frac{\theta_c}{100}\right) - 3.4\left(\theta_c/100\right)^2 \tag{6}$$

In the absence of experimental characterization, the considered moisture content is limited to 4% of the concrete mass. However, tubular columns filled with concrete, with calcareous aggregate, may contain higher levels, close to 10% [1].

The area of the concrete section also influences the development of the temperature field, as the larger the concrete area is, the lower the heating speed of the whole section. The decrease in the heating speed occurs due to the greater amount of the material with lower thermal conductivity and due to the amount of vaporized water contained in the concrete layers [2], [13].

It was also observed that the water flow inside the cross section in tubular columns was altered in the presence of longitudinal reinforcement. With the movement of water in the cross section of the column when heated, part of this water is housed around the bars, and therefore, when there are a significant number of steel bars, there is a disturbance in the temperature field [2], [13].

The presence of water in the concrete pores also causes an increase in the thermal conductivity of the material, since the conductivity of water is greater than that of air, which normally occupies the pores in the absence of water, and due to the heating and evaporation of water, since the vapor is diffused through the pore network, transporting heat [19].

The phenomenon called spalling is related to the moisture content in concrete with the increase in temperature. The water contained in the concrete pores vaporizes between 100 and 140 °C; the temperature above the boiling point is reached depending on the pressure of the water inside the pore. Spalling occurs when the water contained in the concrete is not released, causing an excess of internal pressure [1]; however, it was impossible to visually observe this effect in the columns studied here due to the steel tube involving the concrete.

4.2. Emissivity

The definition of the resulting emissivity is fundamental to achieve results with good approximation to the experimental trials. Assuming the surface temperature of the steel element, without fire protection, to be equal to that of the gases of the burning environment $\left(\theta_a = \theta_g\right)$ results in a response that is normally conservative [20]. It is possible to obtain a more realistic scenario when heat transfer from the environment to the surface of the element occurs through convection and radiation mechanisms.The emissivity of a body, which is the ability to transmit and absorb heat, varies in the interval between 0 and 1 in relation to the capacity of the black body, which absorbs and consequently radiates the heat flow according to the rate defined by Stefan-Boltzmann. There are several bibliographic references with values for the emissivity of steel- and concrete-exposed faces and for the emissivity of fire, as Table 2 compiles.

Table 2. Emissivity of steel, concrete and fire.

Reference	Recommended emissivity values			
	Fire ($e_{m,f}$)	**Steel ($e_{m,s}$)**	**Concrete ($e_{m,c}$)**	
EN1991-1-2 [10]	1	-	-	
EN1992-1-2 [5]	1	-	0.7	
EN1993-1-2 [6]	1	0.7	-	
EN1994-1-2 [3]	1	0.7	0.7	
Lie and Irwin [11]	0.75	0.7	-	
Irwin and Lie [12]	-	0.8	-	
Rush [13]	0.75	0.7	-	
Drysdale [14]	1	0.2	-	
Chaoming et al. [15]	-	0.8	-	Temperature
Paloposki and Liedquist [16]	-	0.2	-	20 to 385 °C
		0.65		550 to 1200 °C
NIST [17]	1	0.32	-	20 °C
		0.32	-	200 °C
		0.85	-	400 °C
		0.95	-	800 °C
		0.95	-	1200 °C
Sadiq et al. [18]	-	0.28	-	θ< 380 °C
		0.003040θ - 0.888		380 ≤θ< 520 °C
		0.69		θ≥ 520 °C

The literature presents different values adopted for the emissivity of steel- and concrete-exposed faces, but the emissivity of fire is usually specified to be 1.00. The values indicated for the emissivity of steel are usually conservative for initial temperatures and underestimated for higher temperatures, and it is worth highlighting that the value of 1 for the emissivity of the fire is described as overrated for oven testing and realistic for fire situations.

As described in Paloposki and Liedquist [16], between 150 and 385 °C, the steel emissivity is about 0.2, increasing sharply to 0.65 until 550 °C, and from this temperature, it was observed that the emissivity remains constant.

Table 3 shows the coefficients of emissivity at the steel and concrete interface extracted from the literature.

Table 3. Emissivity at the steel-concrete interface.

Reference	Emissivity	
1	Concrete ($\varepsilon_{m,c}$)	Steel ($\varepsilon_{m,s}$)
Han and Gillie [21]	0.92	0.23
O'Loughlin et al.[22]	0.97	0.32

5. PARAMETRIC STUDY

5.1. Parameters and analysis development

The three-dimensional model was used to develop thermal and thermal-mechanical analyses; on the other hand, the two-dimensional model was used only for complementary analysis of heat transfer, considering a more detailed evaluation regarding the variation of the moisture content of the concrete and the emissivity of the exposed face of the steel.

5.1.1. Three-dimensional model

Table 4 shows the specimens used to study the sensitivity of the three-dimensional numerical model.

Table 4. List of three-dimensional specimens.

Reference	Section	L or D	t	Fc	Fya	l
1	Cross-section	(mm)	(mm)	(MPa)	(MPa)	(mm)
1- PQ-100-5	Square	100	5	30	350	500
2- PQ-140-5	Square	140	5	30	350	500
3- PQ-200-5	Square	200	5	30	350	500
4- PQ-250-8	Square	250	8	30	350	500
5- PC-114-5	Circular	114.3	5	30	350	500
6- PC-150-5	Circular	150	5	30	350	500
7- PC-195-5	Circular	195	5	30	350	500
8- PC-250-8	Circular	250	8	30	350	500

The variations of the properties in the model were named M1 to M6 and do correspond to the alternation of the concrete expansion values according to the type of aggregate, of the thermal expansion of steel, to the amount of water and to the density of the concrete, as shown in Table 5.

Table 5. Parameters used in the thermal-mechanical numerical model.

<table>
<tr><th></th><th>Thermal expansion of concrete</th><th>Type of aggregate</th><th>Thermal expansion of steel</th><th>Concrete moisture content</th><th>Concrete density</th></tr>
<tr><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>M1</td><td>EN1994-1-2 [3]: 20 °C< $\theta c \leq$ 805 °C: $\Delta l/l,c= -1.2 \cdot 10^{-4}+6 \cdot 10^{-6} \cdot \theta c+1.4 \cdot 10^{-11} \cdot \theta c^3$ 805 °C< $\theta c \leq$ 1200 °C: $\Delta l/l,c = 12 \cdot 10^{-3}$</td><td>Calcareous</td><td rowspan="5">EN1994-1-2 [3]: 20 °C < $\theta a \leq$ 750 °C: $\Delta l/l,a = -2.416 \cdot 10^{-4} +1.2 \cdot 10^{-5} \cdot \theta a+0.4 \cdot 10^{-8} \cdot \theta a^2$ 750 °C < $\theta a \leq$ 860 °C: $\Delta l/l,a = 11 \cdot 10^{-3}$ 860 °C < $\theta a \leq$ 1200 °C: $\Delta l/l,a = -6.2 \cdot 10^{-3} + 2 \cdot 10^{-5} \cdot \theta a$</td><td rowspan="2">3%</td><td rowspan="3">EN1994-1-2 [3]: 20 °C $\leq \theta c \leq$ 115 °C: $\rho(\theta c) = \rho(20$ °C$)$ = 2300 kg/m^3 115 °C < $\theta c \leq$ 200 °C: $\rho(\theta c)=\rho(20$ °C$) \cdot (1-0.02 \cdot (\theta c-115)/85)$ 200 °C < $\theta c \leq$ 400 °C: $\rho(\theta c) = \rho(20$ °C$) \cdot (0.98-0.03 \cdot (\theta c-200)/200)$ 400 °C < $\theta c \leq$ 1200 °C: $\rho(\theta c) = \rho(20$ °C$) \cdot (0.95-0.07(\theta c-400)/800)$</td></tr>
<tr><td>M2</td><td rowspan="4">EN1994-1-2 [3]: 20 °C< $\theta c \leq$ 700 °C: $\Delta l/l,c= -1.8 \cdot 10^{-4}+9 \cdot 10^{-6} \cdot \theta c+2.3 \cdot 10^{-11} \cdot \theta c^3$ 700 °C< $\theta c \leq$ 1200 °C: $\Delta l/l,c = 14 \cdot 10^{-3}$</td><td rowspan="5">Siliceous</td></tr>
<tr><td>M3</td><td>10%</td></tr>
<tr><td>M4</td><td rowspan="3">3%</td><td>2300 kg/m^3</td></tr>
<tr><td>M5</td><td>2400 kg/m^3</td></tr>
<tr><td>M6</td><td>simplified: $\Delta l/l,c = 6 \cdot 10^{-6}$</td><td>simplified: $\Delta l/l,a = 12 \cdot 10^{-6}$</td><td>same density of the M1, M2 and M3 models</td></tr>
</table>

The other properties of steel and concrete, not explained in Table 5, remained according to equations presented in EN1992-1-2 [5] and EN1993-1-2 [6].

The fire resistance times were determined according to EN1363-1 [23], with the axial force applied in the models corresponding to 30% of the plastic resistance of the cross section at room temperature.

Figure 5 shows the monitoring points of the temperatures in the specimens.

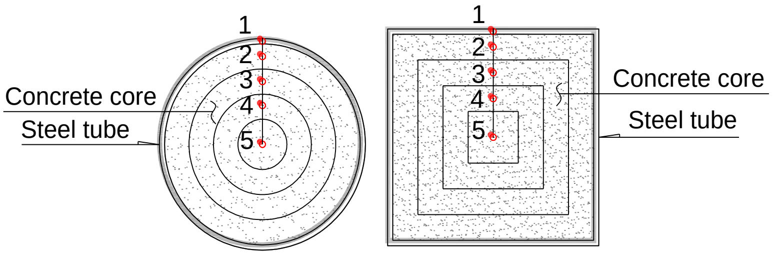


Figure 5. Monitoring points of the temperatures in the cross section.

5.1.2. Two-dimensional model

Using the two-dimensional model, complementary studies were conducted with different values adopted for the specific heat of concrete, according to its moisture content. The models denominated with combinations 1 and 2 refer to Equations 5 and 6, which are used to determine the values of the specific heat of concrete. The influence of moisture in the temperature field was verified considering the specimens indicated in Table 6, with moisture contents alternating between 0, 1.5, 3, 5, 7.5 and 10%.

Table 6. Specimens for modeling with heat transfer analysis.

Reference	Cross section	L or D (mm)	t (mm)	fc (MPa)	Fya (MPa)	l (mm)
1- PC-168-6	Circular	168.3	6.4	-	-	-
2- PC-168-10	Circular	168.3	10	-	-	-
3- PC-300-10	Circular	300	10	-	-	-

The temperatures found with the two-dimensional model were recorded along the track indicated as an example in Figure 6 for specimen 1.

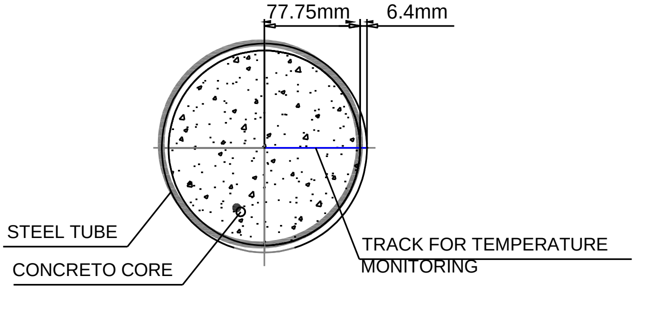


Figure 6. Track for temperature monitoring in the cross section.

The influence of the emissivity adopted for the exposed face in the model was verified by comparing the temperature field, considering the emissivity values of the exposed face as 0.7, 0.8 and 1. In the model, combination two was implemented with dry concrete, a transfer rate by convection of 25 W/m^2 °C, exclusive thermal analysis, and perfect thermal contact in the tube–concrete interface.

5.2. Results and discussions

5.2.1. Three-dimensional model

Table 7 shows, for four specimens, the temperatures in the cross section, along with the fire resistance times, according to the responses of numerical modeling with the alternation of the parameters and properties indicated in Table 5.

Table 7. Response of the parametric analysis of the numerical models.

Specimen (Table 5)	Model M	Fire resistance time (minutes)	Temperature (°C)				
1	1	1			1		
1	1	**1**	**1**	**2**	**3**	**4**	**5**
3-PQ-200-5	1	59.0	905.2	629.8	357.1	219.8	140.9
1	2	50.2	835.5	516.9	243.1	119.6	75.1
1	3	57.0	844.4	471.1	154.3	61.5	43.1
1	4	51.4	833.6	511.5	239.4	118.2	74.7
1	5	52.7	831.1	502.9	229.7	111.3	70.7
1	6	60.9	893.8	612.3	337.8	199.7	123.3
7-PC-195-5	1	45.9	815.1	505.8	250.2	124.4	73.8
1	2	43.2	785.6	458.0	209.7	98.7	61.3
1	3	47.5	804.5	423.3	116.6	55.4	39.4
1	4	43.4	777.0	442.4	198.2	93.7	58.8
1	5	45.9	787.2	451.5	204.1	96.2	60.1
1	6	51.7	852.9	570.0	309.7	174.9	97.2
2-PQ-140-5	1	43.4	815.1	567.7	374.4	254.1	198.0
1	2	36.7	791.3	527.4	332.7	210.4	151.8
1	3	43.7	784.1	453.8	214.9	89.2	62.7
1	4	38.4	789.0	521.1	327.0	206.0	149.0
1	5	38.9	785.9	511.1	315.0	193.2	137.1
1	6	40.7	791.5	529.4	335.1	212.4	153.4
5-PC-114-5	1	31.2	736.3	541.6	344.9	243.2	186.0
1	2	30.0	726.9	524.8	328.1	225.7	164.8
1	3	33.4	725.7	471.4	216.9	89.1	66.3
1	4	30.0	725.0	518.6	322.6	221.5	161.4
1	5	30.0	721.9	508.7	310.5	208.0	146.6
1	6	32.0	753.6	571.5	375.6	275.8	225.4

In this study, it was observed that Model M2, with 3% moisture and concrete density according to the equation described in EN1994-1-2 [3] and EN1992-1-2 [5], presented shorter fire resistance times than those with concrete densities equal to 2300 kg/m^3. For concrete densities equal to 2300 kg/m^3, the fire resistance times increased by up to 10%; the model with 10% moisture content (M3) presented a fire resistance time 16% higher than that with 3% (M2); and the models with constant expansion coefficients showed 18% higher fire resistance times.

Figure 7 graphically shows the results referring to the fire resistance times, as shown in Table 7 for numerical models resolved with the properties and parameters indicated in Table 5 (M1 to M6).

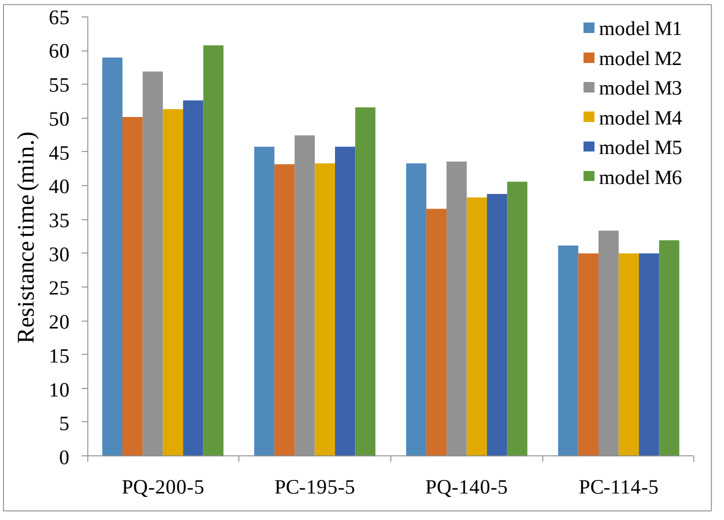
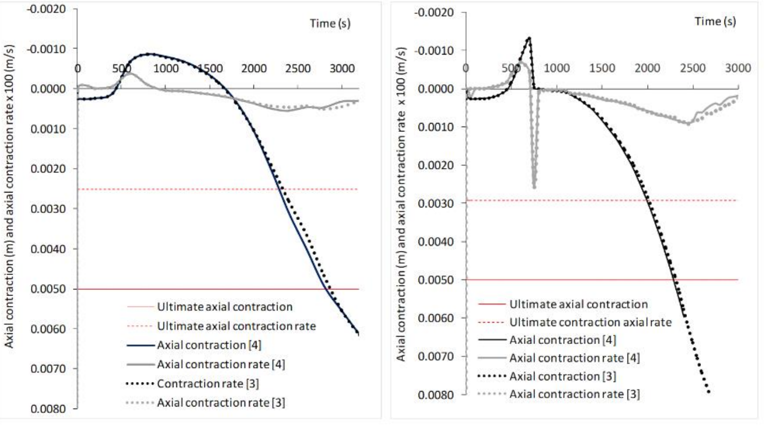


Figure 7. Fire resistance time with alternation of properties in the model.

The thermal properties indicated in ABNT NBR 14323:2013 [4] and EN 1994–1-2 [3] are the same, and the formulations for defining the mechanical behavior are also similar, except for the last deformations and, consequently, the elastic modulus of the concrete.

Experimental studies show that the values of the elastic modulus of concrete determined with the stress–strain diagram at high temperature according to EN19944-1-2 [3] are conservative for concretes of normal strength, and they verified the expressive influence of coarse aggregate types [24]. This suggests that the values determined with the last deformations of concrete at high temperature presented in the Brazilian code are more realistic.

Figure 8 shows that there are small differences in column behavior considering the ultimate deformations and the elastic modulus of concrete, according to EN1994-1-2 [3] and ABNT NBR 14323:2013 [4]. For this analysis, a three-dimensional numerical model was used.

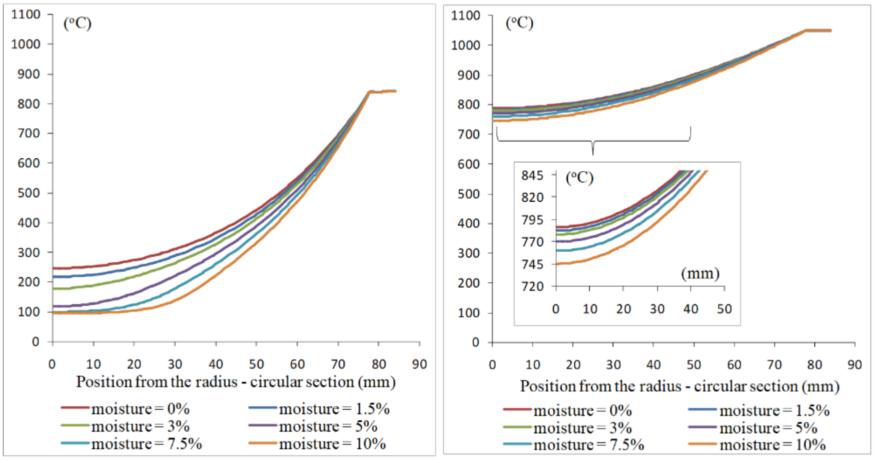


(a) Specimen 3 (b) Specimen 7

Figure 8. The fire resistance time considering the M2 model is indicated in Table 5.

5.2.2. Two-dimensional model

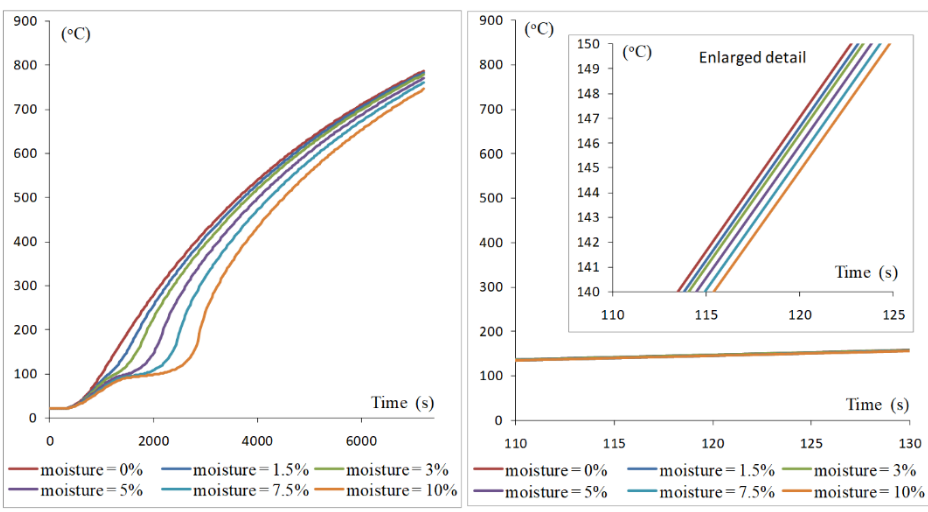
Figure 9 shows the temperatures monitored in the model elaborated with different moisture contents of the concrete and with prefixed times of exposure to fire for specimen 1 (Table 6).



(a) exposure to fire = 30 min (b) exposure to fire = 120 min

Figure 9. Temperature according to the moisture content of the concrete.

Figure 10 shows the temperatures in the center of the concrete and on the inner face of the steel tube.



(a) Temperature at the concrete core center (b)Temperature at the internal face of the tube

Figure 10. Evolution of temperature according to the concrete moisture content.

For the evolution of the temperature of sample one, there is a difference in the center of the concrete core between models with moisture contents of 0% and 10% of 150 °C for 30 minutes of exposure to fire and 50 °C for 120 minutes of exposure to fire. For specimen 3 (Table 6), the temperature difference reaches 190 °C for 30 minutes of exposure to fire and 120 °C for 50 minutes. In the steel tube, the change in the moisture content of concrete results in a small variation in its temperature.

Figure 11 shows the temperatures along the monitoring range, comparing the model with combinations 1 and 2 of sample 1 (Table 6), according to the time of exposure to fire (FET).

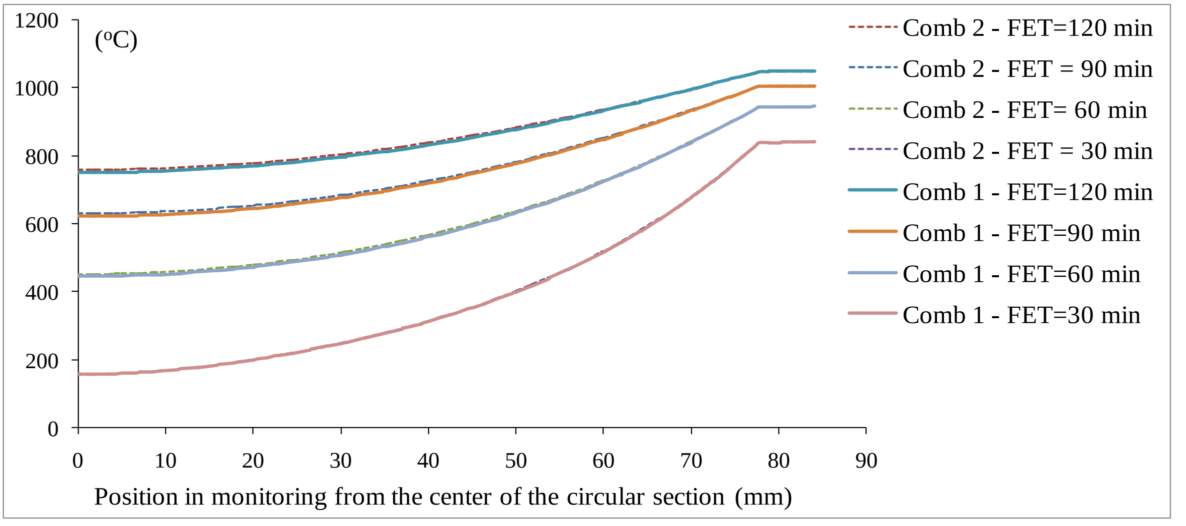


Figure 11. Temperatures along the cross section for combinations 1 and 2.

According to the parametric study, it was found that the responses of the model are coincident; with the combination one or two, but for longer exposure times the combination two presented slightly higher temperatures, but still close.

Figure 12 shows the temperatures over time, on the outer face of the tube and in the center of the concrete core for specimen 1 (Table 6).

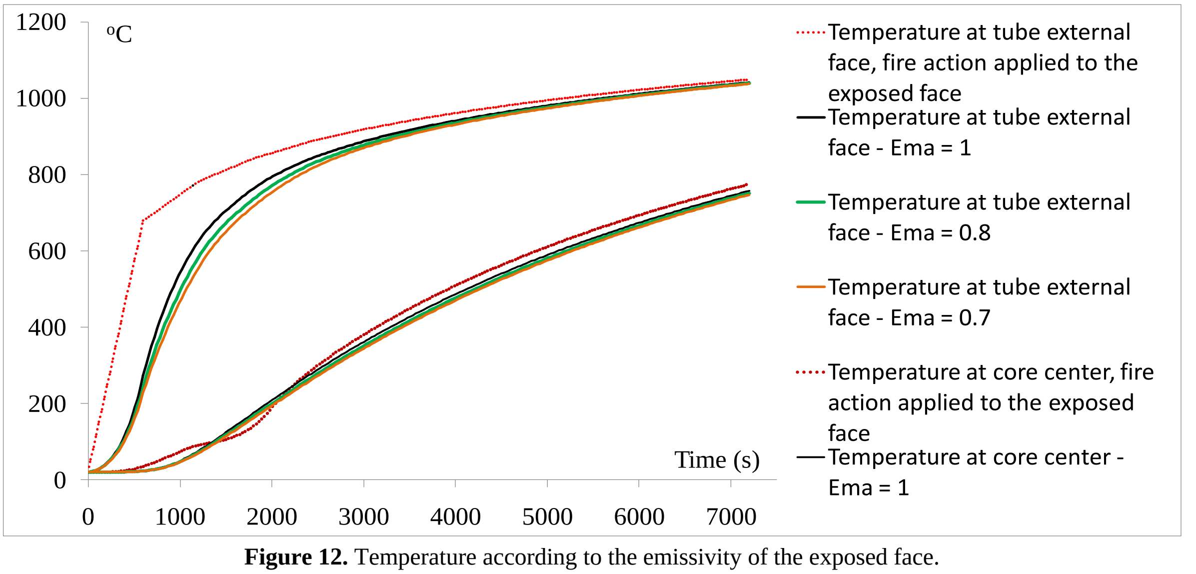


Figure 12. Temperature according to the emissivity of the exposed face.

6. CONCLUSIONS

It was verified that the numerical model was sensitive to the values adopted for the parameters and properties of the materials, and the choice of constant values with a higher degree of simplification should be made judiciously. In this study, it was possible to demonstrate which simplifications most influence the response of the numerical model. Such simplifications seek to facilitate practical applications in numerical and analytical models, but they can reduce the quality of the results. In this sense, some considerations have been presented regarding the study carried out with alternation of modeling parameters and of the properties of steel and concrete.

The equations indicated in the codes EN1992-1-2 [5], EN1993-1-2 [6] and ABNT NBR 14323:2013 [4] should be used preferably without simplifications for determining the values of steel and concrete properties to be adopted in numerical models. The exception is the determination of concrete specific heat, which should favor the equation from EN1994-1-2 [3], which is adjusted for columns composed of tubes filled with concrete. The constant values presented in the Eurocode for the density of concrete and for the coefficients of thermal expansion of steel and concrete should be avoided, since their responses were very divergent from those obtained through the numerical model.

On the other hand, regarding the determination of the mechanical properties of concrete, minimal differences were found between the results of the numerical models according to the Eurocode and the Brazilian code. That is, the results are coincident.

The moisture content considered in the concrete significantly affects the temperature field, especially for the very concrete and for cross sections with greater areas. For the steel tube, the alteration is more discrete, but the decrease in temperature is still perceivable as the moisture content in concrete is increased.

Thus, these results indicate the need for greater knowledge of the concrete moisture content to be adopted in each tubular mixed column. The process used to consider the effect of moisture in the temperature field was also verified to be too simplified. According to bibliographic references, the value of 4% moisture content may be very conservative in some cases but is a reasonable limit when one does not accurately know the moisture effectively contained in concrete; however, for concrete with calcareous aggregate, this limit can be very conservative, evidencing the need for a greater number of experimental tests to generalize these limits.

In numerical models, when considering the heating of the element by the radiation mechanism with the resulting value of the emissivity of the fire and exposed face with alternating values of 0.7 and 0.8, as temperatures undergo small variations. That is, from differences above 15% in the resulting emissivity, the time-temperature curve begins to diverge, presenting a very distinct behavior trend.

7. ACKNOWLEDGEMENTS

The authors thank the support from the University of Campinas and from Catholic University of Santos.

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Editors: Rebecca Gravina, Guilherme Aris Parsekian.