Computational tool for design of steel elements in fire situation with and without fire protection material

Thayná C. S. Marcelino[1], Macksuel S. Azevedo[1], Adenilcia Fernanda G. Calenzani[1]

[1]*Dept. of Civil Engineering, Federal University of Espírito Santo*
Avenida Fernando Ferrari, 29075-910, Espírito Santo/Vitória, Brasil
thayna.marcelino@edu.ufes.br, macksuel.azevedo@ufes.br, adenilcia.calenzani@ufes.br

Abstract. At high temperatures, steel presents changes in its mechanical properties, which can cause severe accidents. Due to this, fire safety engineering has two objectives: the preservation of life and the reduction of property losses. Among the measures that can be adopted to increase the fire resistance time of a structure, the application of passive fire protection materials stands out. Despite the importance of these materials, information about their fire behavior and their thermal properties are still limited, causing, currently in Brazil, the material thickness to be determined based on fixed critical temperature values. Therefore, in this paper, a computational tool was developed to help the design of fire protection materials in steel structures. The tool was developed in Visual Basic for Applications language and performs the design of steel columns and beams at room temperature and in a fire situation, with or without fire coating materials. The computer program considers protective materials such as spray-applied mortar, gypsum board, and intumescent paint. The results obtained by the developed tool, when compared with the literature, were satisfactory, indicating that the tool is a reliable and useful instrument for the correct design and specification of protection materials.

Keywords: steel structures in fire situation, design, fire resistant materials, computer program.

1 Introduction

Steel is a material that detains many advantages, which has favored its use as a structural element. For this reason, the behavior of this material and its sizing at room temperature are already well-known among professionals and engineering students, that query the Brazilian norm, ABNT NBR 8800:2008 [1], to be guided about this matter. However, studies regarding the design of these elements in a fire situation are more recent and, due to their importance, they have been gaining more attention.

The effects of a fire can be particularly severe since it reduces the steel's mechanical properties due to the exposure to high temperatures, leading to the loss of strength and stiffness. To ensure the safety of assets and the preservation of lives, structures must be designed considering the action of fire. In Brazil, the standard that holds the guidelines for this design is ABNT NBR 14323:2013 [2].

In addition, some actions are also adopted to increase the fire resistance time of the structure. For example, the use of fire protection materials such as spray-applied mortars, rigid boards, and intumescent paints, which are some of the measures that stand out. Mróz, Hager and Korniejenko [3] explain that such materials work as a thermal protection that aims to prevent the temperature of the structural element from increasing excessively, keeping it from reaching the critical temperature during a fire.

Despite the importance of these materials, information about their fire behavior and their thermal properties is still limited, which has encouraged some studies on the subject around the world. Piquer and Hernández-Figueirido [4] compared steel columns, with and without protective material, with partially encased steel-concrete composite columns, analyzing the costs and structural performance of the columns at elevated temperatures. Zhang *et al.* [5], in a numerical study, investigated the effect on the steel temperature by varying the thermal properties and thickness of the Spray-applied Fire Resistive Material (SFRM). Kodur and Shakya [6], meanwhile, aimed to evaluate the thermal properties of gypsum and vermiculite-based materials at different temperatures. And the intumescent paints, their thermal properties effects, and the temperature's influence on the material thickness variation were the main subjects of the investigation by De Silva *et al.* [7].

In Brazil, this gap of information also demonstrates another impact: material thickness, particularly for intumescent paints, is usually determined based on fixed critical temperature values. For this reason, Guimarães [8] investigated existing methodologies for the design of fire-proofing materials, using as study material the spray-applied mortar. Besides, Santos [9] also evaluated the thermal and mechanical responses of columns protected with gypsum boards and sprayed mortar through experiments and numerical analysis.

In this paper, to contribute to the subject in question, a computational tool was developed to assist in the design of fire protection materials in steel structures. The modules of the computer program were validated using numerical examples from the technical literature, and the results obtained were compared and discussed, indicating the reliability of the developed tool.

2 Methodology

The computational program was developed in Visual Basic for Application (VBA) language, in the Microsoft Excel environment, and performs the design of steel columns and beams at room temperature and in a fire situation, with and without fire protection material.

The tool has three modules: a module for verification at room temperature, a module for verification in fire situation without protection material, and a module for verification in fire situation with protection material. In each of them it is possible to verify columns subjected to flexo-compression and beams subjected to bending moment.

The database was loaded with hot rolled profiles from Gerdau's catalog [10], welded profiles of the CS, VS, and CVS series, presented by ABNT NBR 5884:2013 [11], and the user can also manually enter the profile's dimension values. Moreover, different steel types with different strengths are available. Fig. 1 shows the screen where the initial information about the analyzed element is given.

Furthermore, in the module for verification in fire situation with protection material, the user has the option of choosing the used protection material: spray-applied mortar, rigid board, or intumescent paint.

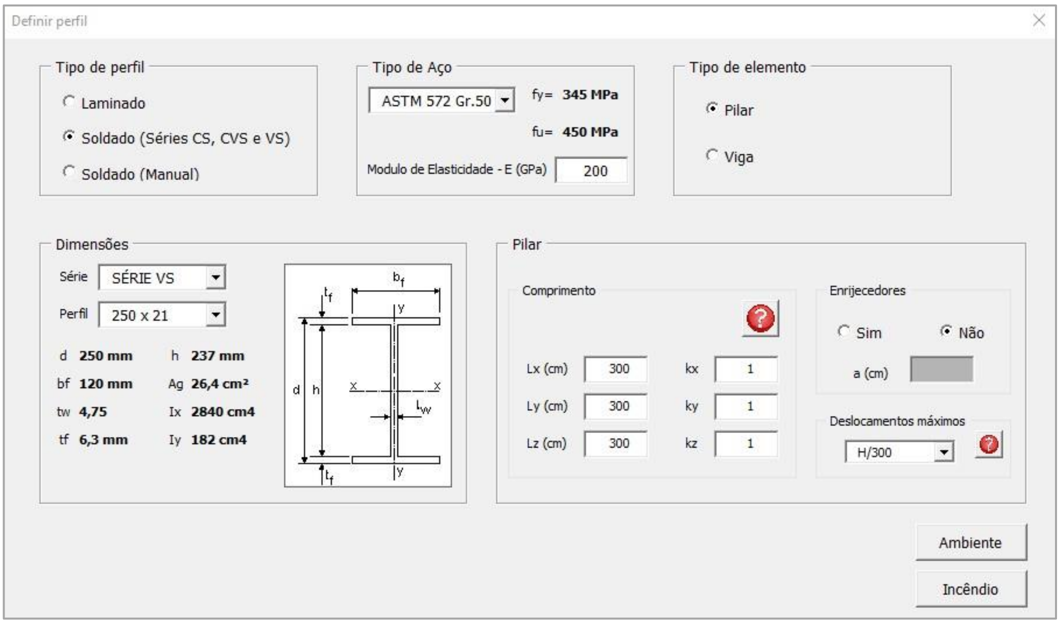

Figure 1. Screen for defining the element to be verified.

In each module, two calculation routines were created, one for flexion-compression (column) and the other for bending moment (beam), for a total of six routines. Thus, to validate the program, six examples from the literature were run, aiming to validate each of the developed routines.

The routines for elements subjected to flexo-compression and bending moment at room temperature were developed in accordance with ABNT NBR 8800:2008 [1], while the routines for verification in a fire situation were developed in accordance with ABNT NBR 14323:2013 [2]. As the focus of this work is the steel elements in a fire situation, item 2.1 focuses on the routines developed for this situation.

2.1 Routines for verification of elements in a fire situation with and without protection material

To achieve the intended results, it was necessary to develop calculation subroutines in each module of the program. Subroutines were made for the determination of the design resistance of a compression member in fire situation ($N_{fi,Rd}$), for the determination of the design resistance moment in fire situation ($M_{fi,Rd}$), and for the verification of members subject to combined bending and axial compression, as shown to Tab. 1.

Table 1. Equations to obtain the design resistance efforts in fire situation.

Design resistance of a compression member		
$N_{fi,Rd} = \chi_{fi}.k_{y,\theta}.A_g.f_y$	for $\frac{b}{t} \leq 0{,}85\left(\frac{b}{t}\right)_{lim}$	(1)
$N_{fi,Rd} = \chi_{fi}.k_{\sigma,\theta}.A_{ef}.f_y$	for $\frac{b}{t} > 0{,}85\left(\frac{b}{t}\right)_{lim}$	(2)
Design moment resistance for the ultimate limit state of local buckling		
$M_{fi,Rd} = \kappa.k_{y,\theta}.M_{pl}$	for $\lambda \leq \lambda_{p,fi} = 0{,}85\lambda_p$	(3)
$M_{fi,Rd} = \kappa.k_{y,\theta}.M_y$	for $\lambda_{p,fi} < \lambda \leq \lambda_{r,fi}$	(4)
$M_{fi,Rd} = \kappa.k_{\sigma,\theta}.M_y$	for $\lambda > \lambda_{r,fi} = 0{,}85\lambda_r$	(5)
Design moment resistance for the ultimate limit state of lateral-torsional buckling		
$M_{fi,Rd} = \kappa.\chi_{fi}.k_{y,\theta}.M_{pl}$		(6)
Interaction equation for members subject to combined bending and axial compression		
$\frac{N_{fi,Sd}}{N_{fi,Rd}} + \frac{8}{9}\left(\frac{M_{x,fi,Sd}}{M_{x,fi,Rd}} + \frac{M_{y,fi,Sd}}{M_{y,fi,Rd}}\right) \leq 1{,}0$	for $\frac{N_{fi,Sd}}{N_{fi,Rd}} \geq 0{,}2$	(7)
$\frac{N_{fi,Sd}}{2N_{fi,Rd}} + \frac{M_{x,fi,Sd}}{M_{x,fi,Rd}} + \frac{M_{y,fi,Sd}}{M_{y,fi,Rd}} \leq 1{,}0$	for $\frac{N_{fi,Sd}}{N_{fi,Rd}} < 0{,}2$	(8)

In Tab. 1, $k_{y,\theta}$, $k_{E,\theta}$ and $k_{\sigma,\theta}$ are the reduction factors for yield strength, stiffness, and yield strength for members subject to local buckling, respectively; χ_{fi} is the reduction factor for flexural buckling in the fire design situation; A_{ef} is the effective area of the cross-section; $\lambda_{p,fi}$ and $\lambda_{r,fi}$ are the slenderness parameters in a fire situation; λ_p and λ_r are the slenderness parameters in normal temperature; M_{pl} is the plastic moment resistance for normal temperature design; M_y is the yield moment resistance for normal temperature, and κ is an adaptation factor that takes into account the beneficial effect of uniform temperature distribution in the cross-section, with all these values described in ABNT NBR 14323:2013 [2].

3 Results

To verify the reliability of the results obtained by the developed computational tool, a total of six validation examples from the literature were calculated, two for each module of the program: one for column and one for beam. For the room temperature design module, the two examples (Example 1 and Example 2) were taken from Fakury, Silva and Caldas [12]. For the fire situation without protective material module, the column example (Example 3) was taken from Rodrigues and Oliveira [13], and the beam example (Example 4) was taken from Nascimento and Ferreira [14]. For the last module, the two examples (Example 5 and Example 6) were taken from Nascimento and Ferreira [14].

3.1 Example 1: Column under axial compression at room temperature

In this example, Fakury, Silva and Caldas [12] propose to verify a welded I profile subjected to a compressive force of 1500 kN. The profile has the following dimensions: d= 650mm, b_f = 400mm, t_f = 9.5 mm e t_w = 8.0 mm. It is made of ASTM A 242 steel and has lengths L_x = 10m, L_y = L_z = 5 m.

Tab. 2 presents the results obtained by the computational tool confronted with the results provided from Fakury, Silva and Caldas [12].

Table 2. Percentage differences between the results of Example 1.

Verification	Fakury, Silva and Caldas [12]	Program results	Difference
Elastic critical force - x (N_{ex})	18693 kN	18693.16 kN	-0.001%
Elastic critical force - y (N_{ey})	8003 kN	8003.09 kN	-0.001%
Reduction factor - outstand flanges (Q_s)	0.53	0.53	0.000%
Reduction factor – internal parts (Q_a)	0.81	0.81	0.000%
Reduction factor - local buckling (Q)	0.43	0.43	0.000%
Non-dimensional slenderness (λ_0)	0.48	0.48	0.000%
Reduction factor - compression (χ)	0.908	0.910	-0.220%
Design compression resistance ($N_{c,Rd}$)	1549 kN	1545.45 kN	0.229%
$N_{c,Sd}/N_{c,Rd}$	0.9684	0.9706	-0.230%

It can be observed in this example that the results obtained by the developed computer program demonstrate a maximum difference of 0.230%, when compared with the literature, which can be justified by rounding or simplifications carried out during the calculations. Thus, the results obtained proved to be reliable.

3.2 Example 2: Beam subjected to bending moment at room temperature

Example 2 consists of a beam with a span of 12 m, formed by a welded profile PS 500 x 300 x 12.5 x 8.0 of USI CIVIL 350 steel that has three different unbraced lengths (L_{b1} = 3 m, L_{b2} = 4 m e L_{b3} = 5m). The beam is subjected to a bending moment of 622.41 kN.m and a shear force of 207.47 kN, and then it's observed in order to verify the beam for ultimate limit states and for deflection. The Tab. 3 displays the results obtained for the example, where it is possible to notice that the largest percentage difference found was 0.020%.

Table 3. Percentage differences between the results of Example 2.

Verification	Fakury, Silva and Caldas [12]	Program results	Difference
Flange Local Buckling (FLB)	651.56 kN.m	651.59 kN.m	-0.005%
Web Local Buckling (WLB)	725.14 kN.m	725.26 kN.m	-0.016%
Lateral-Torsional Buckling (LTB) - L_{b1}	-	725.28 kN.m	-
Lateral-Torsional Buckling (LTB) - L_{b2}	709.69 kN.m	709.84 kN.m	-0.020%
Lateral-Torsional Buckling (LTB) - L_{b3}	725.14 kN.m	725.26 kN.m	-0.016%
Design shear resistance (V_{Rd})	756.18 kN	756.21 kN	-0.004%
Maximum vertical deflection (δ_p)	0.0343 m	0.0343 m	0.000%

3.3 Example 3: Determination of the design resistance effort of a column at elevated temperature

This example proposed by Rodrigues and Oliveira [13] aims to determine the design axial resistance of a column with the profile W 310 x 38.7, for a temperature of 500 ºC. The column is 2.8m long, with steel with yield strength of 345 MPa. The results are shown in Tab. 4.

Table 4. Percentage differences between the results of Example 3.

Verification	Rodrigues and Oliveira [13]	Program results	Difference
$k_{E,\theta}$	0.60	0.60	0.000%
$k_{\sigma,\theta}$	0.53	0.53	0.000%
N_{ex}	21600 kN	21604.87 kN	-0.023%
N_{ey}	1830 kN	1830.41 kN	-0.022%
N_{ez}	2744 kN	2744.25 kN	-0.009%
Q_s	1.000	1.000	0.000%
Q_a	0.947	0.940	0.739%
Q	0.947	0.940	0.739%
$\lambda_{0,fi}$	1.108	1.110	-0.181%
χ_{fi}	0.44	0.44	0.000%
$N_{c,Rd}$	378.60 kN	377.37 kN	0.325%

In Tab. 4, the symbols presented in the first column are defined according to Tab. 1, Tab. 2, and Tab. 3. For this case, it is possible to observe that the largest percentage difference was 0.739% and occurred for the reduction coefficient Q. This small disparity can be disregarded, as it does not even reach 1%.

3.4 Example 4: Verification of a beam in fire situation without fire protection material

Example 4 is a beam with a span of 2.0 m and continuous lateral-torsional restraint, subjected to a bending moment and shear force of 17.6 kN.m and 35.2 kN, respectively. The beam profile is a welded profile VS 250 x 21, with ASTM 572 Gr. 50 steel, with a yield strength of 345 MPa. To calculate the TRRF, Nascimento and Ferreira [14] report that the beam is part of a building with 10 floors of 3 m. The building has a floor area of 600 m², a vertical ventilation area of 100 m², fire detectors, and a normal fire activation risk. The results are summarized in Tab 5.

Table 5 – Percentage differences between the results of Example 4.

Verification	Nascimento and Ferreira [14]	Program results	Difference
Tabular method	90.00 min	90.00 min	0.000%
Time equivalence method (T_{eq})	56.82 min	60.00 min	-5.597%
Required fire resistance time (*TRRF)*	60.00 min	60.00 min	0.000%
Steel temperature (θ_a)	942.50 °C	943.35 °C	-0.091%
Reduction factor - yield strength ($k_{y,\theta}$)	0.0515	0.051	0.971%
WLB - $M_{x,fi,Rd}$	6.24 kN.m	6.22 kN.m	0.321%

In this example, the greatest percentage difference was 5.597%. Nonetheless, this value did not impact the results, just like the moment calculated in the WLB's verification, which presented a difference of only 0.321%. It is important to note that the bending moments for FLB and the design shear resistance were not calculated in this case. This is explained by the fact that Nascimento and Ferreira [14] began the verification by the WLB and, after confirming that the calculated design resistance (6.24 kN.m) was smaller than the bending moment of 17.6 kN.m, they concluded the analysis signaling the need to use a protection material. Item 3.6 shows the continuation of this example.

3.5 Example 5: Column in fire situation with fire protection material

Example 5 consists of a column in welded profile CS 400 x 106. The column belongs to the same building as Example 4, also consisting of ASTM 572 Gr. 50 steel. All its sides are exposed to fire, and it is protected by a sprayed mortar that possess the following properties: t_m = 0.02 m, λ_m = 0.173 Wm/°C, c_m = 2344 J/kg°C e ρ_m = 240 kg/m³. The results for this case are shown in Tab. 6.

Table 6. Percentage differences between the results of Example 5.

Verification	Nascimento and Ferreira [14]	Program results	Difference
θ_a	522.13 °C	521.53 °C	0.115%
$k_{y,\theta}$	0.711	0.713	-0.281%
$k_{E,\theta}$	0.536	0.538	-0.373%
$k_{\sigma,\theta}$	0.479	0.480	-0.209%
Q_s	0.870	0.870	0.000%
Q_a	0.98	0.980	0.000%
Q	0.86	0.860	0.000%
$\lambda_{0,fi}$	0.218	0.230	-5.505%
χ_{fi}	0.892	0.890	0.224%
$N_{c,Rd}$	1714.67 kN	1712.70 kN	0.115%

Again, the percentage differences found in this case are small, with the largest being related to reduced slenderness index in fire (5.505%). It is noteworthy that Nascimento and Ferreira [14], in this example, only request the determination of the temperature of the structural element with protection. The other information calculated and exposed in the table was created in a spreadsheet and compared to the program results.

3.6 Example 6: Verification of beam in fire situation with protective material

Example 6 is a continuation of Example 4, however, it uses spray-applied mortar as a protection material. The material properties are the same as in Example 5 and the results are shown in Tab. 7.

Table 7. Percentage differences between the results of Example 6.

Verification	Nascimento and Ferreira [14]	Program results	Difference
θ_a	686.36 °C	685.52 °C	0.122%
$k_{y,\theta}$	0.263	0.265	-0.760%
FLB - $M_{x,fi,Rd}$	23.16 kN.m	23.84 kN.m	-2.955%
WLB - $M_{x,fi,Rd}$	26.16 kN.m	26.36 kN.m	-0.784%

With these results, it is possible to observe that for the same TRRF of Example 4, the temperature that was previously higher than 900 °C, becomes lower than 700 °C, indicating that the use of fire protection material allowed a temperature reduction of more than 200º in the structural element. It is also noted that this reduction in temperature allowed an increase in the design resistance moment for FLB, from approximately 6 kN.m to approximately 26 kN.m. In addition, for this case, the largest percentage difference found was 2,955%, which is also a relatively small value.

4 Conclusions

The primary objective of this work was to validate a computational tool developed with the purpose of aiding the correct design of steel structural elements exposed to fire. For this purpose, some numerical examples from the literature were run.

The results obtained by the computational tool, when compared with the existing literature, were satisfactory, since the percentage differences found were very small, with the largest being 5,597%. This value, however, is from one of the intermediate results of the example and had no significant impact on the result. It's also important to emphasize that these differences may be due to numerical rounding and some simplifications adopted.

Furthermore, the tool and the analyzed results allowed to observe the importance of the fireproofing material. When using 0.02 m of protection in spray-applied mortar, examples 4 and 6 demonstrated a decrease in steel temperature and an increase in the resistance effort.

Therefore, it is possible to conclude that the developed tool is a reliable and useful instrument for the correct design and specification of fire protection materials.

Acknowledgements

The authors acknowledge the Brazilian Center for Steel Construction (CBCA) and the Brazilian Federal Government Agency CAPES for the financial support provided during the development of this research, and also the Postgraduate Program in Civil Engineering (PPGEC) of the Federal University of Espírito Santo (UFES). The second author thanks the Brazilian Federal Government Agency CNPq for the productivity research grant number 309741/2020-3.

Authorship statement

The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] Associação Brasileira de Normas Técnicas. NBR 8800: Projeto de Estruturas de Aço e de Estrutura Mistas de aço e concreto de Edifícios. Rio de Janeiro, 2008.
[2] Associação Brasileira de Normas Técnicas. NBR 14323: Projeto de Estruturas de Aço e de Estrutura Mistas de aço e concreto de Edifícios em Situação de Incêndio. Rio de Janeiro, 2013.
[3] K. Mróz, I. Hager and K. Korniejenko, “Material solutions for passive fire protection of buildings ans structures and their performances testing”. *Procedia Engineering*, vol. 151, pp. 284-291, 2016.
[4] A. Piquer and D. Hernández-Figueirido, “Protected steel columns vs partially encased columns: Fire resistance and economic considerations”. *Journal of Constructional Steel Research*, vol. 124, pp. 47-56, 2016.
[5] C. Zhang, A. Pintar, J. M. Weigand, J. A. Main and F. Sadek, “Impact of variability in thermal properties os SFRM on steel temperatures in fire”. *Fire Safety Journal*, vol. 123, pp. 103361, 2021.
[6] V. K. R. Kodur and A. M. Shakya, “Effect of temperature on thermal properties of spray applied fire resistive materials”. *Fire Safety Journal*, vol. 61, pp. 314-323, 2013.
[7] D. De Silva, A. Bilotta and E. Nigro, “Experimental investigation on steel elements protected with intumescent coating”. *Construction and Building Materials*, vol. 205, pp. 232-244, 2019.
[8] P. P. O. Guimarães. Sobre o dimensionamento do revestimento contra o fogo de estruturas de aço. Masters dissertation, University of São Paulo, 2007.
[9] M. M. L. Santos. Pilares de aço formados a frio com revestimento contra fogo – análise experimental e numérica. Masters dissertation, Federal University of Pernambuco, 2018.
[10] Gerdau. Tabela de bitolas.
[11] Associação Brasileira de Normas Técnicas. NBR 5884: Perfil I estrutural de aço soldado por arco elétrico. Rio de Janeiro, 2013.
[12] R. H. Fakury, A. L. R. C. Silva and R.B. Caldas. *Dimensionamento de elementos estruturais de aço e mistos de aço e concreto*. Pearson Education do Brasil, 2016.
[13] J. P. C. Rodrigues and R. L. G. Oliveira. *Dimensionamento de estruturas em situação de incêndio: segundo as normas brasileiras*. Oficina de Textos, 2021.
[14] K. O. Nascimento and W. G. Ferreira. *Dimensionamento de estruturas de aço em situação de incêndio: Abordagens conceitual e normativa (com exemplos numéricos)*. LBF, 2021.