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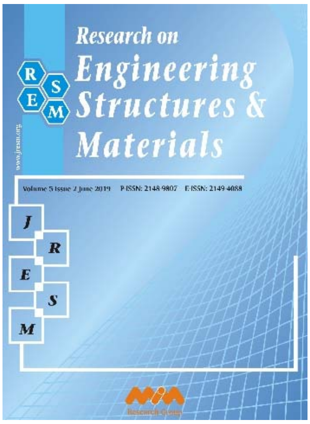

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Research Article

A simplified method for analysis of reinforced concrete beams exposed to fire situation

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Abstract

The reinforced concrete structural design consists in determining the structural members dimensions, steel ratio and location of steel rebars so that a limit state is not reached. Currently, when considering fire effects, commercial design software, in general, are limited to do the verifications only based on the tabular method, according to ABNT NBR 15200, without considering internal and external forces, so the designer needs to change the dimensions of the concrete section. This fact does not stimulate the use of the Brazilian standard codes since they do not present economic solutions. This paper aims to propose a simplified method to design reinforced concrete beams, of harbor structures, in a fire situation, which allows the implementation in commercial design software. Such proposed simplified method intends to involve structural safety, improves design facilities and economy in construction. Then, through a numerical example, the practical application of the tabular and simplified method was demonstrated. The results obtained by the simplified method were more economical than the tabular method. The calculation models validation was done through a comparative study with values found in the literature, as well as those calculated by the 500 °C isotherm method, and with the software ANSYS results. At the end of this work, it was concluded that the proposed simplified method, besides this being a method that allows an easy application, presents results, in general, in favor of safety; and, withal, allows more economics results when compared with the tabular method.

1. Introduction

The reinforced concrete structural design consists in determining the structures members dimensions, steel ratio and the location of the steel bars so that a limit state is not reached. The structure must not reach the ultimate limit state, which could correspond to failure or collapse; neither a serviceability limit state that would make the structure unsuitable for its intended use [1].

Currently, when considering fire effects, design commercial software, in general, are limited to do structural verifications only based on the tabular method, according to [2], without considering internal and external forces, so the designer engineer needs to change the dimensions of the concrete section. This fact does not stimulate the use of the Brazilian Standards since they do not present economic solutions. In this way, the aim of this paper is proposing a simplified method to design reinforced concrete beams, of harbor

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structures, in a fire situation that allows the implementation in commercial design software.

2. Methodology

As pointed out by [2], under usual conditions, the structures are designed at room temperature and, depending on their characteristics and their purpose of use must be verified in a fire situation. There are many methods to do this verification and, Brazilian Standard accepts the following methods: tabular method; simplified calculation method; advanced calculation method and experimental method.

Albuquerque [3] argues that the tabular method is the unique detailed in Brazilian Standard because it is a quite simple and practical method. For the others, the regulation presents only their guidelines for application, since they require specific computer programs or laboratory tests.

However, in this paper will be proposed a simplified method. This model allows beams design in a fire scenario, with manual calculations, in a relatively simple way, without the aid of graphs, abacus, or sophisticated computational programs.

2.1. Tabular method

In order to guarantee the structural safety in fire situation, by the tabular method, it is enough that the beams comply with the minimum dimensions tabulated, as function to the required time of fire resistance (TRRF), determined in accordance with [4], or by the Equivalent Time Method, according to [2]. Such minimum dimensions are presented in Tables 1 and 2.

Table 1 Minimum dimensions for simply supported beams [2]

TRRF (minutes)	Combinations of b_{min}/c_1 (mm/mm)				b_{wmin} (mm)
	1	2	3	4	
30	80/25	120/20	160/15	190/15	80
60	120/40	160/35	190/30	300/25	100
90	140/60	190/45	300/40	400/35	100
120	190/68	240/60	300/55	500/50	120
180	240/80	300/70	400/65	600/60	140

Table 2 Minimum dimensions for continuously supported beams or beams of frames [2]

TRRF (minutes)	Combinations of b_{min}/c_1 (mm/mm)				b_{wmin} (mm)
	1	2	3	4	
30	80/15	160/12	-	-	80
60	120/25	190/12	-	-	100
90	140/37	250/25	-	-	100
120	190/45	300/35	450/35	500/30	120
180	240/60	400/50	550/50	600/40	140

where, b_{min}: minimum width of the cross-section; b_{wmin}: minimum width of the cross-section web of variable width beam; c_1: distance between the longitudinal steel axis (CG) and the concrete surface exposed to fire.

The Brazilian standard NBR 15200 [2], establishes some important prescriptions for the Tabular Method applications; among them, it stands out the case of arranging steel bars just in one layer.

Furthermore, in beams with only one reinforcement layer and width no greater than b_{min} indicated in Table 1 and Table 2, according to the TRRF, the c_{1l} distance (Figure 1) of the beams should be 10 mm larger than the c_1 given by Table 1. This adjustment is necessary due to the fact that there is a temperature concentration along the edges located in the underside of the beam.

As an alternative, to keep the concrete cover both about the underside and to the side of the beam, the following considerations must be applied: for reinforced concrete, to specify corner bars with a diameter immediately greater than the calculated; for prestressed concrete, to consider designing effects, a prestress force equal to 0.7 of the indicated.

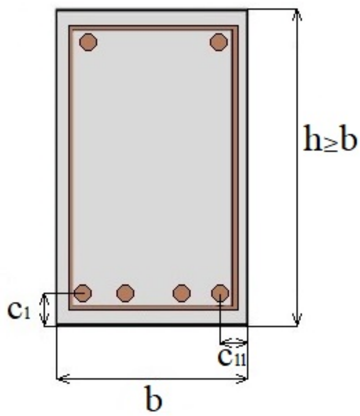

Fig. 1 c_1 and c_{1l} distances, adapted from [2]

2.2. Simplified method

Unlike the Tabular Method, which consists of verification, for a given TRRF, of the minimum beams dimensions, the simplified methods evaluate the fire resistance, by analyzing both the internal and external forces for a given TRRF.

Thus, the fire action usually corresponds to only the reduction of the strength of the material and the structural elements capacity. The ordinary verification of structural safety in a fire situation is guaranteed when the Eq. (1) is satisfied:

$$S_{d,fi} \leq R_{d,fi} \tag{1}$$

where, $S_{d,fi}$: design value of the external force or moment in a fire situation; $R_{d,fi}$: design value of the internal force or moment in a fire situation.

2.2.1 External Bending Moment in Fire Situation

To calculate the external bending moment, considering a fire situation, one can use the Eq. (2).

$$M_{Sd,fi} = \left(1.2M_{gk} + 0.7\psi_2 M_{qk}\right) \quad (2)$$

where, $M_{Sd,fi}$: design value of the external bending moment, in fire situation [kNm]; M_{gk}: characteristic value of the bending moment relative to the permanent action, at room temperature [kNm]; ψ_2: quasi-permanent combination factor for serviceability limit state [5] [dimensionless]; M_{qk}: characteristic value of the bending moment relative to the variable action, at room temperature [kNm].

Alternatively, for simplification, Eq. (3) can be used. It is important to emphasize that such equations are independent of the fire type or time of fire exposure.

$$M_{Sd,fi} = 0.7M_{Sd} \quad (3)$$

where, M_{Sd}: design value of the external bending moment, at room temperature [kNm].

2.2.2 Proposed Internal Bending Moment in Fire Situation

To calculate the internal moment in a fire situation, $M_{Rd,fi}$, by proposed method, the Eq. (4) can be used.

$$M_{Rd,fi} = f_{yk}k_{s,m}A_s\left(d - \frac{f_{yk}A_s}{2f_{ck}b}\right) \quad (4)$$

where, f_{yk}: characteristic value of yield strength of reinforcing steel, at room temperature[kN/cm^2]; $k_{s,m}$: average reduction factor of steel resistance [dimensionless]; A_s: cross sectional area of longitudinal steel bars [cm^2]; f_{ck}: is characteristic value of concrete compressive strength, at room temperature [kN/cm^2]; b: reinforced concrete beam cross-section width [cm].

All the variables of Eq. (4) are obtained from the design at room temperature, except $k_{s,m}$. Then, the main concern of the equation is $k_{s,m}$, whose value is directly related to each steel bar temperature.

These temperatures, in its turn, can be calculated, with a reasonable simplification, from the method proposed by [6] as a function only of fire exposure time, and of each steel bar depth with coordinates x_i e y_i, as expressed by Eq. (5):

$$\theta_{c,xy} = \left[n_w\left(n_x + n_y - 2n_xn_y\right) + n_xn_y\right]\theta_g \quad (5)$$

where n_w, n_x, n_y, e θ_g, are given by the Eqs. (6)-(9):

$$n_w = 1 - 0.0616t^{-0.88} \quad (6)$$

$$n_x = 0.18ln\left({}^{t}/_{x_i^2}\right) - 0.81 \quad (7)$$

$$n_y = 0.18ln\left({}^{t}/_{y_i^2}\right) - 0.81 \quad (8)$$

$$\theta_g = 345log_{10}(480t + 1) + \theta_0 \quad (9)$$

where, t: time [hours]; x_i: horizontal Cartesian coordinate of the steel bar *i* [m]; y_i: vertical Cartesian coordinate of the steel bar *i* [m]; θ_g: gas temperature in the fire compartment [°C]; θ_0: gas temperature at the instant t=0, usually adopted 20°C.

Knowing the temperature of each steel bar, it is possible to determinate the average reduction factor of steel resistance $k_{s,m}$, by the weighted average of the $k_{s,\theta i}$ as a function of the steel area of each steel bar i, according to Eq. (10).

$$k_{s,m} = \frac{\sum k_{s,\theta i} A_{s,i}}{\sum A_{s,i}} \qquad (10)$$

where, $A_{s,i}$: cross-sectional area of bar i of the longitudinal reinforcement [cm^2]; $k_{s,\theta i}$: reduction factor of the yielding strength, at the temperature θ, of the steel bar i, which can be calculated according to Eq. (11).

$$\begin{aligned}
k_{s,\theta i} &= 1 && \text{for } 20^\circ C \le \theta_s \le 400^\circ C \\
k_{s,\theta i} &= 1 - 0.0022(\theta_s - 400) && \text{for } 400^\circ C < \theta_s \le 500^\circ C \\
k_{s,\theta i} &= 0.78 - 0.0031(\theta_s - 500) && \text{for } 500^\circ C < \theta_s \le 600^\circ C \\
k_{s,\theta i} &= 0.47 - 0.0024(\theta_s - 600) && \text{for } 600^\circ C < \theta_s \le 700^\circ C \\
k_{s,\theta i} &= 0.23 - 0.0012(\theta_s - 700) && \text{for } 700^\circ C < \theta_s \le 800^\circ C \\
k_{s,\theta i} &= 0.11 - 0.0005(\theta_s - 800) && \text{for } 800^\circ C < \theta_s \le 900^\circ C \\
k_{s,\theta i} &= 0.06 - 0.0002(\theta_s - 900) && \text{for } 900^\circ C < \theta_s \le 1000^\circ C \\
k_{s,\theta i} &= 0.04 - 0.0002(\theta_s - 1000) && \text{for } 1000^\circ C < \theta_s \le 1100^\circ C \\
k_{s,\theta i} &= 0.02 - 0.0002(\theta_s - 1100) && \text{for } 1100^\circ C < \theta_s \le 1200^\circ C \\
k_{s,\theta i} &= 0 && \text{for } \theta_s > 1200^\circ C
\end{aligned} \qquad (11)$$

As well as in the Tabular Method, in this proposed simplified method the eventual effects of spalling or thermal deformation restrictions are not considered. Besides that simplification, since in the most critical situations (high steel bars temperature), the average yielding strength of steel decreases more than the average compressive strength of concrete, that is, $k_{s,m} < k_{c,m}$ (average reduction factor of concrete compressive strength), consequently $\left(\frac{k_{s,m}}{k_{c,m}}\right)<1$; therefore, since $k_{c,m}$ is difficult to determine, in order to simplify the determination of the internal bending moment in fire situation, in safety favor, it was considered $\left(\frac{k_{s,m}}{k_{c,m}}\right)=1$.

3. Proposed method verification

The validation of the procedure for calculating the internal bending moment in fire situation by the proposed simplified method was done through comparison between results found in the literature, with 500°C isotherm method, and with the values determined by the ANSYS software.

Six beams sections, subjected to different times of fire exposure, were analyzed as shown in Figure 2. The comparison of the internal moment calculated in a fire situation can be observed in Table 3.

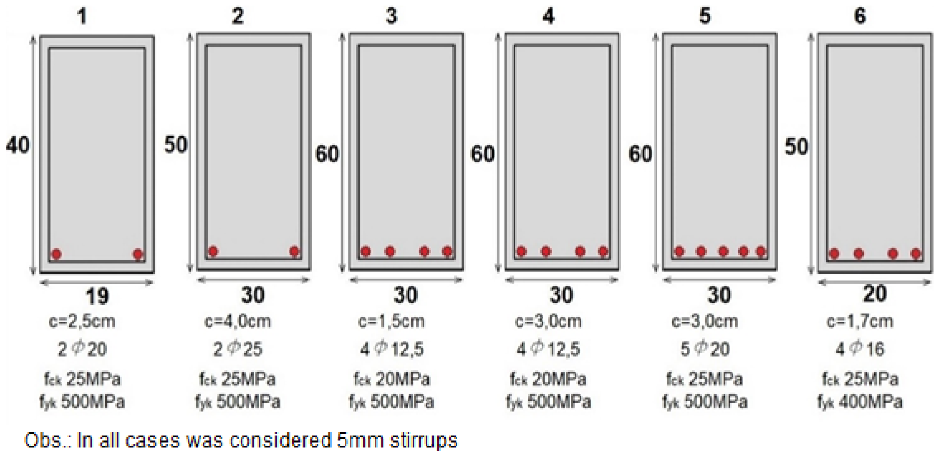

Fig. 2 Representation, without a scale, of analyzed sections, dimensions in centimeters

Through this comparative, the following observations can be made:

- The simplified method proposed presents results very similar to those obtained by 500°C isotherm method, which is an internationally recognizes method;
- The results obtained by the simplified method, compared to those found in the literature, are quite closed in values.
- As illustrated in Table 3, evaluating the proposed simplified method, only one of the results (highlighted in gray) presented a higher value than the ANSYS method, which makes a more rigorous and representative analysis of the reality (since the difference, in this case, was less than 1.0 kNm, that is, negligible); in all other results, lower bending moments than ANSYS were achieved, showing that the proposed simplified method, in general, presents values in favor of the safety.

4. Application example

In this section, it will be demonstrated, through a numerical example, how to apply the tabular and simplified method. The parameters have been defined considering an office building, located in the port area, with TRRF equal to 90 minutes and, from the beam design, taking efforts at room temperature [5] as exposed in Figure 3.

Table 3 Comparison of internal moment calculated in a fire situation

Beam/ Section (Figure 2)	Standard fire time [min]	Comparative Source	Internal moment calculated in a fire situation ($M_{Rd,fi}$)[kNm]			
			Reference value of the comparative source	Steel Temp. ANSYS	Steel temperature Wickström's equation	
				ANSYS Method	500°C Isotherm Method	Simplified Method Proposed
1	90	[3] Albuquerque, 2012	45.3	46.0	38.2	36.4
2	120	[3] Albuquerque, 2012	138.3	137.0	109.4	107.0
3	30	[7] Soares, 2003	127.6	128.4	125.5	125.5
3	60	[7] Soares, 2003	79.7	82.0	81.8	81.0
3	90	[7] Soares, 2003	31.1	47.9	44.7	43.7
3	120	[7] Soares, 2003	21.3	28.7	24.1	23.5
4	30	[7] Soares, 2003	132.1	131.7	131.7	132.1
4	60	[7] Soares, 2003	115.3	120.9	116.4	116.6
4	90	[7] Soares, 2003	78.2	92.7	88.7	88.2
4	120	[7] Soares, 2003	60.8	64.6	60.5	59.6
5	60	[8] Sousa e Silva, 2015	378.4	381.7	367.5	371.8
6	30	[9] Gonçalves, 2007	139.0	139.6	136.8	137.9
6	60	[9] Gonçalves, 2007	94.0	110.6	89.8	88.7
6	90	[9] Gonçalves, 2007	43.0	62.0	47.1	45.3
6	120	[9] Gonçalves, 2007	22.0	32.9	24.8	23.6

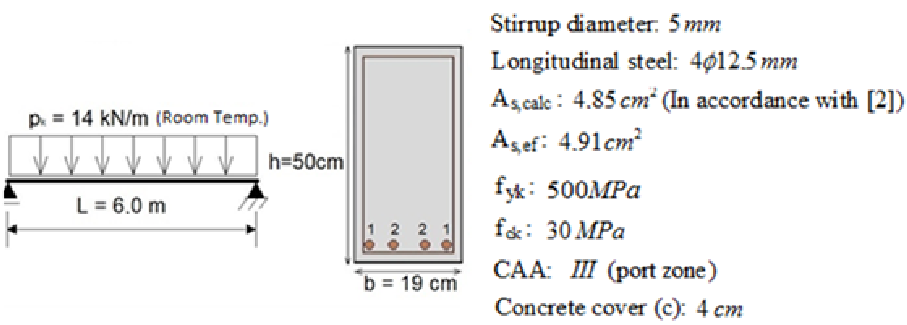

Fig. 3 Reinforced concrete beam parameters

4.1. Tabular method

The first step is to determine the distance between the longitudinal reinforcement axis and the concrete face exposed to fire (c_1). In this case, the calculation can be made as follows:

$$c_1 = \mathrm{c} + \text{Ø}_\mathrm{t} + \frac{\text{Ø}}{2} = 40 + 5 + \frac{12.5}{2} \therefore c_1 = 51.25 \text{ mm}$$

Then, the c_{1min} is determined consulting Table 1, for a TRRF equal to 90 minutes. So, through a simple reading of the table, c_{1min}=45 mm.

Although the tabular method is quite expeditious, there are some alternatives and cares to be taken that may not be so immediate. As previously mentioned in Item 2.1, in sections with only one reinforcement layer and width not greater, in accordance with the TRRF, than b_{min} indicated in column 3 of Table 1, some design changes must be made. This is the case of the analyzed cross-section, where 4 bars with 12.5 mm are arranged in only one layer and the beam width of 190 mm is not greater than 300 mm, as column 3 of Table 1 for TRRF to 90 minutes. This verification with column 3 of Table 1 is suggested by [2]

Therefore, the distance between the longitudinal corner steel axis and the concrete lateral surface exposed to fire (c_{1l}) should be 10 mm higher than c_{1min} found by the tabular method. That is, to ensure structural safety, c_1 must be greater than c_{1l}=c_{1min}+10mm. In this case, c_{1l}=45+10=55 mm. So, it is not in the safety range, since:

$$c_1 = 51.25 \text{ mm} < c_{1l} = 55 \text{ mm}$$

If no alternative is taken, the time of fire resistance (TRF) must be calculated, considering, in safety favor, c_1 reduced by 10 millimeters. For this example:

$$c_1 = 51.25 - 10 = 41.25 \text{ mm}$$

To calculate the piece TRF, by the linear interpolation of the values given in Table 1, it is recommended to proceed as follows:

If for b_{min}= 190 mm and c_{1min} = 30 mm, the TRF is 60 min;

And for b_{min} = 190 mm and c_{1min} = 45 mm, the TRF is 90 min;

So, for b = 190 mm and c_1= 41.25 mm, the TRF, by interpolation, is equal to 83 minutes;

As a result, in this case the TRF is not safe, because:

$$TRF = 83 \text{ min.} < TRRF = 90 \text{ min.}$$

Therefore, in short, the beam of this example, with same characteristics of the design at room temperature, does not present structural safety in a fire situation, in accordance with the normative tabular method. Based on this, some alternatives were pointed out for the correct design in a fire scenario by the tabular method, as following:

I. Replace the two corner bars for only one with the diameter immediately greater, substituting 4Ø12.5 for 2Ø16 in the corners and 2Ø12.5 in the center (TRF=101 min);

II. Increase beam height, from 50cm to 60cm, considering the possibility of c_1 reduction (TRF=92 min);

III. Increase concrete cover, from 4.0 cm for 4.5cm (TRF=92 min);

IV. Arrange the reinforcement in two layers of 2Ø12.5 each one (TRF=99 min);

V. Considering Δc_1, that is, reduced value of c_1 (TRF=84 min).

The alternatives III and IV, although they satisfy the safety condition, for a fire situation, according to the Tabular Method, they are not valid for the beam design at room temperature. Besides that, the alternative V, in its turn, is not enough to achieve a safety condition.

4.2. Proposed Simplified method

First, it is necessary to calculate the characteristic external bending moment at room temperature. Considering the study refers to a simply supported beam, it can be calculated as follows:

$$M_{Sk} = \frac{p_k L^2}{8} = \frac{14\times 6^2}{8} \therefore M_{Sk} = 63.0 \text{ kNm}$$

Also, only for possible comparisons, the calculated external bending moment at room temperature can be determined as follows:

$$M_{Sd} = 1.4 \times M_{Sk} \therefore M_{Sd} = 88.2 \text{ kNm}$$

In this example, considering $M_{Sd,fi}=0.7M_{Sd}$, the calculated external moment in a fire situation can be determined as follows:

$$M_{Sd,fi} = 0.7(88.2) \therefore M_{Sd,fi} = 61.74 \text{ kNm}$$

After determining the external bending moment, the internal bending moment is defined. For this, steel bars temperatures are calculated, considering a standard time of fire exposure equal to the TRRF of 90 minutes. By the Wickström's equation, as presented in Eq. (5), the corner bars temperature will be:

$$\theta_{c,xy1} = [0.957(0.333 + 0.333 - 2 \times 0.333 \times 0.333) + 0.333 \times 0.333]1006 =$$

$$\therefore \theta_{s1} = \theta_{c,xy1} = 539^{o}\text{C}$$

The center bars temperature will be:

$$\theta_{c,xy2} = [0.957(0.170 + 0.333 - 2 \times 0.170 \times 0.333) + 0.170 \times 0.333]1006 =$$

$$\therefore \theta_{s2} = \theta_{c,xy2} = 432^{o}\text{C}$$

From bars temperatures is possible to calculate the reduction strength factor of steel, $k_{s,\theta i}$, as presented in Eq. (11), For θ_{s1} and θ_{s2} respectively

$$k_{s,\theta 1} = 0.78 - 0.0031(539 - 500) = 0.6591$$

$$k_{s,\theta 2} = 1 - 0.0022(432 - 400) = 0.9296$$

As such, the average steel reduction strength factor $k_{s,m}$, can be defined, by considering the area of each bar (A_{si}=A_{s1}=A_{s2}=1.2272 cm^2), according to Eq. (10):

$$k_{s,m} = \frac{2 \times 0.6591 \times 1.2272 + 2 \times 0.9296 \times 1.2272}{4 \times 1.2272} = 0.7944$$

Finally, applying the Eq. (4), the calculated internal bending moment, in a fire situation, by the proposed simplified method, is determined:

$$M_{Rd,fi} = 50 \times 0.7944 \times (4 \times 1.2272)\left[44.875 - \frac{50 \times (4 \times 1.2272)}{2 \times 3 \times 19}\right] = 8329 \text{ kNcm}$$

$$M_{Rd,fi} = 83{,}29 \text{ kNm}$$

To verify if the safety condition ($M_{Sd,fi} \leq M_{Rd,fi}$) is satisfied, Eq. (1) is used. In this case, the safety is guaranteed, since:

$$M_{Rd,fi} = 83.29 \text{ kNm} > M_{Sd,fi} = 61.74 \text{ kNm}$$

4.3. Comparative results

The simplest comparison to do is about the structural safety condition, as in Table 3.

Table 3 Comparative of the structural safety condition (TRRF 90 min)

Structural safety condition	
Tabular Method	Proposed Simplified Method
No satisfied	Satisfied
TRF < TRRF	$M_{Rd,fi} > M_{Sd,fi}$

As shown in Table 3, in this example, the proposed simplified method presents more economical results than the Tabular Method. Another comparison that can be made, according to Table 4, is the beam TRF determined by Tabular Method, by 500°C Isotherm Method, and by the Proposed Simplified Method, considering the mentioned alternatives in Item 4.1 of this paper.

As can be seen in all hypotheses of this example, the proposed method is more economical than Tabular. Also, results similarity is observed between 500°C Isotherm Method and the proposed method one. It is important to note that the TRF values determined with the simplified method were obtained by iteration, changing the fire exposure time until reaching the limiting condition: $M_{Sd,fi} = M_{Rd,fi}$.

5. Conclusions

Through a numerical example, it was demonstrated a practical application of the tabular and simplified methods, analyzing some possible alternatives in the reinforced concrete beams design. From that, a comparison between tabular and proposed simplified method has been made, and the results obtained by the proposed method were more economical than those obtained from the tabular method.

Table 4 Comparative of the beam TRF, determined by Tabular Method, by 500°C Isotherm Method, and by the Proposed Simplified Method

Beam data	Time of fire resistance (min)		
	Tabular	500°C Isotherm	Simplified Method
Initial condition: room temperature 19x50 cm; c = 4.0 cm; 4 Ø 12.5 – one layer	83	113	113
According alternative I: increasing corner bars 19x50 cm; c = 4.0 cm; 2 Ø 16 +2 Ø 12.5 – one layer	101	130	129
According alternative II: increasing beam height 19x60 cm; c = 4.0 cm; 4 Ø 12.5 – one layer	92	125*	125*
According alternative III: increasing concrete cover 19x50 cm; c = 4.5 cm; 4 Ø 12.5 – one layer	92	125	125
According alternative IV: Arrange the reinforcement in two layers 19x50 cm; c = 4.0 cm; 4 Ø 12.5 – two layers	99	113	112
According alternative V: considering Δc_1 19x50 cm; c = 4.0 cm; 4 Ø 12.5 – one layer	84	113	113

* Considering the $M_{Sd,fi}$= 63.95 kNm due to the height of 60 cm; for the other cases $M_{Sd,fi}$ =61.74 kNm (height of 50 cm);

Additionally, the results by the 500°C isotherm method and the proposed simplified one are convergent and very close; however, the proposed method showed advantage when the ease of calculation in the procedure is considered, because, through some simplifications, is not necessary to determine the cross-section reduced width, as a function of the 500°C isotherm.

Then, is also important to emphasize that, in almost all examples, through proposed simplified method were obtained lesser internal bending moments than the ANSYS method, which makes a more rigorous and representative analysis of the problem. This is an evidence that, in general, the proposed method values are in safety favor.

Moreover, the most important advantage of the proposed simplified method is that calculation can be done manually, in a relatively simple way (easier than the 500°C isotherm method or using ANSYS), without using graphics, abacus or sophisticated computational programs. However, even so, it is possible to design reinforced concrete beams, with safety in fire situations, and in some cases, it could be more economical than the normative tabular method.

The validation of calculation models of both temperatures and bending moments in fire situation was done through a comparative study with values found in the literature, as well as those calculated by the 500°C isotherm method and those obtained with the aid of ANSYS software.

Therefore, it is believed that the proposed simplified method, if implemented, could allow development or improvement in some commercial design software. Since, currently in the marketplace, such tools are limited to do the verifications only based on the tabular method, without considering the external and internal forces. In this scenario, the designer often has the need of changing the dimensions of the concrete cross-section. This fact does not present economic advantages and, probably because of that, the use of the Brazilian Standards is not stimulated, as [10] argues that only a small portion of the professionals in this area uses NBR 15200 [2].

Finally, the proposed simplified method, besides being an easy method to apply, presents results usually in safety favor; and, even so, allows more economical results than the tabular method. In cases where the structural design at room temperature does not satisfy the TRRF determined by the tabular method, rather than in the first moment increase the dimensions of the structure, it is recommended to verify by the proposed simplified method. So, the designers will be stimulated to use NBR 15200 [2] in their projects, guaranteeing, in a more economical way, structural safety in a fire situation.

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