Influence of fire resistant steel bars on the fire design of simply supported reinforced concrete beams

Giulianna T. A. Listo[1], Valdir P. Silva[1]

[1]*Dept. of Structural and Geotechnical Engineering, University of São Paulo*
Av. Prof. Luciano Gualberto, 380, 05508-010, São Paulo, Brazil
giuliannalisto@usp.br, valpigss@usp.br

Abstract. The exposure to fire conditions can cause damage to reinforced concrete structures by reducing their strength. As a result, even today these accidents cause irreparable material and immaterial losses. Therefore, it is understood that the technological improvement of structural elements is essential for the advancement of fire safety engineering. A form of improvement that has been studied in recent years are the steels with enhanced fire behavior, or "fire resistant steels", as they are usually known. These special metallic alloys are able to maintain their mechanical properties for longer when exposed to high temperatures and are already applied to metallic structures, although their contribution to the performance of reinforced concrete structures is still poorly understood. The present research seeks to evaluate the influence of this type of material on the fire design of simply supported reinforced concrete beams using a methodology that adapts the tabular method to verify these structures. The developed methodology is similar to those presented in NBR 15200 (ABNT, 2012) and Eurocode 2 (CEN, 2004) and considers the use of the improved steel in replacement to the conventional tensile reinforcement. The study is essentially theoretical and numerical, through the use of the finite element software Super TempCalc, and the results achieved have shown that there can be a reduction in the minimum dimensions required for beams' cross-sections by the aforementioned codes if the fire resistant steels are used.

Keywords: fire safety, fire resistant steels, reinforced concrete, tabular method.

1 Introduction

Reinforced concrete structures have their mechanical performance compromised when subjected to high temperatures such as those verified during a fire event. In these situations, exposure to high temperatures causes degradation of concrete and steel so that, without adequate fire design, premature collapse of the structure can occur, putting neighbors at risk and threatening the safety of users and firefighters.

One of the most conventional ways of checking the fire safety of reinforced concrete beams is through standardized tabular methods. This article addresses discussions based on the requirements of the tabular methods laid out in Eurocode 2 part 1-2 [1] and NBR 15200 [2]. For simply supported beams, the method stablishes minimum cross sectional dimensions to be met in order to ensure that the temperature in the tensile reinforcing bars will not exceed a critical steel temperature (θ_{cr}) of 500 °C during the required fire resistance time (TRRF) [1]. The Brazilian version of the method, presented in NBR 15200 [2], is mostly similar to the Eurocode 2 one, except for covering combinations for TRRFs of up to 180 minutes, while the European version reaches 240 minutes, and for changing the minimum widths from 200 mm to 190 mm and from 150 mm by 140 mm, for which the requirements were defined with the same safety criteria.

It is understood that the behavior of steel is among the main factors that condition the response of reinforced concrete structures in a fire situation and the technological improvement of this material would imply, therefore, an increase in the critical temperature of steel and, with that, of the structural efficiency in a fire scenario. In fact, NBR 15200 [2] clarifies that tests show that in a fire situation the concrete structures usually collapse by bending or flexural compression and not by shear. In this scenario, fire-resistant steels (FRS) are of great interest.

Structural FRS emerged as a way to meet the demands of civil construction focused on steel structures and, unlike the conventional ones, are able to maintain up to 2/3 of their strength up to about 600 °C. In their historical study on the development of fire resistant steels, García *et al* [3] point that articles on the topic of FR steels first appeared in the early 1950s. Later, in the 1960s, the interest in improving the elevated temperature properties of steels grew in Japan, according to Wiltd [4], due to a requirement that structural steels were protected from fire so as to not exceed a temperature limit of 350 °C. The first FRS for structural use in buildings was, then, developed in 1988 by Nippon Steel [3, 5]. The possibility of reducing or exempting the use of fire-resistant coatings in steel frame buildings is one of the attractive aspects of FRS discussed in the works of Sakumoto and Saito [6] and of Fushimi, Chikaraishi and Keira [7], in which the authors discuss real cases in which this occurred.

These enhanced steels are produced in the form of structural profiles and, until then, in the studied literature, the status of development and applications of rebars that have the same improved properties is unknown. Nevertheless, the replacement of the conventional tensile reinforcement by one capable of maintaining its mechanical properties little changed for a longer time when exposed to high temperatures suggests the possibility of reducing the minimum safety criteria required by the standardized tabular method for reinforced concrete beams in NBR 15200 [2] and Eurocode 2 part 1-2 [1].

That being said, the present paper is part of a research project in development at University of São Paulo and seeks to investigate whether the use of steels with improved fire behavior would imply significant advantages for the design of reinforced concrete simply supported beams in fire situations. The study is conducted through numerical and theoretical analysis and the development of a tabular method adapted for reinforced concrete simply supported beams considering the use of steel bars with enhanced fire resistance characteristics in tensile reinforcement. As a simplification, the properties of the bars will be adopted in accordance with the fire resistant steel SM490-FR characterized in the work of Ding, Li and Sakumoto [8].

It should be noted that, due to the theoretical and numerical nature of the study developed here, the data obtained should be used in future research with practical and/or experimental application or by means that provide a more precise observation of the real behavior of the structures. With this, it will be possible to investigate in a more complete way the feasibility of production and implementation of FRS in reinforced concrete beams.

2 EC2 and NBR 15200 tabulated data

The assumptions used to define the critical steel temperature of simply supported beams on EC2 tabular method correspond approximately to a design effect of actions in the fire situation ($E_{d,fi}$) equals to 70 % of those of normal temperature (E_d), a partial safety factor for reinforcing steel (γ_s) equals to 1,15 and an area of reinforcement required for ultimate limit state according to normal temperature design ($A_{s,req}$) equals to the area of reinforcement provided ($A_{s,prov}$) [1]. The said hypothesis applied to eq. 1 result in a steel stress level under fire conditions ($\sigma_{s,fi}$) equal to 60 % of its characteristic strength (f_{yk}) and, through the analysis of the reference curve for reduction factor of the characteristic strength of reinforcing steel ($k_s(\theta_{cr}) = \sigma_{s,fi}/f_{yk}(20\ °C)$), presented in Fig. 1, the critical temperature of 500 °C can be, then, stablished.

$$\sigma_{s,fi} = \frac{E_{d,fi}}{E_d} \times \frac{f_{yk}(20\ °C)}{\gamma_s} \times \frac{A_{s,req}}{A_{s,prov}}. \tag{1}$$

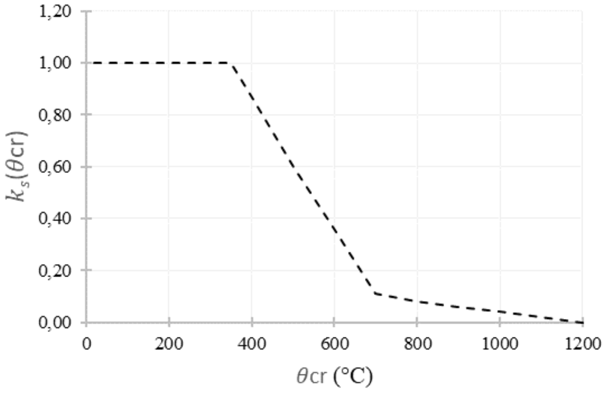

Figure 1. Reference curve for the critical temperature of reinforcing steel [1].

In cases where the steel critical temperature differs from 500 °C, Eurocode 2 [1] provides eq. 2 to calculate an adjust (Δa) of the axis distances of reinforcing steel from the nearest exposed surface available in the tables, valid for θ_{cr} in the range of 350 °C and 700 °C. For temperatures outside this range, or if more accurate results are requested it is suggested to use temperature profiles.

$$\Delta a = 0.1(500 - \theta_{cr}). \tag{2}$$

Figure 2 presents the curve for reduction factor of the characteristic strength of the fire resistant steel SM490-FR given in the work of Ding, Li and Sakumoto [8]. The mathematical model that describes the curve on Fig. 2 was obtained by the authors [8] by least square fitting method applied to experimental data previously available in literature. As can be seen, the limitation of k_s to 0.6 for the mentioned FRS would correspond to a critical temperature of about 630°C.

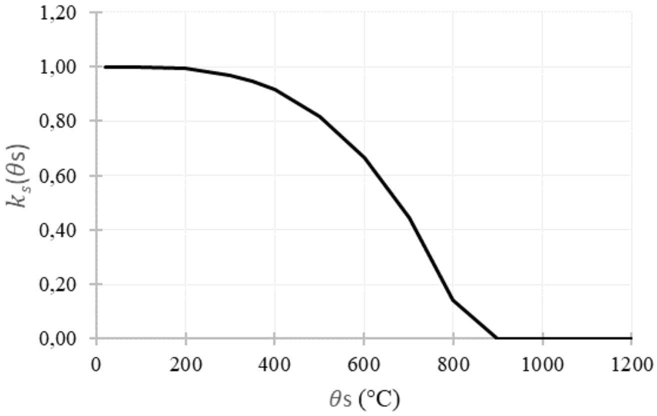

Figure 2. Reduction factor of characteristic strength of the fire resistant steel SM490-FR at high temperatures [8].

3 Analysis

In order to evaluate the influence of FRS tensile reinforcement of the fire design of simply supported beams, a numerical study was carried out using the thermal module Super TempCalc of the software Temperature Calculation and Design [9]. Super TempCalc performs 2-dimensional transient heat flow analysis and solves the thermal problem using the finite element method.

Initially Super TempCalc was used to model all the cross-sectional combinations of axis distance (a) and minimum width (b_{min}) presented in NBR 15200 tabular method [2]. The analysis considered rectangular concrete cross sections, exposed on three sides to fire curve ISO 834 [10] for 3 hours and initial temperature of 20 °C. The heights of the studied sections were set in 2x their minimum width and the thermal properties of the concrete were adopted in accordance with NBR 15200 [2].

Thus, it was possible to manually determine, with the aid of the isotherms in the cross-sections provided by Super TempCalc, a axis distance (a) such that, at the point of coordinates $a \times a$, the temperature found did not exceed $\theta_{cr} = 630\ °C$. Figure 3 exemplifies how the distance a was determined for one of the studied cases.

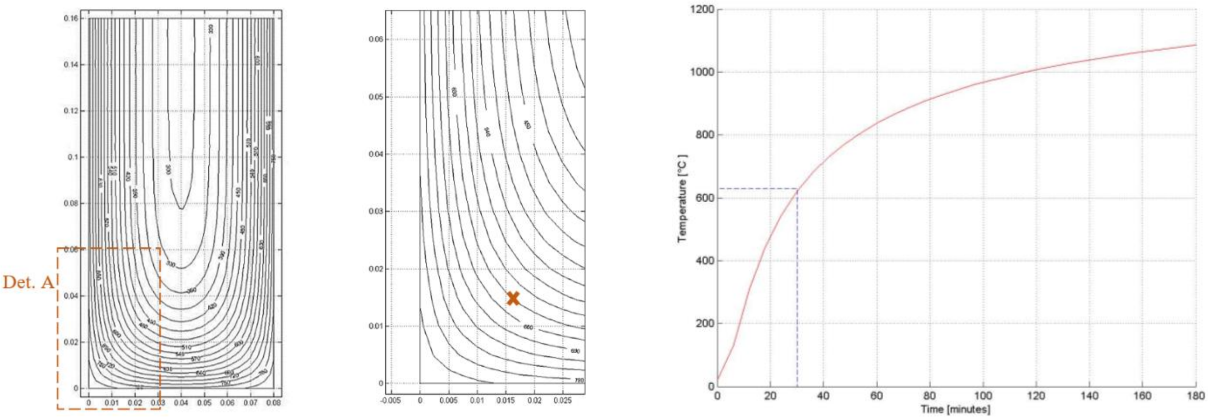

Figure 3. Determination of a from the isotherms for the configuration section $b = 80\ mm$ at $30\ min$.

The results found for all section configurations studied are shown in Tab. 1. Table 2 summarizes the adjustments Δa corresponding to the results shown in Tab. 1.

Table 1. Minimum dimensions for simply supported beams using FRS.

Time (min)	Combination of $b_{mín}/c_1$ (mm/mm)				$b_{wmín}$ (mm)
	1	2	3	4	
30	80/16	120/15	160/15	190/15	80
60	120/22	160/29	190/29	300/29	100
90	140/44	190/40	300/39	400/39	100
120	190/50	240/49	300/48	500/49	120
180	240/66	300/64	400/64	600/64	140

Table 2. Adjust of the axis distances of reinforcing steel from the nearest exposed surface found for simply supported beams using FRS.

Δa (mm) found for the studied sections					
$b_{mín}$ (mm)	Time (min)				
	30	60	90	120	180
80	-9	-	-	-	-
120	-5	-18	-	-	-
140	-	-	-16	-	-
160	0	-6	-	-	-
190	0	-1	-5	-18	-
240	-	-	-	-11	-14
300	-	+4	-1	-7	-6
400	-	-	+4	-	-1
500	-	-	-	-1	-
600	-	-	-	-	+4

As it can be seen from Tab. 2, for three studied cases an increase of about 4 mm in the minimum a value is suggested and, for other six cases, the suggested reductions in the minimum a were non-existent or not very relevant ($\Delta a \cong -1\ mm$). These results suggest that, depending on the number of tensile reinforcing bars on the beam, even if steels with properties of fire resistance were to be used, the structure could be against the safety criteria herein assumed as a critical temperature of 630 °C or have the same performance as a beam using the usual steels. Nevertheless, for these cases, it is possible that for cross-sections with more than 2 bars, the ones further away from the corners might be overly in favor of safety, since the corners are more susceptible to the extreme effects of fire due to the proximity to two heated surfaces. More accurate studies should be conducted to assess whether the use of FRS would offer relevant advantages for sections with more bars.

For 11 of the 20 cases investigated the use of steels with enhanced fire resistance properties would imply in the possibility of reduction in requirements of a for the standardized tabular method on NBR 15200 [2] and Eurocode 2 part 1-2 [1] which, according to the methodology herein proposed, would be in the range of 5 to 18 mm.

Also it must be noted that the direct application of eq. 2, for a critical temperature of 630 °C, would result in the possibility of a 13 mm reduction in the minimum axis distance (a) tabulated if steel bars with fire resistance properties similar to SM490-FR steel were used to replace conventional tensile reinforcement.

Overall, the work developed must be applied by experimental means or through more accurate numerical analysis to confirm the results found, however, at first, it is understood that the use of FRS in tensile reinforcement of simply supported beams can be very advantageous from the point of view of structural optimization in a situation of fire depending on the section evaluated and its required fire resistance time.

4 Conclusions

The fire design of reinforced concrete structures implies concerns inherent to the materials used in them and, when it comes to simply supported beams, the fire behavior of steel is among the main factors that condition the response of the structural element. In this regard, the present paper sought to investigate the influences of the use of steels with improved behavior in the design of reinforced concrete simply supported beams in a fire situation.

In general, the preliminary results achieved showed that the use of tensile reinforcement with enhanced fire resistance properties in simply supported reinforced concrete beams could enable reductions in the minimum tabulated fire safety requirements, depending on the case investigated. In fact, for some sections covered by the tabular methods the results found suggested that, depending on the number of bars, the use of FRS could be contrary to the safety criteria herein assumed as a critical temperature of 630 °C or irrelevant to the fire design of these elements. In these cases, it is suggested to complement the study by experimental means or by more precise numerical means.

This article presents the partial results of a research project in development at University of São Paulo.

Acknowledgements. The authors thank São Paulo Research Foundation: grant 2020/13003-1, São Paulo Research Foundation (FAPESP). The opinions, hypotheses and conclusions or recommendations expressed in this material are those of responsibility of the author(s) and do not necessarily reflect FAPESP's view.

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References

[1] EUROPEAN COMMITTEE FOR STANDARDIZATION. Eurocode 2: Design of concrete structures - Part 1-2: General rules - Structural fire design. 97 p., Belgium, 2004.

[2] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 15200:2012: Projeto de estruturas de concreto em situação de incêndio. 48 p., Rio de Janeiro, 2012.

[3] GARCÍA, H.; BIEZMA, M. V.; CUADRADO, J.; ORBE, A. Study of historical developments in the use of fire resistant steels. *Materials at High Temperature*, v. 30, n. 4, p. 313-319, 2013.

[4] WILDT, R. Fire resistant steel – a new approach to fire safety. In: *Proceedings of 7th World Congress of the Council on Tall Buildings and Urban Habitat*, Nova York, E.U.A., 2005.

[5] KUMAR, W.; SHARMA, U. K.; SHOME, M. Mechanical properties of conventional structural steel and fire-resistant steel at elevated temperatures. *Journal of Constructional Steel Research*, v. 181, 2021.

[6] SAKUMOTO, Y.; SAITO, H. Fire-safe design of modern steel buildings in Japan. *Journal of Construction and Steel Research*, n. 33, p. 101-123, 1995.

[7] FUSHIMI, M.; CHIKARAISHI, H.; KEIRA, K. Development of fire-resistant steel frame building structures. *Nippon Steel Technical Report*, n. 66, 1995.

[8] DING, J.; LI, G. Q.; SAKUMOTO, Y. Parametric studies on fire resistance of fire-resistant steel members. *Journal of Constructional Steel Research*, n. 60, p. 1007-1027, 2004.

[9] FIRE SAFETY DESIGN (FSD). TCD 5.0 User's manual. Fire. 129 p., 2007.
[10] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. *ISO 834: Fire Resistance Test - Elements of Building Construction*. Switzerland, 1975.