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Fire design of reinforced concrete columns. An alternative to the tabular method presented by the Brazilian standard NBR 15200:2004

Dimensionamento de pilares de concreto armado em situação de incêndio. Uma alternativa ao método tabular da nbr 15200:2004

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Abstract

The Brazilian standard ABNT NBR 15200:2004 - Fire design of concrete structures gives a tabular method to the fire design of concrete columns, which associates the load level and the minimal dimensions of the cross-section and the place of the reinforcement centroid to the required time of fire resistance. This paper presents the theory of those tables and a study as a contribution to a future review of NBR 15200. A structural design more optimized, more correct and economic than the tabular method given by the Brazilian standard can be attained using alternative methods.

Keywords: fire, columns, concrete, standartization

Resumo

A ABNT NBR 15200:2004 “Projeto de estruturas de concreto em situação de incêndio” apresenta um método tabular de dimensionamento de pilares em situação de incêndio. O método associa o nível do carregamento e as dimensões mínimas da seção transversal e da posição da armadura na seção, ao tempo requerido de resistência ao fogo (TRRF). Neste trabalho, é apresentada a base teórica que permitiu a construção dessas tabelas e um estudo para contribuir com a futura revisão da NBR 15200. Um dimensionamento estrutural mais otimizado, mais preciso e econômico, se comparado ao método tabular da norma brasileira, pode ser obtido com o uso de métodos alternativos.

Palavras-chave: incêndio, pilares, concreto, normatização

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1. Introduction

The scope of this work is contribute to Brazilian standardization and technical community, disclosing simplified processes for the design of concrete columns in fire situations based on Eurocode 2 [1]. These methods can be used as more precise and economical alternatives to the tabular method presented by ABNT NBR 15200:2004 [2]. Based on European procedures, an expression and a simplified table are derived and it is being proposed to insert them in a revision of NBR 15200. The Brazilian standard is recent and is still being evaluated and understood by the technical community. This work aims to bring an advance in relation to standard's approach.

2. Brazilian standard ABNT NBR 15200:2004's approach

The ABNT NBR 15200:2004 [2] Brazilian standard fixes the design criteria for concrete structures in fire situations. In some states (Sao Paulo [3], Minas Gerais [4] and Goias [5], for instance), there is a specific legislation to be followed and this standard is cited as a reference. The general purposes of verifying structures in fire situations are: lowering the risk to human lives; to limit neighborhood risks and to limit the risks of the property that is exposed to fire. As long as plastic effects, ruins and still local collapses are acceptable, the structure can only be reused, after a fire, if it is inspected, have its remaining capacity checked and its recovering designed and executed. In normal conditions, structures are designed in room temperatures and, depending on its characteristics and use, may be verified for fire situation. This verification can only be done by ultimate limit state, for the corresponding accidental combination.

The action corresponding to fire can be represented by a time interval of exposition to a standardized temperature rising known as standard-fire (ABNT NBR 5628:2001 [6], ISO 834 [7]). ABNT NBR 14432:2000 [8] defines this time interval called required time for fire resistance (RTFR) from the characteristics of the construction and its use. The heat transferred to the structure within this time interval (RTFR) generates in each structural element a certain temperature distribution, which is a function of its shape and exposition to the fire. This process causes the decreasing of material's strength, besides indirect action effects due to axial elongations or thermal gradients. ABNT NBR 15200:2004 [2] admits that efforts generated by heating can, in general, be neglected, since stiffness of the structural elements decreases and the capacity of plastic adaptation increases with temperature.

So, the usual verification of structure in fire situation is reduced by demonstrating the condition of eq. 1.

$$S_{d,fi} = \gamma_{g,fi} F_{gk} + \gamma_{q,fi} \sum_{2}^{n} \psi_{2j} F_{qjk} \leq R_{d,fi} \left[f_{ck}(\theta),\ f_{yk}(\theta) \right] \tag{1}$$

where:

$S_{d,fi}$ – designed value of effect of actions in fire situation

$R_{d,fi}$ – designed value of the resistance in fire situation

$\gamma_{g,fi}$, $\gamma_{q,fi}$ – partial factors for permanent and variable action in fire

ψ_{2j} – factor for quasi-permanent value of a variable action j

F_{gk}, F_{qk} – characteristic values of permanent e variable actions, respectively

f_{ck} (θ), f_{yk} (θ) – reduced characteristic values of concrete and steel strength, respectively, at temperature θ.

For simplicity, NBR 15200 allows that the designed effect of actions in fire situations ($S_{d,fi}$) is 70% of the designed effect of actions at room temperature (eq. 2), whichever the considered actions combination. Eq. 2 neglects any action generated by imposed strains in fire situation.

For the verification of eq. 1, NBR 15200 allows tabular methods, simplified or general design methods and tests.

$$S_{d,fi} = 0{,}70\ S_d \tag{2}$$

In the case of columns, the tabular method explicit shown by NBR 15200 fixes minimum dimensions for columns in fire situation, according to table 1.

where:

$b_{mín}$ is column's minimum dimension

$c_{1mín}$ is the minimum distance between the axis of the longitudinal reinforcement and the nearest surface of concrete exposed to fire

$$\mu_{fi} = \frac{N_{Sd,fi}}{N_{Rd}}$$

$N_{Sd,fi}$ is the design value of the compression force in fire situation, calculated by means of the combination of accidental actions

Table 1 – ABNT NBR 15200:2004 recommendations

TRRF (min)	Combinações de bmin /c1mín (mm/mm)			
	Mais de uma face exposta			Uma face exposta
	μ_{fi} = 0,2	μ_{fi} = 0,5	μ_{fi} = 0,7	μ_{fi} = 0,7
30	190/25	190/25	190/30	140/25
60	190/25	190/35	250/45	140/25
90	190/30	300/45	450/40	155/25
120	250/40	350/45	450/50	175/35

N_{Rd} is the design value of the compression force resistance, considering the eccentricities due to non-linearity (second order) in normal situation.

RTFR is the required time for fire resistance according to ABNT NBR 14432:2000 [8]

NBR 15200 was based in Eurocode 2 [1]

3. EUROCODE 2's approach

NBR 15200 allows the use of more precise methods than that used in the construction of Table 1.

Eurocode 2 [1] presents two simplified methods for concrete column fire design. The method A, developed by Prof. Jean-Marc Franssen of the University of Liege and the method B, developed by Eng. Jose Maria Izquierdo (Information obtained in a meeting with Eng. Izquierdo in 2006, in Madrid.).

The method A is analytic and allows to determine the time of fire resistance (TFR) in function of several parameters, being b_{min} and c_1 among them. By limiting the values of some intervenient parameters in method A, it is possible to build a table of minimum dimensions. This table is presented in Eurocode 2 [1] and it is similar to Table 1, extracted from ABNT NBR 15200:2004 [2].

The method B is tabular and based on the same procedures for column design at room temperature, with the reductions of strenght due to high temperature.

Both methods consider, by hypothesis, that columns have fixed ends in fire situation. It may be remembered that, according to ABNT NBR 8681:2003 [9], wind effects can be overlooked in the presence of thermal action. Thus, these methods can be used in cases where displacements from non-linearities (second order) due to out-of-plumbness, even in normal structures with γ_z a little higher than 1,1, are not relevant. The author suggests that, in any case, $\gamma_z \leq 1,3$ at room temperature.

3.1 The method A

The method A supplied by Eurocode 2 [1] for the design of concrete columns in fire situation was based on the propositions of Franssen [10], presented in SiF 2000 - First International Workshop Structures in Fire, which took place in Copenhague, 2000.

This method resulted from an integrated experimental program, involving numerical and physical experiments, performed by Liège and Gent (Belgium), Braunschweig (Germany) Universities and Ottawa Fire Research Station laboratory (Canada).

As a whole, 82 columns were tested, taking by reference the standard dimensions from the tabular method presented in the 1995 version of Eurocode 2 [9]. The numerical tests were performed with the help of SAFIR computer software.

The tests showed that the dimensions standardized by Eurocode 2 – 1995 [11] lead to unsafe results, because the diameter and number of bars of the reinforcement and the slenderness affect the column's resistance in fire situation.

Besides, 1995's tabular method was not of immediate use as it was supposed to be. It was necessary to calculate the relation

$$\mu_{fi} = \frac{N_{Sd,fi}}{N_{Rd,fi}(0)}$$

the fire resistance when fire is imminent (t = 0). So, an analytic calculation of fire resistance was needed to be used in a method that should be of immediate application. Moreover, when the relation "μ_{fi}" presented results that were different from that tabulated, the strenght should be determined by means of a double linear interpolation, among the geometrical values of the columns' cross section that could provide the required resitance, for it was necessary to determine the resistant fire moment resistanced.

The columns which reinforcement diameters were around 25 mm presented a performance that was quite smaller then the expected, when compared to the columns with diameters around 16 mm. The reduction of fire resistance was due to the incidence of spalling along the edges of the quite bigger section when the column contained high diameter bars (Franssen [10]; Aldea et al. (1997), apud Costa [12]; Franssen (2001) apud Costa [13].

The tests also confirmed the influence of the loading level, the slenderness and the cross section dimensions over the column's fire resistance (Franssen [10]).

Based on experimental and numerical results, a new model of calculation was stablished taking into account the loading level, the mechanical ratio of reinforcement, the distance c_1, the buckling lenght, cross section dimensions and number of bars along the section. The column's fire resistance time can be evaluated by means of eq. 3, which was included to Eurocode 2, in the versions later than 1995.

$$TRF = 120\left(\frac{R_\mu + R_a + R_L + R_b + R_n}{120}\right)^{1,8} \quad (3)$$

Where:

$$R_\mu = 83\left[1 - \mu_{fi}\left(\frac{1+\omega}{\dfrac{0,85}{\alpha_{cc}} + \omega}\right)\right]$$

$R_a = 1,60\,(c_1 - 30)$, c_1 in mm

$R_\ell = 9,60\,(5 - \ell_{0,fi})$

$R_b = 0,36\,b'$

$R_n = 0$ for n = 4, where n is the number of longitudinal bars

$R_n = 12$ for n > 4

Where:

$$\omega = \frac{A_s f_{yd}}{A_c f_{cd}}$$ the mechanical ratio

$$\mu_{fi} = \frac{N_{Sd,fi}}{N_{Rd}}$$

$N_{Sd,fi}$ is the design value of the axial force in fire situation

N_{Rd} is the design value of the compression resistance at room temperarure according to ABNT NBR 6118:2004 [14], with γ_m for room temperature including the effects of geometrical non-linearities (2nd order) and an initial eccentricity equal to the eccentricity of $N_{Sd,fi}$.

$c_{1mín}$ is the shortest distance between the centroid of the longitudinal reinforcement and the nearest surface of concrete exposed to fire

$\ell_{0,fi}$ is the effective lenght (buckling) of the column in fire situation in meters

$b' = 2 A_c/(b+h)$

A_c is the area of the column's cross section, in square milimeters

b is the shortest dimension of the column's cross section in milimeters

h is the longest dimension of the column's cross section in milimeters

Eq. 3 is conditioned to the following limits:

- $A_s/A_c \le 0{,}04$
- $25\ \text{mm} \le c_1 \le 80\ \text{mm}$
- $200\ \text{mm} \le b' \le 450\ \text{mm}$
- $h \le 1{,}5\ b$
- $e \le 0{,}15\ b$ (1st order eccentricity)
- $\ell_{0,fi} \le 6\ \text{m}$

Where

A_s is the total area of the reinforcement

"e" is the 1st order eccentricity of the compression force

3.1.1 On the determination of R_μ

From the general equation (4) and the particular equation (5), for $\alpha_{cc} = 0{,}85$, it is possible to derive eq. 6.

$$N_{Rd\alpha} = f_{yd}\, A_s + \alpha_{cc}\, f_{cd}\, A_c \tag{4}$$

$$N_{Rd} = f_{yd}\, A_s + 0{,}85\, f_{cd}\, A_c \tag{5}$$

$$\frac{N_{Rd\alpha}}{N_{Rd}} = \frac{1+\omega}{\dfrac{0{,}85}{\alpha_{cc}} + \omega} \tag{6}$$

Admitting that $\alpha_{cc} = 0{,}85$ (deleterious effect of the long duration loads, better known as Rüsch effect, concrete maturation and shape of the proof test body), eq. 6 is simplified and R_μ can be calculated as $R_\mu = 83\ (1 - \mu_{fi})$. It is pointed out that Table 1, extracted from NBR 15200, was constructed from Eurocode 2, which considered $\alpha_{cc} = 1{,}0$, hence in the next revision of the Brazilian standard the tabulated values may be adapted to Brazilian reality, i.e., $\alpha_{cc} = 0{,}85$.

The NBR 15200 suggests that $N_{Sd,fi}$ can be evaluated by $0{,}70 \times N_{Sd}$. By this way, μ_{fi} would be equal to $0{,}70 \times N_{Sd}/N_{Rd}$. Considering, for safety, $N_{Sd} = N_{Rd}$, one finds that $\mu_{fi} = 0{,}7$ and, finally, eq. 7.

$$R_\mu = 24{,}9 \tag{7}$$

3.1.2 On the determination of R_a

c_1 is the shortest distance between the longitudinal reinforcement axis and the concrete surface exposed to fire. When reinforcement bars are disposed in layers, c_1 is the mean distance to the concrete surface (c_{1m}). The value of c_{1m} must always be the smallest value between the following:

$$c_{1m} \le \begin{cases} \dfrac{\sum c_{1xi} A_{si}}{\sum A_{si}} \\[2ex] \dfrac{\sum c_{1yi} A_{si}}{\sum A_{si}} \end{cases}$$

Where c_{1xi} and c_{1yi} are the distances from bar i, with area A_{si}, to the closest heated surface

In the example of figure 1, supposing fire at the four faces, we have:

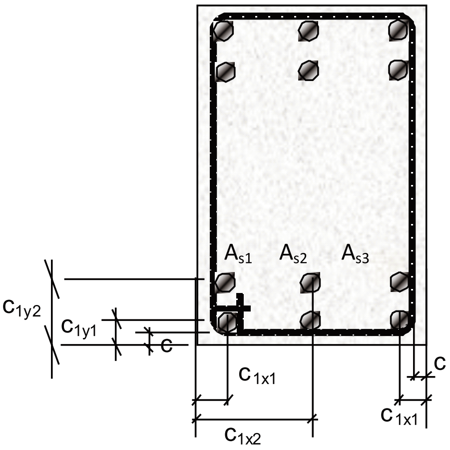
$$c_{1xm} = \frac{c_{1x1} A_{s1} + c_{1x2} A_{s2} + c_{1x1} A_{s3}}{A_{s1} + A_{s2} + A_{s3}}$$

$$\text{and} \qquad c_{1ym} = \frac{(c_{1y1} + c_{1y2})(A_{s1} + A_{s2} + A_{s3})}{2\,(A_{s1} + A_{s2} + A_{s3})}$$

If all bars diameters are equal, it results:

$$c_{1xm} = \frac{2\ c_{1x1} + c_{1x2}}{3} \quad \text{and} \quad c_{1ym} = \frac{c_{1y1} + c_{1y2}}{2}$$

Figure 1 – Distance between the centroid of reinforcement and the concrete surface exposed to fire



3.1.3 On the determination of R_ℓ

The effetive lenght of one column in fire situation $\ell_{0,fi}$ can be supposed to be the effective lenght (buckling) at room temperature ℓ_0 for all cases. For bracing structures of buildings which floors are compartmented, where RTFR is higher than 30 min, the effective lenght ℓ_0 can be supposed to be 0,5 ℓ for intermediate floors and 0,7 ℓ for the top floor, where ℓ is the column's actual lenght (center to center) as figure 2 (Eurocode 2 [1]).

Therefore, for the columns of multiple story buildings, where it is supposed that the compartment under fire is fixed to the upper and lower cold floors and that the highest floor column has a structural reserve that is greater then that of the other floors, it can be supposed that $\ell_{0,fi} = \ell/2$ for all floors and, hence, in simplified form, R_ℓ can be calculated using eq. 8.

$$R_\ell = 48 - 4,8\ \ell \tag{8}$$

Where ℓ is the actual lenght of the column, in meters.

Despite the fact that the perfect two ends fixing of the columns in the cold floors have been objected by international researchers (Wang [15]; Gomes et al. [16]; Rodrigues et al. [17]), it was decided to keep this simplification in this work having in mind that Eurocode, the basis of the main Brazilian structure standards, still keeps it.

3.1.4 On the determination of R_b

R_b may be rewritten as: 0,36 A_c/u, where u is the perimeter of column's cross section in milimeters. Following the limitations of use for eq. 3, according to Eurocode 2 [1], the expression for the calculation of R_b must obey, simultaneously, the limits of inequalities 9a and 9b:

$$50\ \text{mm} \le A_c/u \le 112,5\ \text{mm} \tag{9a}$$

$$h \le 1,5\ b \tag{9b}$$

Inequality 9a can be rewritten in the shape of inequality 10.

$$100\ (b + h) \le b\ h \le 225\ (b + h) \tag{10}$$

Inequality 9b can be rewritten in the shape of inequality 11.

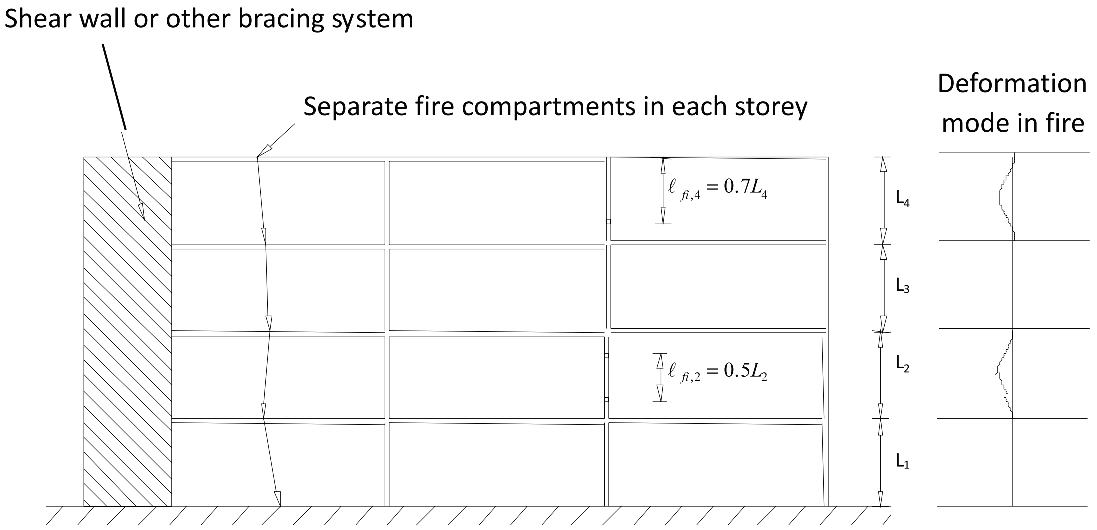
$$R_b \le 0,108\ b \tag{11}$$

Separating inequality 10, we have:

- For 100 ≤ b ≤ 200,

$h \ge \dfrac{100b}{b-100}$ and $h \ge \dfrac{225\,b}{b-225}$ the last inequality is automatically respected, since h must be positive. So, it is enough to satisfy the

Figure 2 – Columns of compartmented floors fixed in the cold floors



first inequality, which can be rewritten in the form: $R_b \geq 18$ mm

– For 200 < b ≤ 225,

$h \geq \dfrac{100b}{b-100}$ and $h \geq \dfrac{225\,b}{b-225}$ the first inequality is always respected in view that, by definition, h is higher than or equal to b and the second inequality is automatically respected since h must be positive.

– For 225 < b ≤ 375,

$\dfrac{100b}{b-100} \leq h \leq \dfrac{225b}{b-225}$. This interval is always verified, in view that b ≤ h ≤ 1,5b.

– For b > 375,

$\dfrac{100b}{b-100} \leq h \leq \dfrac{225b}{b-225}$ the lowest limit is always verified, in view that h is, by definition, higher than or equal to b. So, it is enough to verify the highest limit that can be rewritten in the form: $R_b \leq 40{,}5$ mm.
This analysis can be performed graphically (fig. 3) in which the shaded area represents the limit hxb for the determination of R_b.
Therefore, a simple way to present the calculation of R_b, and its limitations, would be in the form shown by ineq. 12.
For b ≥ 200 mm, the lowest limit of eq. 12 will be always respected.
For h = b = 190 mm, an usual value in Brazil, the lowest limit will result 17,1 mm. The author believes that this small variation of the lowest limit does not impair the method's use.

$$18\ \text{mm} \leq R_b = 0{,}36\ A_c/u \leq 40{,}5\ \text{mm or } 0{,}11\ b\ \text{(the smallest)} \qquad (12)$$

3.2 *The method B*

From the direct method for design concrete columns, Izquierdo (see beginning of item no. 3) constructed tables 2 to 10, that are inserted in Eurocode 2 (2004). These tables indicate the minimum dimensions and distance (c_1) from the bars' axis to the nearest surface for concrete columns of rectangular or circular sections with more than one face exposed to fire.
For columns where $A_s \geq 0{,}02\,A_c$, an uniform reinforcement distribution is necessary along the section sides for RTFR ≥ 90 min
In table 2 and 10, the following simbology is used:

$\omega = \dfrac{A_s\,f_{yd}}{A_c\,f_{cd}}$ – reinforcement's mechanical ratio

$n = \dfrac{N_{0Sd}}{A_c \cdot f_{cd} + A_s \cdot f_{yd}}$ – column's loading level at room temperature

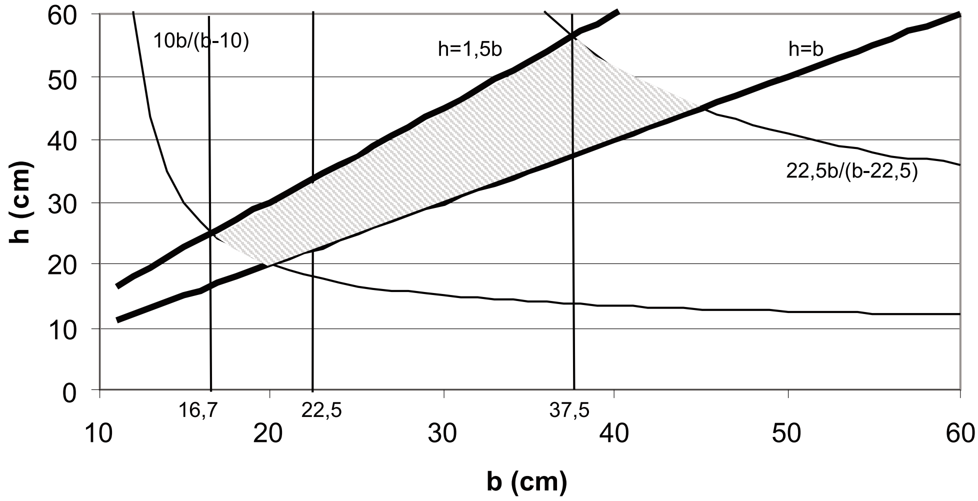
$e = \dfrac{M_{0Sd}}{N_{0Sd}}$ – 1st order eccentricity at room temperature

A_s is the total area of reinforcement' bars sections;
A_c is the area of concrete section;
f_{yd} is the design value of steel's strength at room temperature

$f_{cd} = 0{,}85\,\dfrac{f_{ck}}{\gamma_c}$ is the design value of concrete's strenght for compression at room temperature

N_{0Sd} is the design value of 1st order compression resistance at room tempertaure
M_{0Sd} is the design value of 1st order bending moment at room temperature

Figure 3 – Limits for determination of R_b



$\lambda_{fi} = \frac{\ell_{0,fi}}{r}$ is the slenderness in fire situation (for rectangular sections $r = \frac{h}{\sqrt{12}}$)

r = $\sqrt{\frac{I}{A}}$ is the radius of gyration

Table 2 – ω = 0,1; e = 0,025 b ≤ 10 mm

TRF (min)	λ	b_{min} /c_1			
		n = 0,15	n = 0,3	n = 0,5	n = 0,7
30	30	150/25	150/25	150/25	150/25
	40	150/25	150/25	150/25	150/25
	50	150/25	150/25	150/25	200/25
60	30	150/25	150/25	200/25	200/30:250/25
	40	150/25	150/25	200/25	250/25
	50	150/25	200/25	250/25	300/25
90	30	150/25	200/25	200/50:250/25	250/30:300/25
	40	150/35:200/25	200/30:250/25	250/25	300/25
	50	200/25	250/25	300/25	350/50:400/25
120	30	200/25	250/25	250/25	300/45:350/25
	40	250/25	250/25	250/25	400/25
	50	250/25	300/25	350/50:400/25	450/50:500/25

Table 3 – ω = 0,1; e = 0,25 b ≥ 100 mm

TRF (min)	λ	b_{min} /c_1			
		n = 0,15	n = 0,3	n = 0,5	n = 0,7
30	30	150/25	150/25	200/30:250/25	300/30:350/25
	40	150/25	150/30:200/25	300/25	500/40:550/25
	50	150/25	200/40:250/25	350/40:500/25	550/25
60	30	150/30:200/25	200/40:300/25	300/40:500/25	500/25
	40	200/30:250/25	300/35:350/25	450/50:550/25	550/40:600/25
	50	200/40:300/25	350/45:550/25	550/30:600/30	600/55
90	30	200/40:250/25	300/40:400/25	500/50:550/25	550/40:600/25
	40	250/40:350/25	350/50:550/25	550/35:600/25	600/50
	50	300/40:500/25	500/60:550/25	600/40	(1)
120	30	250/50:350/25	400/50:550/25	550/25	550/60:600/45
	40	300/50:500/25	500/50:550/25	550/50:600/25	(1)
	50	400/50:550/25	550/50:600/25	600/60	(1)

(1) Width ≥ 600 mm. Specific analysis is required

Table 4 – $\omega = 0,1$; $e = 0,5\,b \leq 200$ mm

TRF (min)	λ	b_{min}/c_1			
		n = 0,15	n = 0,3	n = 0,5	n = 0,7
30	30	150/25	400/40:550/25	500/25	(1)
	40	200/25	550/25	550/35:600/30	(1)
	50	250/30:300/25	550/30:600/25	(1)	(1)
60	30	300/35:500/25	500/50:550/25	550/50:600/40	(1)
	40	350/40:550/25	550/40:600/30	(1)	(1)
	50	450/50:550/25	550/50:600/40	(1)	(1)
90	30	350/50:550/25	550/45:600/40	600/80	(1)
	40	500/60:600/30	550/60:600/50	(1)	(1)
	50	550/40	600/80	(1)	(1)
120	30	550/40:600/30	550/50	(1)	(1)
	40	550/50:600/45	600/70	(1)	(1)
	50	550/55:600/50	(1)	(1)	(1)

(1) Width ≥ 600 mm. Specific analysis is required

Table 5 – $\omega = 0,5$; $e = 0,025\,b \geq 10$ mm

TRF (min)	λ	b_{min}/c_1			
		n = 0,15	n = 0,3	n = 0,5	n = 0,7
30	30	150/25	150/25	150/25	150/25
	40	150/25	150/25	150/25	150/25
	50	150/25	150/25	150/25	200/25
60	30	150/25	150/25	150/30:200/25	200/35:250/25
	40	150/25	150/25	200/25	250/30:300/25
	50	150/25	150/35:200/25	200/40:250/25	250/40:350/25
90	30	150/25	150/40:200/25	200/40:250/25	250/40:300/25
	40	150/25	200/35:250/25	250/30:300/25	300/40:400/25
	50	150/40:200/25	200/45:250/25	250/45:350/25	350/45:550/25
120	30	150/35:200/25	200/40:250/25	250/45:300/25	350/45:500/25
	40	200/25	250/25	300/45:350/25	400/50:550/25
	50	200/40:250/25	250/45:300/25	350/45:450/25	450/50:600/25

Table 6 – $\omega = 0,5$; $e = 0,25\,b < 100$ mm

TRF (min)	λ	b_{min}/c_1			
		n = 0,15	n = 0,3	n = 0,5	n = 0,7
30	30	150/25	150/25	150/25	200/30:250/25
	40	150/25	150/25	150/25	300/45:350/25
	50	150/25	150/25	200/30:250/25	350/40:450/25
60	30	150/25	150/35:200/25	250/35:350/25	350/40:550/25
	40	150/25	200/30:300/25	300/35:500/25	450/50:600/30
	50	150/30:200/25	200/40:350/25	300/45:550/25	500/50:600/35
90	30	150/35:200/25	200/45:300/25	300/45:550/25	550/50:600/40
	40	200/35:250/25	250/45:500/25	350/50:600/25	550/50:600/45
	50	200/40:300/25	300/45:550/25	550/50:600/35	600/55
120	30	200/45:300/25	300/45:550/25	450/50:600/25	550/60:600/50
	40	200/50:350/25	350/50:550/25	500/50:600/40	600/55
	50	250/45:450/25	450/50:600/25	550/55:550/45	600/80

Table 7 – $\omega = 0,5$; $e = 0,5\,b \leq 200$ mm

TRF (min)	λ	b_{min}/c_1			
		n = 0,15	n = 0,3	n = 0,5	n = 0,7
30	30	150/25	150/25	250/35:300/25	500/40:500/25
	40	150/25	150/30:200/25	300/35:450/25	550/30
	50	150/25	200/30:250/25	400/40:500/25	550/50:600/40
60	30	150/30:200/25	200/40:450/25	450/50:550/30	550/50:600/40
	40	150/35:250/25	250/40:500/25	500/40:550/35	600/60
	50	200/35:300/25	30/45:550/25	500/55:550/40	(1)
90	30	250/40:450/25	300/50:500/25	500/55:600/40	600/80
	40	200/50:500/25	350/50:550/35	550/60:600/50	(1)
	50	250/45:550/25	500/45:550/40	600/60	(1)
120	30	250/50:550/25	500/50:550/40	550/50	(1)
	40	300/50:600/25	500/55:550/45	550/60:600/55	(1)
	50	400/50:550/35	500/60:600/45	600/80	(1)

(1) Width ≥ 600 mm. Specific analysis is required

Table 8 – $\omega = 1{,}0$; $e = 0{,}025\,b \geq 10$ mm

TRF (min)	λ	b_{min}/c_1			
		n = 0,15	n = 0,3	n = 0,5	n = 0,7
30	30	150/25	150/25	150/25	150/25
	40	150/25	150/25	150/25	150/25
	50	150/25	150/25	150/25	150/30:200/25
60	30	150/25	150/25	150/25	200/40:300/25
	40	150/25	150/25	200/30:250/25	250/35:350/25
	50	150/25	150/30:200/25	200/40:250/25	250/40:350/25
90	30	150/25	200/25	200/40:250/25	250/45:600/25
	40	150/25	200/35:250/25	250/35:350/25	300/45:600/30
	50	150/35:200/25	200/40:250/25	50/45:400/25	350/45:600/35
120	30	150/40:200/25	200/45:250/25	250/40:400/25	400/40:600/25
	40	200/30:250/25	250/25	300/45:400/25	400/50:600/30
	50	200/40:250/25	250/35:300/25	350/40:550/25	550/45:600/40

(1) Width ≥ 600 mm. Specific analysis is required

Table 9 – $\omega = 1{,}0$; $e = 0{,}25\,b < 100$ mm

TRF (min)	λ	b_{min}/c_1			
		n = 0,15	n = 0,3	n = 0,5	n = 0,7
30	30	150/25	150/25	150/25	200/30:300/25
	40	150/25	150/25	150/25	250/30:450/25
	50	150/25	150/25	200/25	300/35:500/25
60	30	150/25	150/30:200/25	200/40:400/25	300/50:600/30
	40	150/25	150/40:250/25	250/40:500/25	400/50:600/35
	50	150/25	200/35:400/25	300/40:600/25	500/45:600/40
90	30	200/25	200/40:300/25	250/40:550/25	500/50:600/45
	40	200/30:250/25	200/50:400/25	300/50:600/35	500/60:600/50
	50	200/35:300/25	250/50:550/25	400/50:600/40	600/55
120	30	200/40:250/25	250/50:400/25	450/45:600/30	600/60
	40	200/45:300/25	300/40:500/25	500/50:600/35	(1)
	50	250/40:400/25	400/40:550/25	550/50:600/45	(1)

(1) Width ≥ 600 mm. Specific analysis is required

Table 10 – ω = 1,0 ; e = 0,5 b ≤ 200 mm

TRF (min)	λ	b_{min}/c_1			
		n = 0,15	n = 0,3	n = 0,5	n = 0,7
30	30	150/25	150/25	200/30:300/25	500/30:550/25
	40	150/25	150/25	250/30:450/25	500/40:600/30
	50	150/25	150/30:200/25	300/35:500/25	550/35
60	30	150/25	200/35:450/25	350/40:600/30	550/45:600/40
	40	150/30:200/25	200/40:500/25	450/50:500/35	600/60
	50	150/35:250:25	250/40:550/25	500/40:600/35	600/80
90	30	200/35:300/25	250/50:550/25	500/50:600/40	600/70
	40	200/40:450/25	300/50:600/30	500/55:600/45	(1)
	50	200/45:500/25	350/50:600/35	550/50	(1)
120	30	200/50:450/25	450/450:600/25	550/55:600/50	(1)
	40	250/50:500/25	500/40:600/30	600/65	(1)
	50	300/40:550/25	500/50:600/35	(1)	(1)

(1) Width ≥ 600 mm. Specific analysis is required

4. Proposal of alternative design methods to NBR 15200

4.1 Simplified Analytic Method

From eq. 3, supposing: $\mu_{fi} = 0{,}7$, $\alpha_{cc} = 0{,}85$ and that the lowest limit of eq. 12 is acceptable for b = 190 mm, we have :

$$\mathrm{TFR} = 120\left(\frac{R_\mu + R_a + R_L + R_b + R_n}{120}\right)^{1{,}8} =$$

$$= \left[120^{(1/1{,}8-1)}\left(24{,}9 + 1{,}6\,c_1 - 48 + 48 - 9{,}6\,\ell_{0,fi} + 0{,}18\left(\frac{b\,h}{b+h}\right) + R_n\right)\right]^{1{,}8} =$$

$$= \left[2{,}966 + 0{,}1906\,c_1 - 1{,}1434\,\ell_{0,fi} + 0{,}0214\left(\frac{h}{h/b + 1}\right) + 0{,}119\,R_n\right]^{1{,}8} \cong$$

$$= \left[3 + 0{,}2\,c_1 - 1{,}15\,\ell_{0,fi} + 0{,}021\left(\frac{h}{h/b + 1}\right) + 10/7\; R_n/12\right]^{1{,}8}$$

From simplifying, it results eq. 13.

$$\mathrm{TRF} = \left[3 + \frac{h}{50\left(h/b + 1\right)} + \frac{c_1}{5} - 1{,}15\,\ell_{0,fi} + 10\,N\right]^{1{,}8} \qquad (13)$$

Where:

TFR – column's time of fire resistance, in min;

h – biggest column's dimension, in mm. For h ≥ 1,5 b, use h = 1,5 b

b – smallest column's dimension, in mm

For $\dfrac{h}{h/b + 1} \geq 225\,\mathrm{m}$ use $\dfrac{h}{h/b + 1} = 225\,\mathrm{m}$

c_1 – distance between the geometric center of the bars and the nearest heated surface, in mm

$\ell_{0,fi}$ – effective lenght (buckling) of the column in fire situation, in m (see item 2.1.3)

N=0 if the number of longitudinal bars is 4

N=1/7 if the number of longitudinal bars is greater than 4

Eq. 13 is valid for:

- b ≥ 190 mm
- $\ell_{0,fi} \leq 6$ m
- $\mu_{fi} \leq 0{,}7$
- $A_s/A_c \leq 0{,}04$
- 25 mm ≤ c_1 ≤ 80 mm
- e ≤ 0,15 b
- $\alpha_{cc} = 0{,}85$

Figure 4 shows the results of a parametric analysis of time of fire resistance (TFR) as a function of b, L (actual), c_1, μ_{fi} and number of bars. The basic values for this analysis were: 30 cm, 4 m, 40 mm, 0,7 and 4 bars, respectively, h = 1,5 b and $\ell_{0,fi} = \ell/2$. This analysis also served for comparison of results by means of eq. 3 (Eurocode 2) and eq. 13, here suggested for standardization. As one can see, TFR varies sensibly with parameters variation. The results obtained by eq. 13 are slightly against safety if compared to Eurocode 2 [1], but, having in mind the method's simplicity, it is perfectly acceptable.

4.2 Proposal for a new tabular method

Table 1 of ABNT NBR 15200:2004 was constructed from the method A, considering the extreme limits of dimensions, among them $\ell_{0,fi} \leq 3$ m, that, for intermediate columns of multiple story buildings, means 6 m of actual length. Therefore, it is possible to build more economical tables opting for limits that are less bold than that of table 1, respecting the field of validity of eq. 3, specially the small eccentricity. For columns of high eccentricity, the use of the method B is recommended.

From the methods A and B it is feasible to create table 11, which immediate use is proposed for reinforced concrete design and that should be considered in a future revision of ABNT NBR 15200, for:

– it leads to more economical results than the table 1 (extracted from ABNT NBR 15200:2004) for current cases

– it fits in the advanced methods allowed by the Brazilian standard

– it is applicable to the majority of current cases of columns for buildings

– it includes the validity limitations of table 1 that are not explicit in ABNT NBR 15200:2004

For the construction of "e ≤ 0,15 b" table's column, the expression of the method A of Eurocode 2 was used, with the following assumptions:

$h = b$
$\mu_{fi} = 0,7$
$\ell = 4$ m
$\ell_{0,fi} = \ell / 2$
$\alpha_{cc} = 0,85$

For the construction of "e ≤ 0,25 b" table's column, the method B of Eurocode 2 was used.

The limitations indicated by table 11 must be respected. The other limitations cited in this work are automatically verified if the tabulated values are used.

Figure 4 – Variation of TFR for a column with width, length, c_1, numbers of bars and loading level

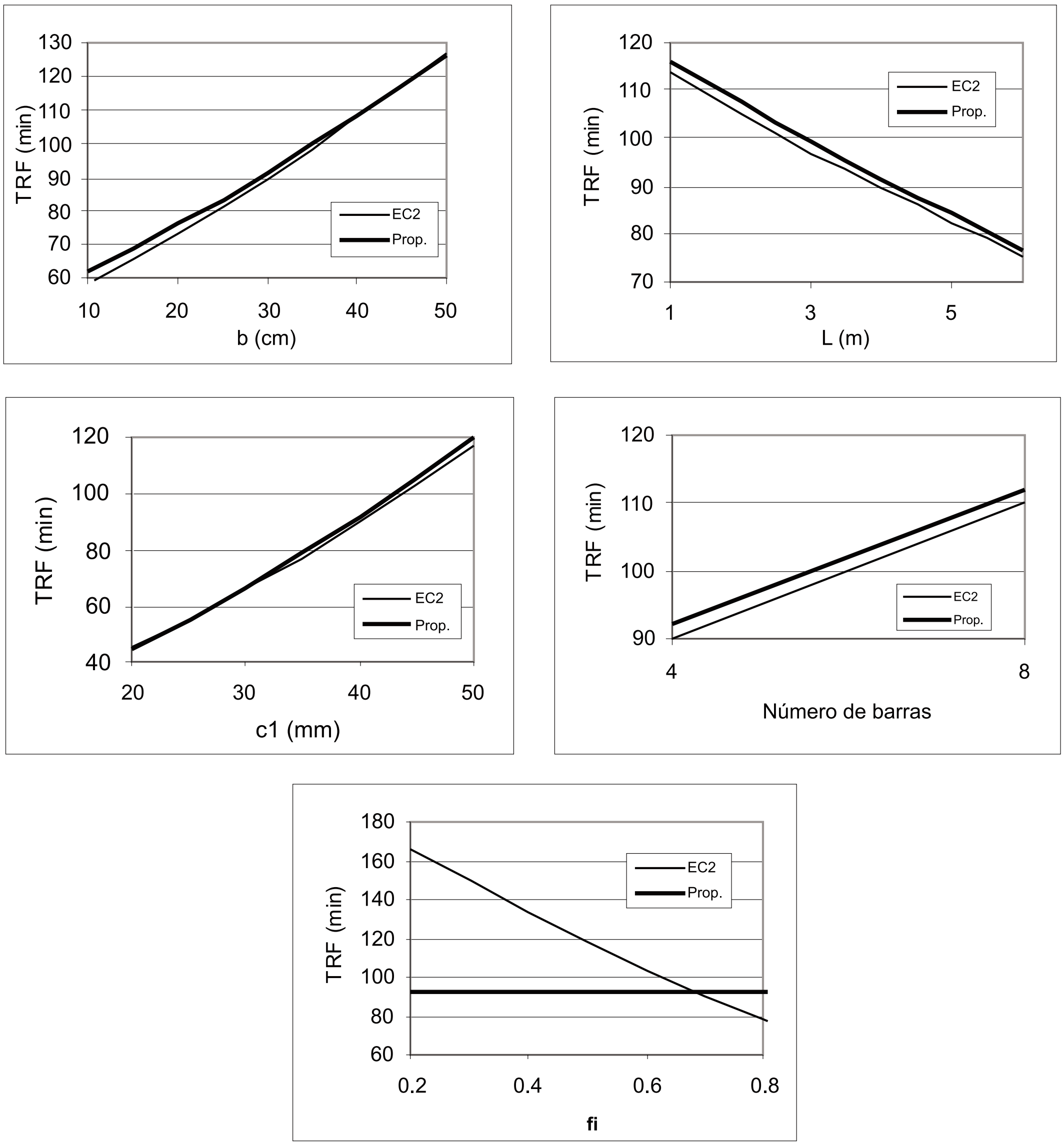


Table 11 – Proposal for a new tabular method

RTFR (min)	b/c_1			
	e ≤ 0,15 b*	e ≤ 0,25 b**		
		ω = 0,1	ω = 0,5	ω = 1,0
30	190/25	300/30	230/30 190/30 (ℓ ≤ 3,3m)	230/30 190/30 (ℓ ≤ 3,3m)
60	190/35	500/25 300/40 (n ≤ 0,5)	350/40 325/25 (n ≤ 0,5)	300/50 400/25 (n ≤ 0,5)
90	190/50 350/40 250/39***	550/40 300/40 (n ≤ 0,3)	500/50 300/45 (n ≤ 0,5)	500/50 400/25 (n ≤ 0,5)
120	350/44***	600/45 550/25 (n ≤ 0,5) 400/50 (n ≤ 0,3)	500/60 600/50 450/50 (n ≤ 0,5) 300/45 (n ≤ 0,3)	600/60 450/45 (n ≤ 0,5)

* $A_s/A_c \leq 0{,}04$

*** 8 bar sminimum

** n ≤ 0,7, except where otherwise noted

*,** columns with fixed ends in fire, $\ell \leq$ 4m, except where otherwise noted

Note: *According to ABNT NBR 8681:2004 [9], the effect of wind can overlooked for accidental combination. This table can be used in the case of normal structures with* γ_z *slightly higher than 1,1, where non-linear (2nd order) displacements due to out-of-plumbness can be overlooked. The author suggests that, in any case,* $\gamma_z \leq 1{,}3$ *at room temperature.*

The cases not covered by table 11 can be resolved by the direct utilization of both methods presented by this work.

5. Conclusion

This work presented the methods that are recommended by Eurocode 2 [1] for fire columns design: the method A, analytic and the method B, tabular general.

These methods are applicable for bracing structures, although, according to ABNT NBR 8681:2003 [9], the effect of wind can be disregarded in exceptional combination. So, these methods can be used in the cases of normal structures with γ_z slightly higher than 1,1, when non-linear displacements (2nd order) due to out-of-plumbness can be overlooked. It is suggested, however, that, in any case, $\gamma_z \leq 1{,}3$ at room temperature.

One of these methods (A) was used as a basis for the tabular method presented by ABNT NBR 15200:2004 [2]. Nevertheless, some restrictions for its use were omitted and, on the other hand, with the transformation of the analytic method in tables, some limit situations were considered, which lead to anti-economical values for o high number of current situations. Here, a simplified analytic expression is proposed for standardization purposes.

From both methods, an alternative table is also proposed to that of ABNT NBR 15200:2004 [2], valid for more common situations than that admitted (without being explicit) by the Brazilian standard. This table leads to more precise and economical values when compared to the standard.

6. References

[01] EUROPEAN COMMITTEE FOR STANDARDIZATION (CEN). Eurocode 2: Design of concrete structures – Part 1.2: General Rules – Structural Fire Design. EN 1992-1-2. Brussels. 2004.

[02] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (ABNT). Projeto de estruturas de concreto em situação de incêndio (Fire design of concrete structures). NBR 15200. Rio de Janeiro. 2004.

[03] CORPO DE BOMBEIROS – POLÍCIA MILITAR DO ESTADO DE SÃO PAULO (CB-PMESP). Segurança estrutural nas edificações – Resistência ao fogo dos elementos de construção (Fire Safety of Buildings - Fire resistance of constructive elements). Instrução Técnica do Corpo de Bombeiros (Technical Instructions of Fire Department). IT 08:04. Sao Paulo. 2004.

[04] CORPO DE BOMBEIROS MILITAR DO ESTADO DE MINAS GERAIS. Segurança estrutural nas edificações (Fire safety of buildings). Instrução Técnica. IT 06:05. Belo Horizonte. 2005.

[05] CORPO DE BOMBEIROS MILITAR DO ESTADO DE GOIÁS. Segurança estrutural nas Edificações – Resistência ao Fogo dos Elementos de Construção (Fire Safety of Buildings- Fire resistance of constructive elements). Norma Técnica 08. Goiania. 2007

[06] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (ABNT). Componentes construtivos estruturais - Determinação da resistência ao fogo (Fire resistance determination). NBR 5628. Rio de Janeiro. 2001.

[07] INTERNATIONAL ORGANIZATION FOR STANDARDZATION (ISO). Fire-Resistance

Tests – Elements of Building Construction – Part 1.1: General Requirements for Fire Resistance Testing. ISO 834. Geneva. 1990. [Revision of first edition (ISO 834:1975)]
[08] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (ABNT). Exigências de resistência ao fogo de elementos construtivos das edificações (Fire-resistance requirements for building construction elements). NBR 14432. Rio de Janeiro. 2000.
[09] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (ABNT). Ações e segurança nas estruturas (Actions and safety of the structures). NBR 8681. Rio de Janeiro. 2003.
[10] FRANSSEN, J.-M. Design of concrete columns based on EC2 tabulated data – a critical review. In: Structures in fire – proceedings of the first international workshop. 2nd edition. Copenhagen: University of Liege/Danish Institute of Fire Technology/CIB-W14 Fire, 2000.
[11] EUROPEAN COMMITTEE FOR STANDARDIZATION (CEN). Eurocode 2: Design of concrete structures – Part 1.2: General Rules – Structural Fire Design. prEN 1992-1-2. Brussels. 1995.
[12] COSTA, C. N. Estruturas de concreto em situação de incêndio (Concrete structures in fire). Dissertation for master degree in Civil Engineering – Structures. Escola Politécnica da Universidade de São Paulo. Sao Paulo, 2003
[13] COSTA, C. N. Trial of the tabular “A”method of the Eurocode 2-1-2:2004 for the fire of reinforced columns. Final Report. MACE-UMIST. Manchester. 2006
[14] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (ABNT). Projeto de estruturas de concreto (Design of concrete structures). NBR 6118. Rio de Janeiro. 2004.
[15] WANG, Y. C. Steel and Composite Structures. Behaviour and Design for Fire Safety. Spon press. London. 2002.
[16] GOMES, F. C .T.; PROVIDÊNCIA, P.; RODRIGUES, J. P. C.; NEVES, I. C. Buckling Length of a Steel Column for Fire Design. Engineering Structures. 2007.
[17] RODRIGUES, J. P. C.; PROVIDÊNCIA, P.; NEVES, I. C.; GOMES, F. C. T. Factores que influenciam a encurvadura de pilares de aço em caso de incêndio (Buckling of steel columns in fire). CMNE/CILAMCE 2007, Oporto, Portugal. 2007.