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ORIGINAL ARTICLE

RC beams with rectangular openings in case of fire

Vigas de concreto armado com aberturas retangulares em situação de incêndio

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Abstract: Openings in reinforced concrete (RC) beams may be required due to building installations (electrical, water, etc.). They weaken its cross-sectional area and, in case of fire, can increase the thermal field of the structure. NBR 15200 does not consider this. The paper evaluated the influence of rectangular openings on the Fire Resistance Rating (FRR) of RC beams by the Simplified Method of NBR 15200. This method combines a non-linear thermal analysis (isotherms) with the evaluation of the flexural strength of the beams using a manual design calculation method. The thermal field were obtained by a thermal model solved by finite element analysis (FEA) with Abaqus software. Thermal parameters of NBR 15200 were used. This FRR was compared with equivalent beams without openings solved by the Tabular Method of NBR 15200. Twelve 60 cm high beams with different widths and dimensions of openings were studied. Beams with openings had a FRR up to 60 min lower than the equivalent beam without openings. The larger the size of the rectangular opening, the greater the mechanical degradation of the beam in fire. NBR 15200 Tabular Method proved to be unsafe in this case. Prescriptions for beams with openings must be shown in NBR 15200.

Keywords: reinforced concrete, beams, fire, openings, NBR 15200.

Resumo: As aberturas e furos em vigas de concreto são corriqueiramente exigidas em virtude das instalações prediais (de água, elétrica, etc). Elas fragilizam a seção e, em situação de incêndio, podem amplificar o campo térmico do elemento estrutural. A NBR 15200 não faz menção à essa situação. Este estudo avaliou a influência de aberturas retangulares no Tempo de Resistência ao Fogo (TRF) de vigas de concreto pelo Método Simplificado da NBR 15200. O método combina a definição de uma análise térmica não linear (isotermas) com o cálculo manual da resistência a flexão destas vigas. As isotermas foram obtidas por um modelo térmico resolvido pela teoria dos elementos finitos com auxílio do software Abaqus. Os resultados foram comparados com o TRF obtido em vigas sem aberturas pelo Método Tabular normatizado. Doze vigas de 60 cm de altura e com diferentes larguras e dimensões de aberturas foram avaliadas. As vigas com aberturas tiveram um TRF até 60 min inferior às sem aberturas. Quanto maior a dimensão da abertura, tanto maior foi a degradação mecânica da viga ao incêndio. O Método Tabular se mostrou inseguro nessa circunstância. Prescrições a vigas com aberturas devem ser apresentadas na NBR 15200.

Palavras-chave: estruturas de concreto, vigas, incêndio, aberturas, NBR 15200.

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1. INTRODUCTION

In the design of reinforced concrete (RC) beams under normal temperature conditions, it may be required to incorporate openings for the passage of plumbing, electrical, telephone and/or internet installations. The openings can occur in the direction of the width or height of the beam and must be allowed in the structural design through specific standardized procedures.

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In Brazil, NBR 6118 [1] shows these beams structural integrity and safety requirements. Horizontal and vertical reinforcement adjacent to the opening can be used to compensate for the loss of its cross-section.

The subject has been studied for decades and still arouses interest among researchers.

Studies show alternatives to optimize the steel consumption of reinforcement in the opening region, mitigate the concrete stresses and cracks and propose more current calculation techniques than those already established by Leonhardt and Monnig [2] and Sussekind [3]. Research has been carried out, for example, by Shoeib and Sedawy [4], to understand the magnitude of mechanical damage in these beams; by El-Mar et al. [5], to analyze the region where concrete cracks begin; by Sayed [6], to investigate the shear stresses along the beam; by Mansour [7], to understand the use of steel fibers in crack mitigation and stress dissipation, among others.

Herrera et al. [8] and Elsanadedy [9] showed that failure of RC beams with openings under normal temperature conditions predominantly occurs under excessive shear stresses. In this sense, Campione and Minafò [10] evaluated beams with a low span-depth ratio to make these stresses critical. It was concluded that if the opening is placed in the region next to the columns, where the shear stresses are greater, reducing its structural capacity from 18 to 30%. Using vertical reinforcement increases the structural capacity in these regions by 15%. Similar research was presented by Mansour [7] and Ashour and Rishi [11], indicating that the RC beam mechanical capacity reduces as the openings approach the supports. Sayed [6] concluded that the opening size generates a more damaging structural consequence than the number of openings in the beams.

In this sense, Aykac et al. [12] experimentally evaluated the influence of multiple openings arranged in RC beams, both rectangular and circular. The authors show that the transverse reinforcements next to the supports prevent their premature failure by the Vierendeel action, which is only possible due to the longitudinal reinforcements surrounding the openings, in the flanges. The authors also concluded that circular openings are less harmful than rectangular ones, which was also showed by Tsavdaridis et al. [13] in the behavior of composite steel and concrete beams. Both researches [12], [13] were experimental. However, experimental procedures should be considered with caution to RC beams with openings. According to Shoeib and Sedawy [4], laboratory tests on RC beams with openings are influenced by load application points.

Research has focused on analyzing RC beams with openings under normal conditions (i.e., normal temperatures). A lack of studies has analyzed them in extreme conditions, such as in a fire. The subject is interesting because the opening can increase the thermal field of the cross-section, which accelerates the mechanical damage of the RC beam in case of fire.

It is known that in the fire design of a building, not all beams must meet the thermal insulation requirement. In these cases, the openings do not need passive protection (e.g., intumescent collars, fire stop, etc). In this case, pipes would be unprotected. Due to their constitutive characteristics, normally based on synthetic plastic polymers, they would disintegrate in a short period of fire, providing faster beam heating than those that do not have openings. The thermal field of beams with openings is probably higher.

A lack of research evaluated the influence of openings in RC beams in case of fire. This gap may even justify the negligence of standards such as NBR 15200 [14] and EN 1992.1-2 [15] regarding the fire design of RC beams with openings. According to Issa and Izadifard [16] and Kodur et al. [17], most current practices are more of a visual descriptive approach that is more concern with the adequate steel bar minimum cover and member size while ignoring a more meticulous approach of understanding the thermal and mechanical behavior and real building conditions of RC members exposed to fire.

This paper aims to fill this gap. Under normal temperature conditions, Sayed [6], Herrera et al. [8], Elsanadedy [9], Tsavdaridis et al. [13] showed that openings tend to cause beam failure by shear, which contradicts research on beams without openings in case of fire, as Li et al. [18], Gedam [19], Silva [20] and Xu et al. [21], showing that failure of RC beams does not occur due to shear stresses. Design standards cannot predict all situations. In this sense, performance-based fire safety design approach is becoming the method of choice, leading to numerical simulation of RC members at elevated temperatures, as can be seen in recent researches as Kumar and Kodur [22].

This research evaluates the influence of openings on the Fire Resistance Rate (FRR) of RC beams. First, the beams were designed at a normal temperature according to NBR 6118 [1]. Subsequently, for fire design requirements, they were evaluated by the Simplified Method of NBR 15200 [14], based on the thermal field obtained through a numerical model solved by FEA with the Abaqus software. The thermal field makes it possible to define the temperature at the cross-section of the beam with opening and later calculate the flexural strength of these beams using a manual design calculation method. These results were compared to the Tabular Method of NBR 15200 admitting equivalent beams without openings. Twelve cross-sections were evaluated. The research was motivated by the lack of standardized prescriptions and research on the fire performance of RC beams with openings.

2. ANALYTICAL AND NUMERICAL PROCEDURES

Two cases of RC beams were employed: one without openings and another with openings. First, the longitudinal and transverse reinforcement were calculated for normal temperature according to NBR 6118 [1]. Subsequently, they were verified in fire according to NBR 15200 [14], where its Fire Resistance Rate (FRR) was defined. In beams without openings, the FRR was obtained by the Tabular Method of NBR 15200 [14], which is the most conservative. In the beam with an opening, given the inapplicability of the Tabular Method, the verification was done by the Simplified Method of NBR 15200 [14].

The description of these procedures is detailed below.

2.1 Beams characteristics

In the beams without openings, 3 rectangular cross-sections with a height of 60 cm and breadth "b" of 15, 20 and 25 cm were used, as shown in Figure 1a. These beams were named Vb15, Vb20, Vb25, respectively.

The beams with openings were analyzed with the same height and breadth as the previous ones. Three rectangular openings were admitted. The opening length of the opening (parallel to the beam axis) was 30 cm, while the height "h" was 10, 15 or 20 cm, as shown in Figure 1b. The summary of beams with openings is shown in Table 1.

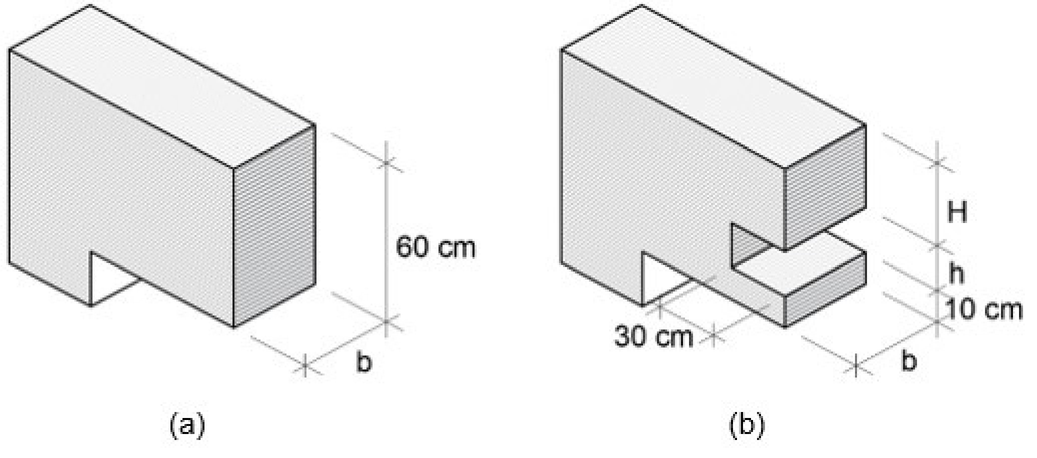

Figure 1 – Beams cross-section (a) without and (b) with openings

Table 1 – Beams with openings

Beam	b (cm)	h (cm)	H (cm)
Vb15h10		10	40
Vb15h15	15	15	35
Vb15h20		20	30
Vb20h10		10	40
Vb20h15	20	15	35
Vb20h20		20	30
Vb25h10		10	40
Vb25h15	25	15	35
Vb25h20		20	30

It is understood that the proposed values of b, h and H are the ones commonly found in Brazilian buildings, and represent the common geometry of reinforced concrete beams.

Twelve cross-sections were studied: 3 without openings and 9 with openings. In a fire situation, all were verified for 30, 60, 90 and 120 min of exposure to ISO 834 [23].

2.2 Criteria for analysis at normal temperature

The beams without openings were designed based on NBR 6118 [1] of Ultimate Limit State (ULS). The design was carried out per section 17.2.2 of the NBR 6118 criteria. The sagging moment was 10 tf·m in all cases. To define the cross-sectional area of the reinforcements, the theory of balance of internal forces and deformation (i.e., concrete and reinforcements) was used, with support from Carvalho and Figueiredo [24] and NBR 6118 [1] (flexural theory of RC beams). This procedure begins with defining the type of crack that the RC beam will present in the failure. Hence, it is necessary to use the relation between the depth of the neutral axis (x) and the useful height (d), since this parameter (x/d) determines if it will be a fragile or ductile failure. For RC elements with fck up to 50 MPa, NBR 6118 [1] limits this value to 0.45. Thus, the tensile stresses of the concrete and positive steel are calculated.

To comply the durability criteria of NBR 6118 [1] for CAA II (environmental aggressiveness class #2, in Portuguese), typical of urban environments, the reinforcement cover thickness was 30 mm and the concrete compressive strength was 30 MPa.

For the analysis of RC beams with opening, the requirements of section 13.2.5 of NBR 6118 [1] were used. It was assumed that the opening was positioned in the region of the maximum sagging moment – i.e., 10 tf·m – of the RC beam. The design of longitudinal and transverse rebars was based on the classical procedure of Leonhardt and Monnig [2], according to the Equation 1 to 6. The upper flange (cross-section above the opening) was designed by combined bending and axial compression (N_c and M_c) and shear force (V_c) while the lower one (cross-section below the opening) for flexo-traction (N_t and M_t) and shear force (V_t). The Leonhardt and Monnig theory was used due to its validation over time, in addition to allowing the adjustment of the equations for the application of the Simplified Method of NBR 15200.

$$N_c = \frac{M_{sd}}{z} \quad (1)$$

$$N_t = \frac{M_{sd}}{z} \quad (2)$$

$$V_c = 0{,}80 \cdot V_{Sd} \quad (3)$$

$$V_t = 0{,}20 \cdot V_{Sd} \quad (4)$$

$$M_c = \frac{V_c}{0{,}50 \cdot L_{opening}} \quad (5)$$

$$M_t = \frac{V_t}{0{,}50 \cdot L_{opening}} \quad (6)$$

2.3 Criteria for analysis in fire

The fire analysis was made according to NBR 15200 [14]. The FRR of the beam without opening was obtained by the Tabular Method, as it is the most used in commercial structural design software. In beams with opening, given the inexistence of any tabulated method in this case, the analysis was made by the Simplified Method of NBR 15200.

The Tabular Method application followed the definition of the minimum dimensions of each cross-section and the C_1 coefficient, which for these beams was 40 mm. The coefficient was defined by the reinforcement cover thickness (30 mm), stirrup diameter (hypothetically arbitrated in 5 mm) and half of the longitudinal reinforcement diameter (arbitrated in 10 mm).

The application of the Simplified Method used the thermal field of the cross-section of the beam and its respective mechanical damages to the materials (i.e., concrete and steel). The beam in case of fire was designed with the same theoretical basis to normal temperature, but with $\gamma_s = 1{,}0$ and $\gamma_c = 1{,}0$ and without the long-term coefficient α=0.85, given the exceptionality of this case. The bending moment applied was equal to 70% of that used in the design at normal temperature. This criterion is defined by the NBR 15200 [14].

2.4 FEA model

The thermal field in the beam cross-section was solved by FEA (Finite Element Analysis) with the Abaqus software. The FEA model was made assuming the thermal diffusivity parameters of the concrete and steel. Thermal conductivity and density were proposed at NBR 15200 [14]. The specific heat was also taken from NBR 15200 [14]. They are presented in Annex A, being the specific heat of the steel shown in Figure A1 and their thermal conductivity in Figure A2. The density of the steel was constant (7850 kg/m^3). For concrete, the specific heat is in Figure A3, the density in Figure A4 and the thermal conductivity in Figure A5.

Figure 2 shows the FEA thermal model. The cross-section was the one adjacent to the beam opening. The FEA model of the beam without opening was similar, but without the opening.

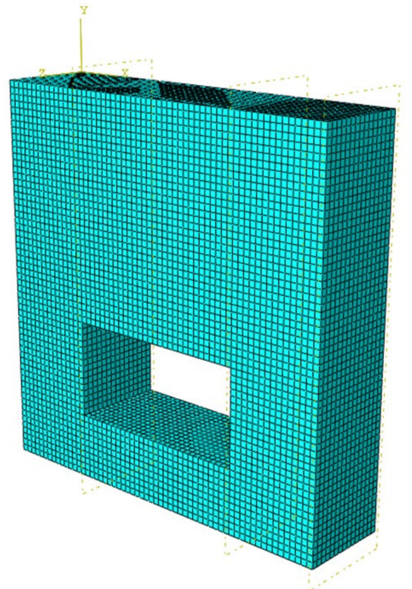

Figure 2 – Computational thermal model (beam with opening)

The concrete was modeled with a general 3D solid 8-node linear isoparametric (DC3D8) finite element from the Abaqus software library and the reinforcement with a truss of 2-node link (DCC1D2), as performed by Issa and Izadifard [16], Li et al. [18] and Xu et al. [21], and others. A mesh sensitive analysis was performed, and the size of the elements is approximately 0.5 x 0.5 x 0.5 mm for the DC3D8 and 0.5 mm for the DCC1D2. The total coupling of the rebars in the concrete was used, admitting a total interaction between them.

The FEA model was solved by Abaqus (non-linear model) by the Equation 7, which represents the thermal diffusivity that produces a thermal field in the cross-section of the beam. The analysis depends on the density ρ, thermal conductivity k and specific heat C_p of the materials (i.e., steel and concrete).

$$\alpha = \frac{k}{\rho . C_p} \quad (7)$$

On the bottom surface of the beam, the ISO 834 [23] fire curve was considered by thermal convection (with a heat transfer coefficient α=25 W/m^2.K) and radiation (with a thermal emissivity Ɛ=0,70 according to EN 1992.1-2). On the top surface of the beam, an ambient temperature of 25ºC was considered by convection (with α=9 W/m^2·K). The absolute zero of the model was -273,15 ºC and the Stefan-Boltzmann Constant (σ=5,67$\cdot 10^{-8}$ W/m$^2\cdot$ K^4).

The surfaces to which the heating was applied are shown in Figure 3. In Figure 3a, the cross- section without opening is shown, with the heating applied peripherally, excluding the beam's upper surface. Figure 3b details the cross-section with the opening. Heating is also done around the perimeter, including the opening region. The upper surface of the lower and upper flanges was not heated. The criterion was based on the principles of thermodynamics developed in an environment under fire.

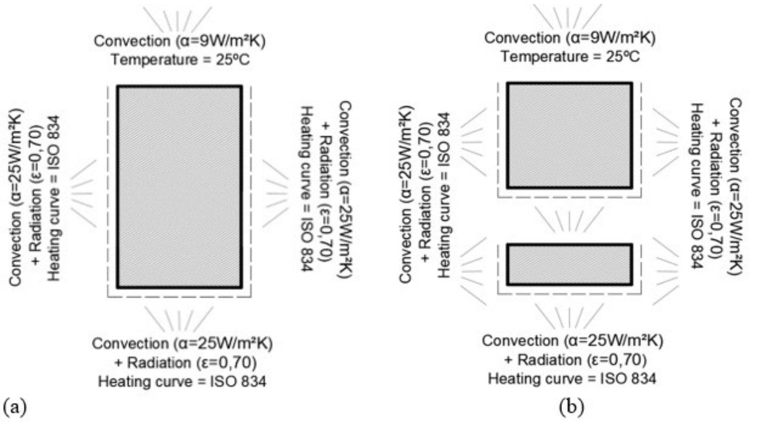

Figure 3 – Heating surfaces in the cross-section of the beams (a) without and (b) with opening

The temperature of the concrete cross-section was defined by the average between the reading points of Figure 4a and Figure 4b for the beam without and with opening, respectively. Since the concrete cross-section at the beam's load-bearing capacity is above the neutral axis, only reading points in this region were used for beam without opening. For beams with openings, reading points on both the lower and upper flanges were considered, since both participate in the beam's load-bearing capacity in this region, according to the classical theory of Leonhardt and Monnig [2]. Figure 4c shows the procedure for defining the temperatures in the reinforcements. Four rebars were chosen, numbered from 1 to 4, which were positioned at the region usually used in the structural design.

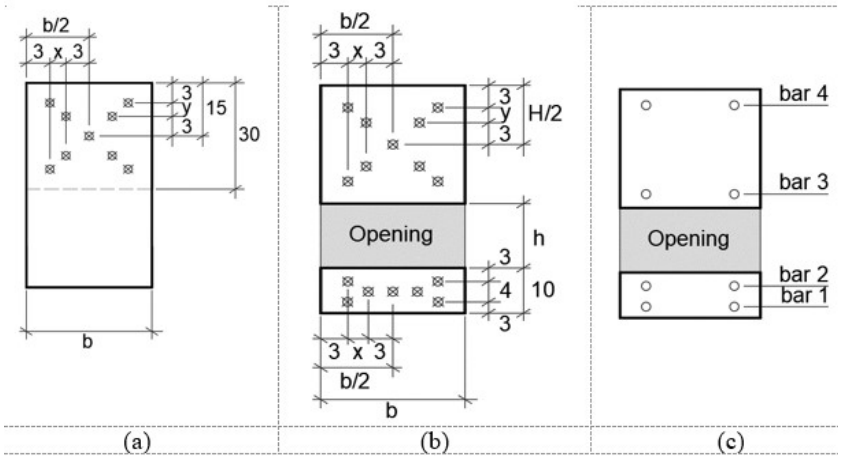

Figure 4 – Temperature reading points in the cross-section of the beams (a) without and (b) (c) with openings

3. RESULTS

3.1 Design at normal temperature

The reinforcement design of the beams with and without openings is presented.

a) Beams without openings

Table 2 shows the required reinforcement area for Vb15, Vb20 and Vb25. The longitudinal and transverse reinforcement area, the longitudinal reinforcement ratio, the elongation of the concrete and reinforcements, deformation domain, depth of the neutral axis and the ductility requirement according to NBR 6118 [1] are shown.

Table 2 – Structural design of beams without opening

Beam Name	$A_{s,min}$ (cm²)	A_s (cm²)	$A_{sw,min}$ (cm²)	A_{sw} (cm²)	$\frac{A_s}{A_c}$(%)	ε_s (%)	ε_c (%)	Domain number	X (cm)	$\frac{x}{d}$
Vb15	1,4	4,4	1,7	3,6	0,5	10	1,8	2	8,7	0,16
Vb20	1,8	4,3	2,3	2,1	0,4	10	1,3	2	6,4	0,11
Vb25	2,3	4,2	2,9	1,2	0,3	10	1,0	2	5,1	0,09

The longitudinal reinforcement area used in these beams was between 4.2 and 4.4 cm^2. As expected, increasing the RC beam width subtly reduces the reinforcement area required. However, it affects the total area of transverse reinforcement (stirrups), but they will not be analyzed because, according to [18]–[21], the beams do not fail by shear in a fire. The beams are in domain 2 of deformation (according to section 17.2.2 of the NBR 6118), meeting the requirements of these standard. The standardized ductility limit is also respected.

It can be concluded that the beams Vb15, Vb20 and Vb25 can be used because they respect the standardized requirements of structural design of RC.

b) Beams with openings

Table 3 shows the required longitudinal and transverse reinforcement area, both in the upper (compressed) and lower flange (tension) around the opening. The shear and suspension transverse reinforcements were also defined.

Table 3 – Structural design of beams with opening

Beam Name	$A_{st,min}$ (cm²)	A_{st} (cm²)	$A_{sc,min}$ (cm²)	A_{sc} (cm²)	$A_{swc,min}$ (cm²)	A_{swc} (cm²)	$A_{swt,min}$ (cm²)	A_{swt} (cm²)	A_{sws} (cm²)
Vb15h10	0,2	8,3	0,9	0,0	1,7	5,4	1,7	4,9	2,2
Vb15h15	0,2	8,3	0,8	0,0	1,7	6,9	1,7	4,9	2,2
Vb15h20	0,2	8,3	0,7	0,0	1,7	8,8	1,7	4,9	2,2
Vb20h10	0,3	8,2	1,2	0,0	2,3	4,4	2,3	3,8	1,1
Vb20h15	0,3	8,2	1,1	0,0	2,3	5,8	2,3	3,8	1,1
Vb20h20	0,3	8,2	0,9	0,0	2,3	7,6	2,3	3,8	1,1
Vb25h10	0,4	8,1	1,5	0,0	2,9	3,3	2,9	2,7	0,0
Vb25h15	0,4	8,1	1,3	0,0	2,9	4,7	2,9	2,7	0,0
Vb25h20	0,4	8,1	1,2	0,0	2,9	6,5	2,9	2,7	0,0

The longitudinal reinforcement area of the tensioned flange (lower) was between 8.1 and 8.3 cm^2, while in the compressed flange (upper) the use of reinforcement is unnecessary. In this case, the minimum reinforcement area practiced by NBR 6118 [1] was used, being between 0.7 and 1.5 cm^2. Comparing the beam above (section a, beam without opening), it is necessary to add longitudinal reinforcements in the opening region. Reinforcements used outside the cross-section around the opening (i.e., beam without opening according to Table 2) would not be sufficient. The transverse reinforcements (stirrups) were not analyzed due to the abovementioned circumstances [18]–[21].

3.2 Thermal field in cross-section

Figure 5 shows the average temperatures in the cross-section of the beams in case of fire.

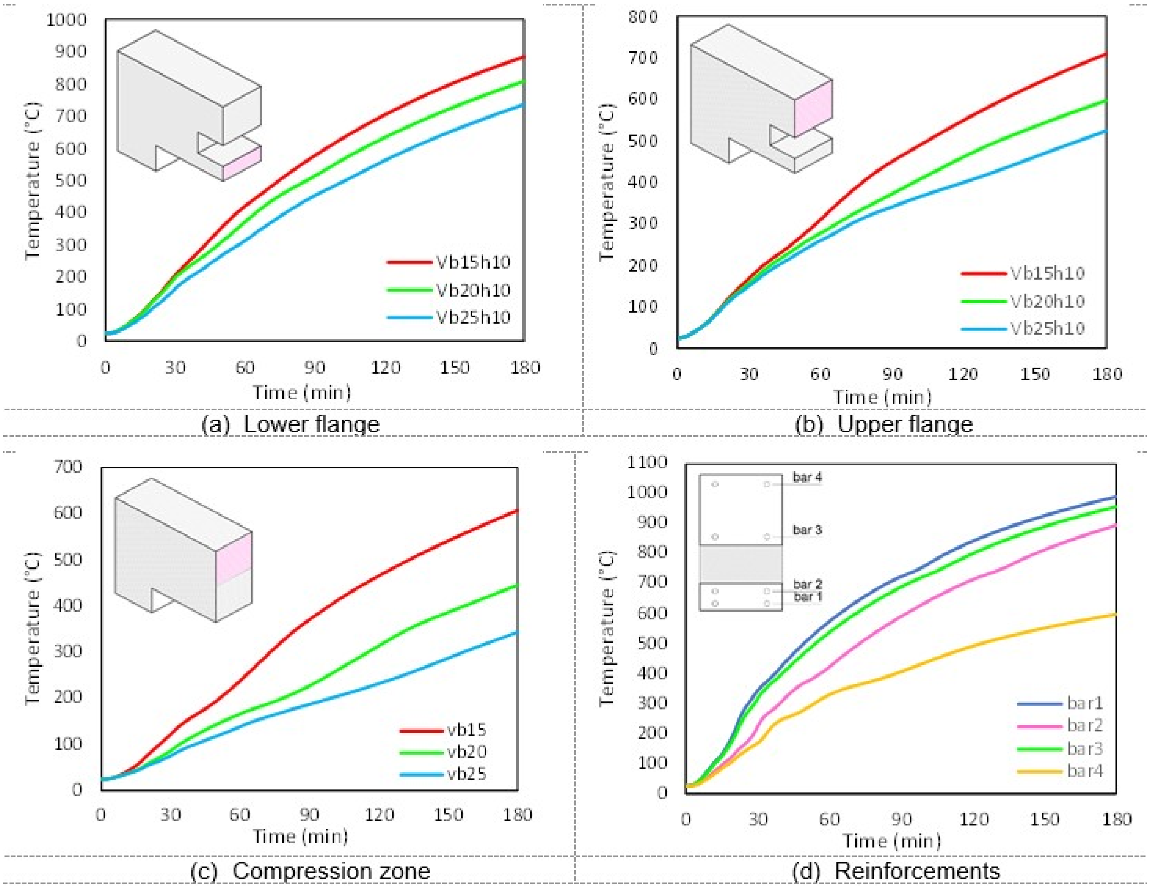

Figure 5 – Thermal field in (a) lower and (b) upper flange of the concrete (beam with opening), (c) in the compresses region of the concrete (beam without opening) and (d) in the reinforcements

Figure 5a shows beams with an opening of h=10 cm (see Figure 1 and Table 1), i.e., Vb15f10, Vb20f10 and Vb25f10. The size of the opening does not affect the cross-sectional area of the lower flange (see Figure 1b) and therefore its average temperature. On the other hand, Figure 5b shows the average temperatures of the upper flange, which change with the opening dimensions. For the other beams, the temperatures are in Table 4. The comparison between beam without and with opening is shown in Figure 6. Control points of Figure 4a and b were used. For the reinforcements in Figure 5d, the criterion shown in Figure 4c was used.

Table 4 – Average temperatures in the cross-section of beams with openings

Beam Name	Average temperature (°C)							
	Upper flange				Lower flange			
	Time (min)				Time (min)			
	30	60	90	120	30	60	90	120
Vb15h10	160	310	449	548				
Vb15h15	163	314	452	552	210	426	585	703
Vb15h20	175	323	462	562				
Vb20h10	155	278	374	467				
Vb20h15	156	279	377	469	200	374	517	636
Vb20h20	174	312	411	497				
Vb25h10	151	262	342	401				
Vb25h15	153	263	345	405	170	311	456	564
Vb25h20	154	264	347	410				

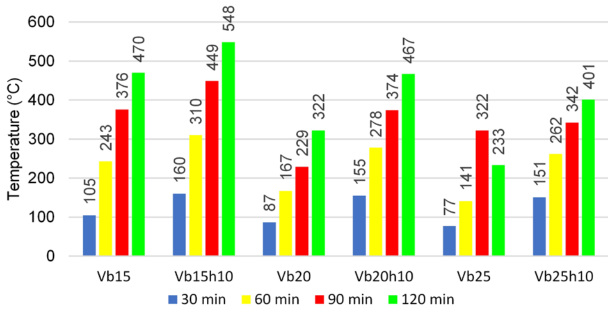

Figure 6 – Average temperature on the upper flange (beam with opening) and the compression zone (beam without opening)

The reduced cross-section of the lower flange and the heating by its surface justify the higher average temperature, as shown in Figure 5a and Table 4. This region is the most affected by temperatures, causing more severe damage to the mechanical parameters of the materials that constitute it. For every 5 cm increase in the breadth of the beam, their average temperatures decreased around 20, 55, 65 and 70 °C for, respectively, 30, 60, 90 and 120 min of exposure to high temperatures (ISO 834 heating curve).

Therefore, increasing the breadth of the beam decreases the average temperature of the lower flange. However, for design purposes, the magnitude of the temperature reduction contributes subtly to the maintenance of the mechanical properties of the materials at each analysis time.

In the upper flange, the opening dimension influences the concrete's thermal field, as shown in Figure 5b and Table 4. Increasing the opening reduces the total area of the upper flange cross-section, increasing its average temperature. The increase in the opening causes, in addition to the reduction of the load-bearing capacity of the beam (due to the reduction of its cross-section), promotes more accentuated damage to the mechanical properties of materials (steel and concrete) in a fire situation.

Comparing the temperature between the beam with (Figure 5b) and without opening (Figure 5c), it is noted that the average temperature is always higher in the first case. This comparison was shown in Figure 6. The largest temperature difference recorded was at 120 min, between Vb25 and Vb25h10, which was 178 °C. The smallest difference was at 30 min, noted between Vb15 and Vb15h10, which was 55 °C.

In the case of the beam with an opening, it is shown that the concrete above the neutral axis has a temperature that can be almost 200 °C higher about the beam without an opening.

Figure 5d shows that the critical region of the beam with an opening is the lower flange, where the reinforcements (bar 1 and bar 2) reached the limit temperature of 500 °C around 60 min. This is the critical temperature according to FIB Bulletin nº 46 [25], the temperature at which the mechanical strength of the steel is practically negligible. Failure of these reinforcements can trigger a structural collapse, which should be evaluated in future research.

Figure 7 and Figure 8 show, respectively, the thermal field of the RC beams with and without openings. The opening in the beam becomes a critical condition, providing a more aggressive temperature evolution along the cross-section.

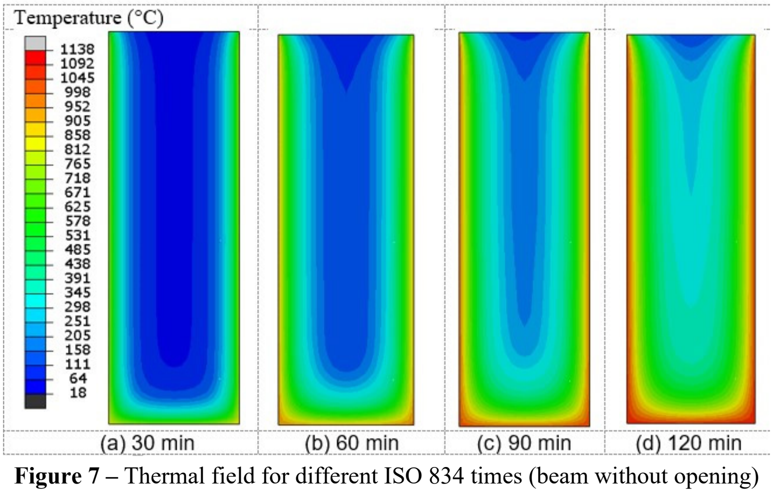

Figure 7 – Thermal field for different ISO 834 times (beam without opening)

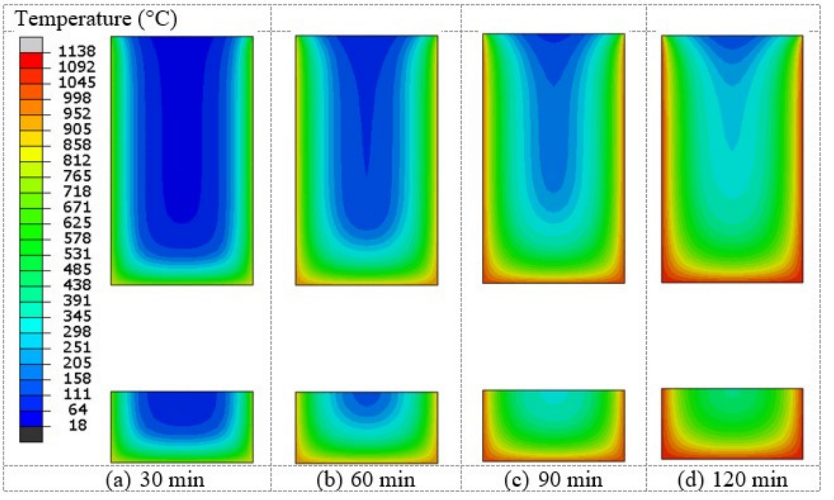

Figure 8 – Thermal field for different ISO 834 times (beam with opening)

Based on the reinforcement designed by NBR 6118 (section 3.1) and the thermal field already shown (section 3.2), the verification in fire according to NBR 15200 is carried out.

3.3 Fire design

The analysis in case of fire of the beams designed at normal temperature is shown.

a) Beams without openings

Based on the geometric characteristics of Vb15, Vb20 and Vb25 and applying the Tabular Method of NBR 15200 [14], it is concluded that the beams in question meet the FRR of, respectively, 60, 60 and 90 min if designed as simply supported at both ends, and 60, 90 and 120 min if fixed at both ends (structurally continuous). Each condition depends on the analytical design model, which this research will not analyze.

b) Beams with openings

Table 5 shows the required area of longitudinal reinforcement in the lower and upper flange for the 30, 60, 90 and 120 min of ISO 834 heating curve.

Table 5 – Required area of longitudinal reinforcement (beam with opening)

Viga	FRR (min)				FRR (min)			
	30	60	90	120	30	60	90	120
	$A_{st.fi}$ (cm^2)				$A_{sc,fi}$ (cm^2)			
Vb15h10	4,8	6,7	-	-	0,0	0,0	-	-
Vb15h15	5,1	6,8	-	-	0,0	0,0	-	-
Vb15h20	5,3	6,9	-	-	0,0	0,0	-	-
Vb20h10	4,5	6,5	14,8	-	0,0	0,0	0,0	-
Vb20h15	4,9	6,7	14,9	-	0,0	0,0	0,0	-
Vb20h20	4,9	6,9	15,1	-	0,0	0,0	0,0	-
Vb25h10	4,4	6,4	14,5	35,1	0,0	0,0	0,0	0,0
Vb25h15	4,9	6,8	15,0	35,7	0,0	0,0	0,0	0,0
Vb25h20	4,9	7,0	13,9	37,7	0,0	0,0	0,0	0,0

According to Table 5, in the case of the b=15 cm, the verification at 90 and 120 min cannot be done due to the excessive damage of the mechanical property of the concrete and steel in the lower flange, causing a mathematical inconsistency in the calculation. The same is valid for the beam with b=20 cm in the time of 120 min.

In the case of the beam without opening, the analysis made in Table 3 (show in section 3.1) has already indicates that the required steel reinforcement area on its lower face depends on the width of the beam, about 8.1 to 8.3 cm^2. Table 5 shows that the area of reinforcement required for the beam with openings in fire is always greater than 8.1 to 8.3 cm^2 after 90 min. In this case, the structural design in fire would prevail over the design at normal conditions (without fire). An addition of reinforcement should be made, except the beam with a b=15 cm, at 90 and 120 min; and b=20 cm, at 120 min; for the reasons mentioned in the previous paragraph. Although there is no mathematical inconsistency in the beam b=25 cm at 120 min, it is clear that the required reinforcement area is excessive, and complex to be carried out in structural design of beams with openings.

The upper flange is less mechanically damaged by fire and the existing concrete cross-section area is sufficient to balance of internal forces. It is not necessary to add reinforcements to the upper flange. The lower flange is the most fire damaged.

Table 5 (if analyzed together with Table 3) show that the FRR of the beam with the openings is 60 min, justified by the excessive heating of the lower flange. It is possible to increase the FRR with the increase of the reinforcement area, as shown in Table 5. However, the required reinforcement area is impractical.

3.4 Final remarks

Table 6 shows the comparison between RC beams without and with openings. The first (i.e., without opening) was verified by the tabular method of NBR 15200, admitting two cases: simply supported at both ends (SSBE) and fixed at both ends (FBE). The second (i.e.,with opening) was determined by applying the Simplified Method.

The RC beam with an opening shows a FRR lower than the beams without openings, especially those with greater widths. The tabular method proved unsafe to be applied to RC beams with openings, which presented the FRR twice as long as it had.

In the simply supported beams without opening with b = 25 cm, the FRR was 30 min longer than the equivalent beam (b = 25 cm) with an opening. On the other hand, in case of fixed beams with b = 20 cm and b = 25 cm, their FRR was 30 and 60 min higher than the equivalent beams with openings, respectively.

Table 6 – FRR of the RC beams used in the research

Without opening			With opening	
Beam number	**Tabular (SSBE)***	**Tabular (FBE)****	**Beam number**	**Simplified**
Vb15	60	60	Vb15h10	60
			Vb15h15	60
			Vb15h20	60
Vb20	60	90	Vb20h10	60
			Vb20h15	60
			Vb20h20	60
Vb25	90	120	Vb25h10	60
			Vb25h15	60
			Vb25h20	60

*SSBE: simply supported at both ends. **FBE: fixed at both ends

3.5 Future work

Others numerical and experimental researches should be done to increase the range of results. FE thermomechanical models should be made to better understand the fire performance of RC beams, especially the stress distribution along the opening. Analysis with more realistic fire curves, as proposed by Rein et al. [26], can produce new answers and conclusions and need to be developed.

4. CONCLUSIONS

This paper evaluated the influence of opening in RC beams in case of fire. The research was motivated by the lack of NBR 15200 prescriptions for these cases. The following conclusions of this research may be outlined:

- Preserving the same beam height, the increase in the opening dimension causes an increase in the thermal field in the beam cross-section;
  - Increasing the size of a beam opening causes, in addition to the reduction of its load-bearing capacity caused by the opening, greater mechanical damage to materials due to increased thermal field developed in the cross-section in fire;
  - In case of fire, beams with openings are more thermally affected than beams without openings, being more susceptible to collapse;
  - The average temperature of the beam cross-section with an opening can be up to 178 °C higher than that of the beam without opening;
  - The NBR 15200 tabular method is unsafe if applied to RC beams with openings, as it showed a longer FRR than they actually have. This difference was up to 60 min;
  - The beams with openings showed a FRR up to 50% lower than the equivalent beams without openings;
  - The NBR 15200 tabular method cannot be applied to RC beams with openings;
  - It is recommended that RC beams with openings be fire designed by the simplified, advanced or experimental method of NBR 15200;
  - It is suggested that NBR 15200 shows requirements for the evaluation of RC beams with openings in case of fire;
  - The use of intumescent collars and thermal protection of passing pipes can mitigate the damage and the thermal field of these beams. However, their effectiveness must be evaluated experimentally, through laboratory tests within the scope of NBR 5628 [27] and equivalent standards;
  - As a suggestion for future research, it is recommended to experimentally evaluate whether the failure of beams with openings – which occurs by shear stresses at normal temperature – can also occur in case of fire. A set of tests is recommended to evaluate different positions of openings in RC beams exposed to high temperatures.

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NOTATION:

$A_{s,min}$ Cross-sectional area (minimum) of longitudinal reinforcement (beam without opening)
A_s Cross-sectional area of longitudinal reinforcement (beam without opening)
$A_{st,min}$ Cross-sectional area (minimum) of longitudinal reinforcement in tension flange (opening region)
A_{st} Cross-sectional area of longitudinal reinforcement in tension flange (opening region)
$A_{st.fi}$ Cross-sectional area of longitudinal reinforcement in tension flange (opening region) in case of fire
$A_{sc,min}$ Cross-sectional area (minimum) of longitudinal reinforcement in the compression flange (opening region)
A_{sc} Cross-sectional area of longitudinal reinforcement in compression flange (opening region)
$A_{sc,fi}$ Cross-sectional area of longitudinal reinforcement in compression flange (opening region) in case of fire
$A_{sw,min}$ Cross-sectional area (minimum) of transverse reinforcement (beam without opening)
A_{sw} Cross-sectional area of transverse reinforcement (beam without opening)
$A_{swt,min}$ Cross-sectional area (minimum) of transverse reinforcement in tension flange (opening region)
A_{swt} Cross-sectional area of transverse reinforcement in tension flange (opening region)
$A_{swc,min}$ Cross-sectional area (minimum) of transverse reinforcement in compression flange (opening region)
A_{swc} Cross-sectional area of transverse reinforcement in the compression flange (opening region)
A_{sws} Cross-sectional area of suspension transverse reinforcement (opening region)
A_s/A_c Reinforcement ratio (area of steel reinforcement in the beam cross-section)
CAA Class of environmental aggression of NBR 6118 standard
$L_{opening}$ Length of the opening in the beam
N_c Compression force acting on the compressed (upper) flange of the opening
N_t Tensile force acting on the tensioned (bottom) flange of the opening
M_{sd} Bending moment acting on the beam in the opening region
M_c Bending moment acting on the compressed (upper) flange of the opening
M_t Bending moment acting on the tensioned (bottom) flange of the opening

V_{Sd}	Shear force action on the beam in the opening region
V_c	Shear force action on the compressed (upper) flange of the opening
V_t	Shear force action on the tensioned (bottom) flange of the opening
x	Neutral axis depth
x/d	Beam ductility according NBR 6118 requirements
z	distance between axes of the compressed and tensioned flange of the opening
ε_s	Theoretical steel reinforcement elongation
ε_c	Theoretical shortening of concrete
γ_c	Partial factor for concrete
γ_s	Partial factor for steel reinforcement

Annex A. Fea model: thermal properties of concrete and steel reinforcement.

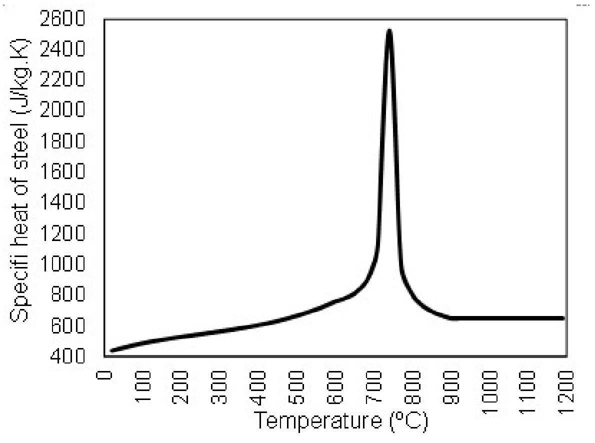

Figure A1 – Specific heat of steel

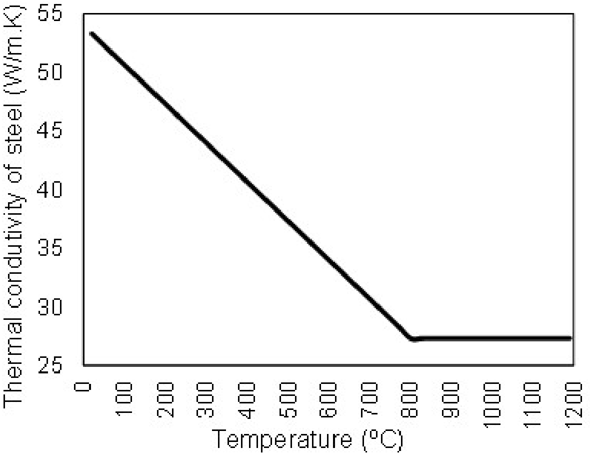

Figure A2 – Thermal conductivity of steel

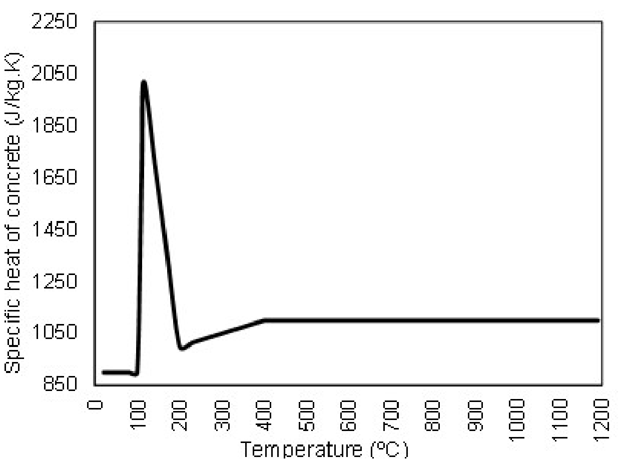

Figure A3 – Specific heat of concrete

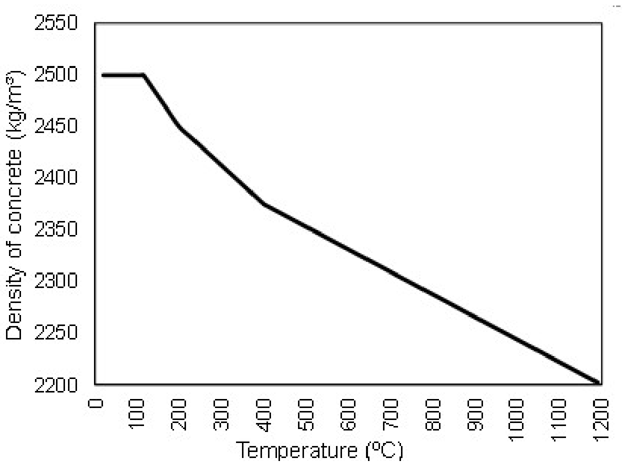

Figure A4 – Density of concrete

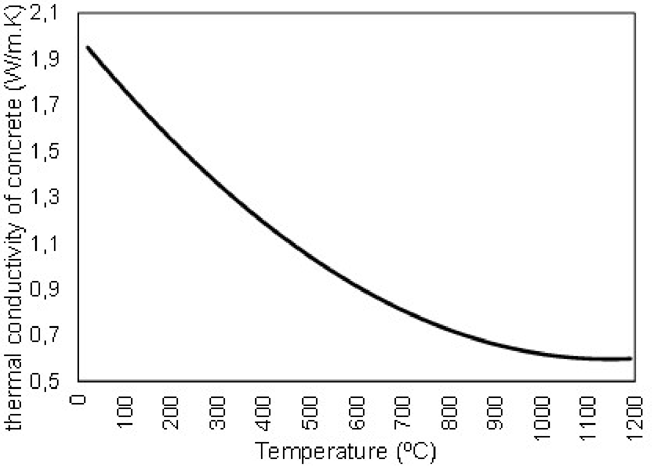

Figure A5 – Thermal conductivity of concrete