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Abstract

The structural elements of steel when subjected to the action of a fire suffer degeneration of their physical and chemical characteristics as a consequence of the high thermal effect, decreasing their resistance and rigidity, and causing alterations in the conditions of the initial state of the structure?s tensions and deformations. The stability guarantee of a structural element of steel under the action of a fire is provided by handling time, temperature and resistance. The sizing criteria are established as a function of the temperature curves versus time, which allows the possibility to calculate the effect of thermal action on the structural elements. The objective of this work is to compare the simplified sizing methods for the calculation of the traction of bars under the effect of high thermal gradients as proposed by ABNT NBR 14323: 1999 and the one presented in the most recent version of this guideline, published in 2013.

Index terms— thermo-structural analysis, metal structures, fire, sistematical analysis and dimensioning.

1 I. Introduction

uring the occurrence of the phenomenon of fire in a compartment, the analysis of the resistance of the steel structures can be performed by measuring conditions that the structure is submitted to in room temperature, combined with the simultaneous effect of high thermal gradients of a fire, thus designing buildings capable of withstanding the demands of such a situation. (Rigobello, 2011).

Components of the structure. Therefore, it is not taken into account the interaction between those elements during the heat propagation phase in the structure. **??**Kirchh of, 2004).

Fire safety engineering procedures are based on complex analysis when compared to the same phenomenon at room temperature. It should be considered that the behavior of the fire can change depending on the situation in such a way that its effects are attenuated and cannot be discarded during the design phase of the building. (Rigobello, 2011).

The results of the systematical analysis will be fundamental to evaluate the technological development in the field of research on steel structures under a fire situation, thus making it possible to stimulate the technical adoption of measures to protect the structures in an efficient, economical and simplified way.

When submitted to high thermal gradients due to a fire, the steel structures gradually suffer resistance and rigidity decreases, as well as changes in the conditions observed on their initial state of equilibrium, creating tensions and structural deformations. **??**Silva,1997).

The guarantee of the stability of a structural steel element under the action of fire is verified by handling the variables of time, temperature and resistance.

According to Mesquita (2013), in the temporal sphere the structure must be designed to withstand without collapsing during a period that allows the safe escape of the users and the safety of firefighting teams. In Brazilian standards and regulations, it is related to the Required Time of Resistance to Fire. It is represented by Equation 1?? ð ??"ð ??",?? > ?? ð ??"ð ??",??????**(1)**

Where: ?? ð ??"ð ??",?????? -is the required time of resistance to fire;

?? ð ??"ð ??",?? -is the calculation value of fire resistance based on standart fire ISO 834.

In order for the structural steel element avoid collapsing during the thermal action, its temperature must be below the critical temperature. This criterion is called verification in the temperature domain. In addition, according to Silva (2001), the safety of the structures is met in a fire situation when the temperature affecting the steel structural elements is lower than the temperature that promotes structural collapse, that is, the critical temperature.

The Equation #2 represents the structural safety check by the temperature degree analysis. Where:?? ?? ? ?? ????**(2)**

?? ?? -is the temperature of the steel; ?? ???? -is the critical temperature.

For the calculations concerning the resistance sphere, it must be taken into account the simultaneous effect of the actions that the structure is subjected to at room temperature, along with the exceptional actions (fire action). Based on this accidental combination, it is possible to calculate the resistance capacity of the structural elements, which should be lower than the calculation of the request in a fire situation (Mesquita, 2013).?? ð ??”ð ??”ð ??”ð ??” ,?? ? ?? ð ??”ð ??”ð ??”ð ??” ,??**(3)**

?? ð ??”ð ??”ð ??”ð ??” ,?? -is the requesting effort of calculation in situation of fire, obtained from the combination of actions;

?? ð ??”ð ??”ð ??”ð ??” ,?? -is the corresponding resistance effort of the structural element to the maximum limit state under consideration in a fire situation.

2 III. METHODOLOGY

The analytical model addressed in this study refers to the simplified sizing method, proposed by NBR 14323: 2013 for the determination of the thermal action that reaches the structure during the occurrence of a fire in a building. With this tool, it is possible to calculate the thermal gradient by means of the flux of radiation and convection emanating from the flames.

The simplified sizing method is applied to the structural elements engulfed by the hot gases, caused by the occurrence of a fire inside a compartment. It can be also applied in safety analysis of elements external to the building, but this will not be addressed in this study (Silva, 2001).

Without dismissing the deformations caused by thermal effects, the resistance analysis will be carried out so that the modulus of elasticity of the steel and its respective flow limit is constant and with its value adopted at elevated temperature **??**NBR 14323: 1999). The purpose of this analysis is to determine the ultimate load of the structural strength of steel.

In order to obtain the values of the resistant capacity of the structural steel elements through this method, it is necessary to take into account that the thermal analysis used is the stationary type, that is, the distribution of temperature and other thermal quantities along the cross section and the length of the steel element shall be considered uniform (Rodrigues, 2013).

For those cases in which safety engineering adopts the standard fire, the same expressions of this method can be employed, considering the effects of a variable temperature distribution through factors such as outflow resistance reduction and the modulus of elasticity corresponding to the highest temperature reached by the element during the action of the thermal gradient. **??**NBR 14323: 2013).

The calculation methodology discussed in this paper will follow the calculation procedures established by Silva (2001). However, it will be readapted to the new formulation proposed by NBR 14323: 2013. In this sense, it will continue with the determination of the resistance efforts of the structural elements in the traction, comparing it with the results obtained in the previous version of the norm in 1999.

According to Silva (2001), the analytical simulations that will be presented in this study were performed with the following simplifying assumptions:

? The structural element is fully immersed in the burning environment; ? The distribution of temperature in the structural element is uniform; ? There is an one-dimensional heat flux in the structural element; ? It is recommended to consider? ?? < 5??.

3 IV. DETERMINATION OF TEMPERATURE IN THE STRUCTURAL ELEMENT

For a more sophisticated analysis of the behavior of the steel piece subjected to the high heat exchanges caused by fire action, it is necessary to understand how the temperature distribution is carried out along its cross section through the analysis of heat transfer (Campêlo, 2008).

When the phenomenon of fire occurs in an environment, the temperature of the structural elements after a time interval tends to approach the temperature of the hot gases (Kimura, 2009). This temperature inequality generates a thermal action, characterized by a heat flux which is transferred to the structure by radiation and convection, causing a rise in temperature in the structural element (Silva, 2001).

Radiation is defined as the process in which heat does not need a physical medium to propagate. It flows in the form of waves from one body at elevated temperatures to the surface of another with lower temperature (Dorr, 2010).

Convection concerns the transfer of heat through the movement of fluids, gases or liquids. When the heat transfer occurs through the convective flow, the flame propagation is analyzed by the movement of the smoke and by the presence of the hot gases in the Global Journal of Researches in Engineering ( ) Volume XVIII Issue II Version I ceiling or out of the burning compartment (Azevedo, 2010).

The main mechanisms of thermal analysis of a structural element subject to the action of a fire are: test results, simplified models, and advanced or computational models (Rigobello, 2011). It is possible to determine the temperature increase by considering the thermal equilibrium between the heat coming from the fire and the heat absorbed by the steel profile (Campêlo, 2008).

4 V. MASS FACTOR

The temperature that the structure reaches during a fire is strongly influenced by the relationship between the surface area exposed to heat and the mass of the profile. This relationship is called a mass factor (Bellei, 2008).

For prismatic bars, the mass factor can be expressed by the relation between the perimeter exposed to the fire (u) and the area of the cross section of the bar, also known as the form factor of the section (Silva, 2001).

Regarding the structural elements of steel without thermal protection subject to fire action, the mass factor can be expressed by equation 4 ?? ð ??”ð ??” -is the cross-sectional area of the structural steel element.

It is possible to deduce that concerning elements with the same area, those that have less exposure to the fire will have a slower heating when compared to the other elements. And for the elements with the same exposed surface to the fire, the one that has greater mass will experience a slower heating as well. (Rodrigues, 2013) Therefore, the lower the mass factor of a structural element is, the greater is its resistance to the various temperatures it undergoes (Bellei, 2008).

5 a) Generality

NBR 14323: 2013 establishes that for an uniform temperature distribution along the cross section, the temperature rise,??? ??,?? , of a structural steel element uncoated against the fire inside of a building, over a period of time, can be determined by means of equation 5.??? ??,?? = ?? ??,? (?? ?? ð ??”ð ??” ?) ?? ?? ?? ?? ??? ??**(5)**

Where:

??? ??,?? -is the temperature change in a steel structural element, during a time periodÎ?”t; ?? ??,? -is a correction factor for the shading effect, which can be taken equal to 1.0 or determined as we will see later; ?? ?? ð ??”ð ??” ? -is the mass factor for structural steel elements with no protection against fire, expressed in meters at a minus one (m-1); ?? ?? -is the specific mass of the steel, expressed in kilograms per cubic meter (??ð ??”ð ??”/?? 3); ?? ?? -is the specific heat of the steel, expressed in joules per kilogram and by degrees Celsius (J / kg ° C);

??-is the value of the heat flux per unit area, expressed in watts per square meter (??/?? 2); ? ?? -is the time period, expressed in seconds.

6 b) Shading effect

The shading effect is characterized by the fact that it acts on concave shaped profiles in cross sections H or I. It is caused by local obstructions of the thermal radiation due to the shape of the steel profile, as shown in figure 1 (Rigobello, 2011).?? ??? = 0,9 (?? ?? ð ??”ð ??” ?) ?? (?? ?? ð ??”ð ??” ?)**(6)**

Where:

(?? ?? ð ??”ð ??” ?) ?? -is the value of the mass factor, defined as the ratio between the perimeter exposed to the fire of a hypothetical box that surrounds the profile and cross-sectional area of the profile;

(?? ?? ð ??”ð ??” ?)-is the mass factor for structural steel elements with no protection against fire.

For closed cross-sections such as the coffin and tubular, circular and rectangular sections, and solid ones as the rectangular sections, all fully exposed to fire, the value of k_sh = 1, according to Figure 1.

7 Consider:

? a (t = 0) = 20? (7) Where:

? a (t = 0)-is the temperature of the steel at room temperature. If t = 5s.

The temperature of the gases is determined: ? g (t) = 345 log(8t + 1) + 20 (8) Where:

? g (t)-is the temperature of the gases at time t; t -is the time in minutes.

The heat flux due to radiation is determined:? r (t) = 5,67x10 ?8 ? res ??? g (t) + 273? 4 ? (? a (t ? ? t) + 273) 4?**(9)**

If ? t = 5/60 min and ? res = 0,7.

Where: ?? ?? -is the component of the heat flux due to radiation; ?? ?????? -is the resulting emissivity; ?? ð ??”ð ??” (??)-is the temperature of the gases at time t; ?? ?? (?? ? ? ??)-is the temperature of the steel at time t -Î?”t.

The heat flux due to convection is determined: Where: ?? ?? -is the coefficient of heat transfer by convection, taken equal to 25 W / m². The heat flux is determined:?? = ?? ?? + ?? ??**(11)**

Where: ??-is the value of the heat flux per unit area;

The temperature variation of the steel ??? ??,?? .

??? ??,?? = ?? ??? (??/?? ð ??”ð ??”) ?? ?? ?? ?? ??? ?? (12) It is determined the value of the temperature of the steel:?? ?? (??) = ?? ?? (?? ? ???) + ??? (**13**)

We return to item c, with t + Î?”t, instead of t.

Figure 2 shows the influence of the mass factor in determining the temperature of the structural element. Assuming that the member is subject to an ISO 834 standard fire action, determine the element resistance after

30 minutes of exposure. Consider that in the first case the four sides of the structural element are exposed to the flames and in the second case there is the exposure of only three of its sides. Make sure that the profile has the minimum conditions for temperature and resistance evaluations.

Assuming that the element has all four sides exposed, according to NBR 14323: 2013 we will have:?? ð ??"ð ??" = 345 log(8 * 30 + 1) + 20 = 842?**(14)**

Determination of the temperature of the gases:

The mass factor is then calculated according to the characteristics of the profile, as follows in Chart1. Assuming that the element has all four sides exposed, according to NBR 14323: 1999 we will have: The temperature of the gases: ?? ð ??"ð ??" = 345 ????ð ??"ð ??"(8 * 30 + 1) + 20 = 842?The mass factor according to the characteristics of the profile shown in figure **??** Then, the model of Franssen and Real (2012) is used to determine the temperature of the steel devoid of thermal protection, exposed 30 minutes to the fire ISO 834, at time t -Î?"t, as presented in Chart 2. However, for this version of the 1999 standard it was not taken into account the effect of shading, that is, ?? ??? = 1. The following is the heat flow by Then, the temperature increase of the steel is determined by: The Chart 5 shows a summary of the calculation to determine the profile resistance, considering that the heat unprotected steel element has 3 of its sides exposed. According to NBR 14323:1999: ?? ?? = 823,96?? ?? ?? ?? ? (?? ???) ? ?? ?? ?? ? ?? (?? ???) ?? ð ??"ð ??"ð ??"ð ??" ? ?? ?? ?? ? (?? ???) ?? ?? (?? ? ? ??)(??? ?? = (??/

Then, the flow limit reduction factor is determined for the calculation of the tensile strength of the structural element in a fire situation. For this, Chart 3 Thus, for the intermediate values of ?? ?? (?? ? ???), it is necessary to interpolate. In this study the determined value was ?? ?? (?? ? ???) = 823,28?.Then, the radioactive flow of heat is determined:

8 VIII. Conclusion

In this study, the fundamental concepts for the analysis of the resistance of steel structural elements subjected to a fire phenomenon were studied, using the simplified method of design used by ABNT NBR 14323 when submitted to an axial tensile load. In addition, it dealt with how the heat transfer from the flames to the structure occurs, also addressing the necessary checks of the safety conditions of the buildings.

It became evident how important that the mass factor is concerning the dimensioning of the structures under a fire situation. The larger the mass of the element is, the greater is its ability to absorb heat and withstand the thermal effect. On the other hand, its cooling will occur slowly. In cases where the mass of the element is small, the heat flow entering the element is characterized by rapidly raising the temperature of the profile, rendering its resistance capacity lower in a shorter time.

It was possible to verify that the nonconsideration of the shading effect by the 1999 norm leads to conservative results, that is, the element has less design resistance. In the calculation of the radiation share the emissivity used by the 1999 standard is 0.5, which contrasts with the resulting emissivity of 0.7 adopted by the referred standard in 2013. Thus, it is not possible to verify a significant difference when comparing the methods to traction-moved elements. [1]

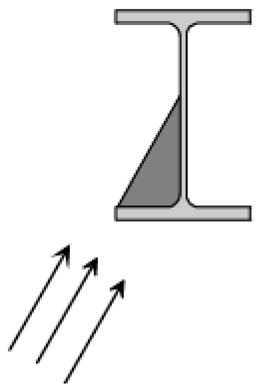


Figure 1:

1

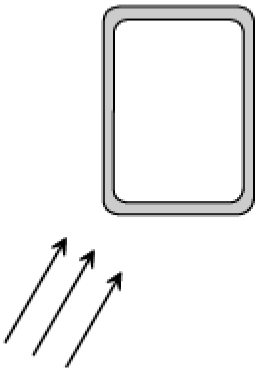


Figure 2: Figure 1 :

2

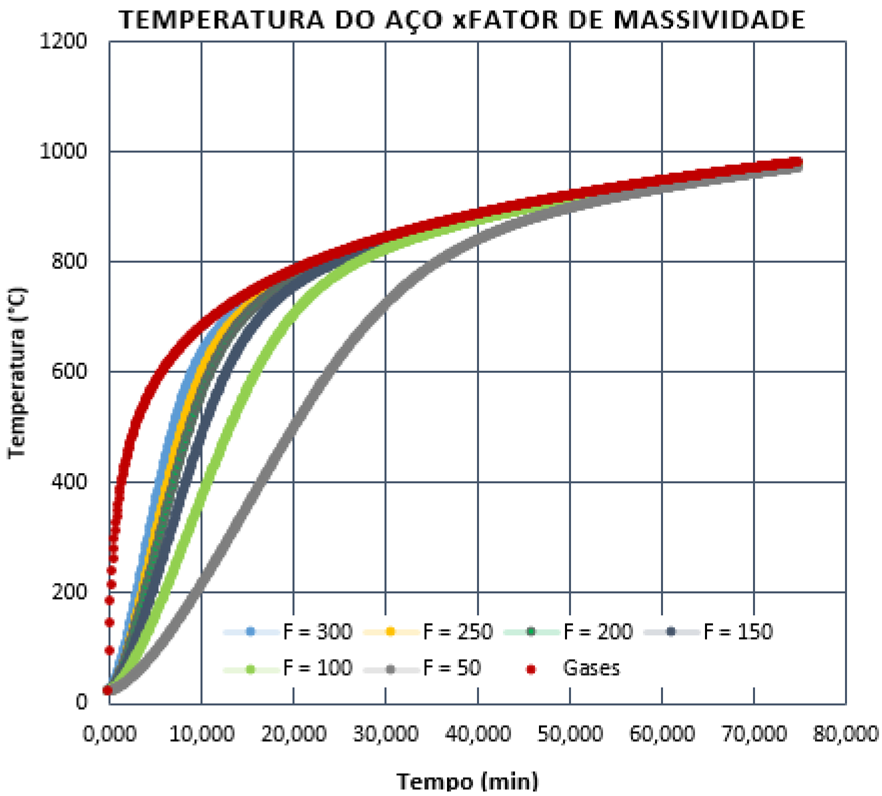
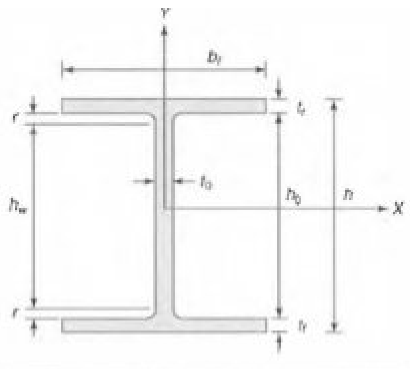


Figure 3: Figure 2 :

8 VIII. CONCLUSION



Perfil	Massa	Alt.	Área	Alma		Mesa		Eixo X–X				Eixo Y–Y				J		
I	m	h	A	t_0	h_0	t_f	b_f	I_x	W_x	i_x	Z_x	I_y	W_y	i_y	Z_y		$b_f/2t_f$	h_w/t_0
	kg/m	mm	cm²	mm	mm	mm	mm	cm⁴	cm³	cm	cm³	cm⁴	cm³	cm	cm³	cm⁴		
14 W 150 × 37,1	37,1	162	47,8	8,1	139	11,6	154	2244	277,0	6,85	313,5	707	91,8	3,84	140,4	20,6	6,6	14,7

Figure 4: Chart 1 : 4 ?

Temperature of unprotected steel in °C, exposed to the ISO 834 fire curve for different values of $k_{sh}\frac{A_m}{V}$, $[m^{-1}]$ (continued)

Time [min.]	10 m⁻¹	15 m⁻¹	20 m⁻¹	25 m⁻¹	30 m⁻¹	40 m⁻¹	60 m⁻¹	100 m⁻¹	200 m⁻¹	300 m⁻¹	400 m⁻¹
24	197	271	337	396	448	532	641	726	767	791	799
25	207	284	353	414	467	552	658	732	780	801	807
26	217	298	369	432	485	570	674	735	792	809	813
27	227	311	385	449	503	588	688	739	803	816	820
28	237	324	401	466	521	604	701	746	813	823	826
29	247	338	416	482	538	621	712	756	821	829	831
3 ~~30~~	~~257~~	~~351~~	~~431~~	~~498~~	~~554~~	~~636~~	~~721~~	~~767~~	828	835	837

Figure 5: Chart 3 :

?? ? . (4)
??

[Note: ð ??"ð ??"??-is the perimeter of the steel structural element, exposed to fire;]

Figure 6:

?? ?? ??
??
(??/?? ??)

161,05 132,21 118,19 785,18 1099,55

Chart 4: Determination of the strength of the structural steel element, as NBR 14323:2013

Verifications:

Temperature Domain

??
ð ??"ð ??"ð ?
,???? ?
ð ??"ð ??"ð ?
,???? 151,
(????)
200(????)
(Does not rei

?? ???? = 39,19 ???? ? 1 0,9674. ?? ??,?? 3,833 ? 1? + 482 < ?? ??

?? ???? = 39,19 ???? ? 1 0,9674. 0,1226 3,833 ? 1? + 48786,71

?? ???? = 784,084 < 787,767?

(Does not check)

Figure 7: °C)

is used observing that there was no change in the respective values of the coefficients in the update from one norm to another.
By interpolation, the value of?? ??,?? = 0,09802.
For traction, the calculation resistance is:
Verifications
Temperature Domain

?? ???? = 39,19 ln ?	1 0,9674.?? ?? ,??	3,833 ? 1? + 482 < ?? ??
?? ???? = 39,19 ln ?	1 0,9674. 0,09802 3,833 ? 1? + 482	

< 823,96 ?? ???? = 832,18? >
823,96?
(Does not check)
Resistance Domain
?? ð ??"ð ??"ð ??"ð ??" ,???? ? ?? ð ??"ð ??"ð ??"ð ??" ,????
117,1339 (????) ? 200 (????)
?? ?? ?? ?? ????? (Does not resist)

??? 193,263337,4.5 = 0,6847?
?? 7850
= 600

Figure 8:

[Kimura ()] , E F A Kimura . *SP* 2009. Análise Termoestrutural de Pilares de Aço em Situação de Incêndio, Dissertação de Mestrado do Programa de Pós-Graduação e Concentração em Engenharia de Estruturas, Escola de Engenharia de São Carlos, Universidade de São Paulo

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