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Influence of mortar coating on the thermal analysis of steel profiles in a fire situation

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ABSTRACT. This article aims to perform the thermal analysis of different welded profiles of the VS and CS series with and without thermal protection subjected to fire action according to the nominal fire curve ISO 834. The fire protection studied was the contour type of constant thickness and the coating material considered was Blaze Shield II mortar. The temperature evolution in the profiles was evaluated using the analytical models prescribed by ABNT NBR 14323:2013 and three-dimensional numerical models using the ABAQUS® software. In general, it was observed that the results obtained by the analytical methods were in agreement with the numerical ones and that the use of mortar as fire protection evaluated in this study proved to be an efficient solution for fire protection. It was also possible to demonstrate that the increase in coating thickness, the reduction in thermal conductivity, and the increase in the specific heat of the constituent material provide a slower evolution of the temperature of the steel structural elements.

Keywords: steel structures; numerical analysis; thermal protection; fire situation.

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Introduction

It is possible to observe a large volume of statistical data on fires that have occurred in recent years in Brazil (*Instituto Sprinkler Brasil* [ISB], 2021). Therefore, the importance of the wide dissemination of knowledge regarding the aspects involved in fire safety projects is highlighted.

Structural elements, when subjected to high temperatures, undergo important changes in their mechanical-structural behavior, the main one being the decrease in their strength and rigidity, which can cause the premature collapse of a given structural element or even the entire structure. Steel, in particular, is a material that has high thermal conductivity and this allows the development of high temperatures in a short period. Therefore, the use of thermal protection capable of delaying the structural element's heating is recurrent. In this sense, the thermal analysis of a structural element, which consists of obtaining its temperature development as a function of time when subjected to thermal action, represents a very important step in the evaluation of a structure in a fire situation, since discrepancies in this analysis can lead to serious design errors (Real, 2003).

Thermal analysis can be performed through experimental tests, analytical methods, or numerical methods via computational modeling. However, it is noteworthy that the use of analytical methods prescribed in technical standards is a frequent practice in the design of structures in fire situations worldwide (Oliveira, Fonseca, Campilho, & Piloto, 2021). In Brazil, the design of steel structures and steel-concrete composite structures for buildings in fire situations is guided by NBR 14323 (ABNT, 2013). However, it is important to emphasize that the analytical methods prescribed by the Brazilian standard, which in turn are based on Eurocode 3 (European Committee for Standardization [CEN], 2005), assumes some hypotheses to enable the practicality of application. Some of them are the uniform temperature distribution to the cross-section of the structural element and the uniform temperature spread in the fire environment. Given this, it is concluded that the investigation, whether through numerical analysis or experimental tests, of the analytical methods' conformity when applied to different structural profiles and fire exposure situations.

The study of structures in a fire situation is a topic that, due to its relevance, has been studied by several authors in recent years. Among them, the research by Franssen (2006), Wald, Chlouba, Uhlíř, Kallerová, and Štujberová

(2009), and Wong (2017) can be highlighted. More recent studies of thermal analysis of steel profiles with and without thermal protection were also carried out by Dias and Karam (2021), and Oliveira, Fonseca, Campilho, and Piloto (2021). Regarding the normative aspects of NBR 14323 (ABNT, 2013), it is possible to find the literary works that discuss its criteria, such as the work by Silva and Melão (2018).

This paper aims to study the temperature evolution in the cross-sections of steel profiles subjected to fire. The analyses were carried out on welded profiles of the VS and CS series without and with coating mortar as thermal protection. It is intended to evaluate the viability of this solution and, in addition, to present the influence of thermal conductivity, specific heat, and thickness of the coating material in the thermal analysis. Through numerical analysis, the impact of considering the thermal properties of the mortar as constant or variable will also be analyzed.

Material and methods

Systematic review standard temperature-time curve ISO 834

In the technical literature, there are several methodologies and procedures to represent the behavior of a fire under real conditions, such as the real fire curve and the various nominal models proposed by technical standards. Nominal fire models are temperature-time curves that do not depend on physical parameters and the dimensions or type of the building (Real, 2003).

For this study, the standard temperature-time curve proposed by the International Organization for Standardization (ISO) was adopted through the ISO 834 (ISO, 1999) standard. Oliveira et al. (2021) mention that the ISO 834 curve is the standard fire curve most used internationally for fire resistance tests. This curve has only one ascending branch, assuming that the temperature of the gases is always increasing with time, and is mainly used to represent a fully developed fire in a room.

According to ISO 834 (ISO, 1994), which was the basis for the standard fire curve of NBR 14432 (ABNT, 2000), the temperature of hot gases is given by Equation 1.

$$\theta_g(t) = \theta_a + 345 \cdot \log(8 \cdot t + 1) \quad (1)$$

where:
t represents time, in minutes; θ_a the room temperature before the start of heating, in degrees Celsius, generally taken as equal to 20°C; and $\theta_g(t)$ the gases temperature, in degrees Celsius, at time t.

Thermal properties of materials

The thermal analysis of a cross-section of a steel profile requires not only the characterization of the thermal action but also the knowledge of the thermal properties of the constituent materials. In this section, the main thermal properties of structural steel and thermal protection mortar are described.

Structural steel

NBR 14323 (ABNT, 2013) provides the thermal properties of structural steel. The specific heat and thermal conductivity of steel have values dependent on temperature. However, according to NBR 14323 (ABNT, 2013), it is possible to use a specific heat value of steel, C_a, constant and equal to 600 J kg^{-1} °C; and a thermal conductivity value of steel, λ_a, constant and equal to 45 W m^{-1} °C for the entire temperature range. Figure 1 graphically shows the evolution of thermal properties as a function of steel temperature according to NBR 14323 (ABNT, 2013).

From Figure 1a, it can be seen that structural steel has a high thermal conductivity. However, as its temperature increases, this value decreases until it remains constant from 800°C onwards. In turn, the specific heat behavior of structural steel (Figure 1b) stands out for a peak between 600 and 800°C, due to the metallurgical transformation of this material.

Oliveira, Fonseca, Campilho, and Piloto (2021) concluded that considering the constant thermal properties of structural steel does not lead to significant changes in the thermal analysis by considering the properties variability as a function of temperature. However, in the analysis of this paper, the variable behavior of steel properties was used.

Finally, the unit weight of structural steel (ρ_a) is constant in a fire situation, being equal to 7850 kg m^{-3}.

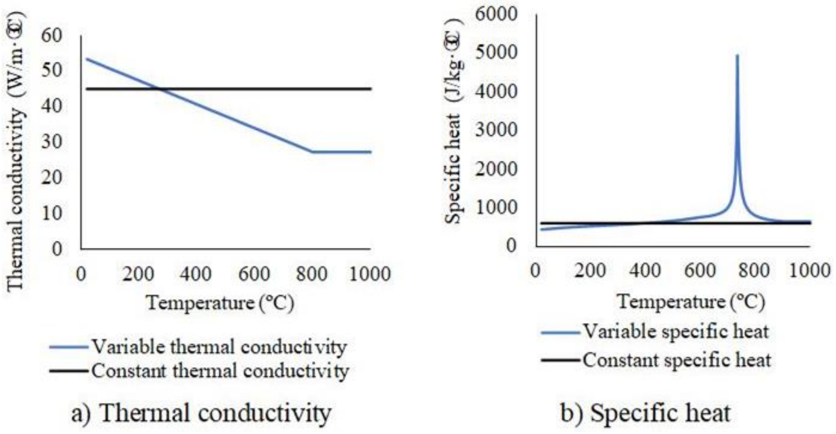

Figure 1. Thermal properties of structural steel as a function of temperature: a) thermal conductivity and b) specific heat.

Blaze shield II mortar (thermal protection)

The type of fire protection arrangement is generally carried out in the following ways: a) protection arranged along the profile contour, usually used with mortars or intumescent paints (Figure 2a) or b) protection arranged in boxes, consisting of rigid plates, such as plasterboard (Figure 2b).

In this research, the analyzes were carried out considering the protection along the profile contour with Blaze Shield II mortar as a fire-retardant coating. This mortar is made of rock fiber and has a nominal density of 240 kg m^{-3}. It is a non-toxic product and is applied by projection directly onto the structure, eliminating the use of pins or screens for fixation. Its thickness can vary between 10 and 70 mm (Silva, 2005).

Silva (2001) presents the thermal properties of Blaze Shield II designed mortar. Thermal conductivity and specific heat as a function of temperature are shown in Table 1 and 2, respectively.

In their research, Silva (2005) considered, for simplification, constant thermal properties. Silva (2005) considered the thermal conductivity, λ_m, equal to 0.15 W m^{-1} °C; specific heat, c_m, constant and equal to 2300 J kg^{-1} °C and the specific mass, ρ_m, equal to 240 kg m^{-3}. This paper intends to demonstrate, through numerical analysis, the impact of considering the properties mentioned as constants or variables in thermal analysis.

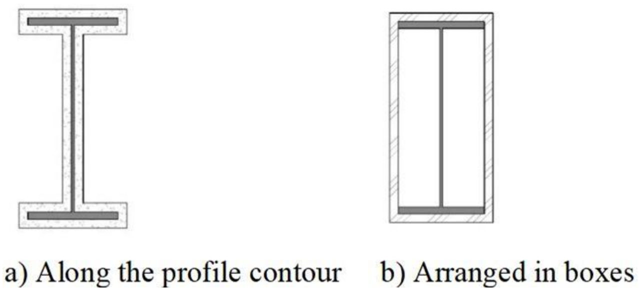

Figure 2. Thermal properties of structural steel as a function of temperature: a) thermal conductivity and b) specific heat.

Table 1. Thermal conductivity of projected mortar Blaze Shield II. Adapted from Silva (2001).

Temperature (°C)	Thermal conductivity (W m^{-1}·°C)
100	0.061
200	0.080
400	0.112
482	0.147
600	0.173
1093	0.208

Table 2. Thermal specific heat of projected mortar Blaze Shield II. Adapted from Silva (2001).

Temperature (°C)	Thermal specific heat (J kg^{-1}·°C)
96	2093
104	837
150	1675
482	2303
1093	2512

Analytical method for determining temperature in steel structures

Once the gas temperature evolution curve is known (fire standard temperature-time curve), it is possible to determine the temperature-time curve of the structural element. This section presents the analytical methods prescribed by NBR 14323 (ABNT, 2013), based on Eurocode 3 (CEN, 2005), to obtain the temperature evolution in the cross-section of steel profiles without and with thermal protection. It is noteworthy that these methods consider only isolated structural elements, that is, the influence of the surrounding structure is not taken into account, and they consider uniform temperature distribution along the element cross-section.

Structural element without fire protection

For a uniform temperature distribution along the cross-section, NBR 14323 (ABNT, 2013) establishes Equation 2 to represent the temperature rise ($\Delta\theta_{a,t}$) of a steel structural element, without fire coating, located inside of a building, during a given time.

$$\Delta\theta_{a,t} = k_{sh} \cdot \frac{(u/A_g)}{c_a \cdot \rho_a} \cdot \varphi \cdot \Delta t \qquad (2)$$

where:
k_{sh} represents the correction factor for the shading effect; u the structural element perimeter exposed to fire; A_g the cross-section of the structural element; u/A_g the massivity factor, expressed in m^{-1}; ρ_a the specific mass of the structural steel; c_a the specific heat of the structural steel; Δt the time interval, expressed in seconds, taken as less than or equal to 5 seconds; and φ the heat flux per unit area, expressed in W m^{-2}, determined according to Equation 3.

$$\varphi = \varphi_c + \varphi_r \qquad (3)$$

where:
φ_c is the heat flux due to convection and φ_r is the heat flux due to radiation. Such parameters can be calculated by Equation 4 and 5, respectively.

$$\varphi_c = \alpha_c \cdot (\theta_g - \theta_a) \qquad (4)$$

$$\varphi_r = 5{,}67 \cdot 10^{-8} \cdot \varepsilon_{res} \cdot [(\theta_g + 273)^4 - (\theta_a + 273)^4] \qquad (5)$$

where:
α_c is the heat transfer coefficient, which, for practical purposes, can be taken as 25 W m^{-2}·°C and ε_{res} is the resulting emissivity, which can be taken as 0.7.

As this method is an incremental process, the results depend on the value adopted for the time interval (Δt). Oliveira, Fonseca, Campilho, and Piloto (2021) analyzed the responses obtained for different values of Δt and found that the results are quite susceptible to time variation in the first 15 min., making it impossible to use time intervals longer than five seconds. A time interval of five seconds (Δt = 5 s) was used for the analysis of the present research.

It is worth noting that the analytical model of NBR 14323 (ABNT, 2013) does not use the thermal conductivity of steel as a calculation variable.

Structural element with fire protection

To determine the temperature of the cross-section of the steel profile with a fireproof coating material, the thermal balance involving the gases temperature, the heat absorption by the coating material and the heat absorption by the structural elements must be considered. For a uniform temperature distribution along the cross-section, NBR 14323 (ABNT, 2013) establishes Equation 6 to represent the temperature rise ($\Delta\theta_{a,t}$) of a structural steel element surrounded by a fire-resistant coating material, located inside of a building, during a given time.

$$\Delta\theta_{a,t} = \frac{\lambda_m \cdot (u_m/A_g)}{t_m \cdot c_a \cdot \rho_a} \cdot \frac{(\theta_{g,t} - \theta_{a,t}) \cdot \Delta t}{1 + (\frac{\xi}{4})} - \frac{\Delta\theta_{g,t}}{(\frac{4}{\xi}) + 1}, but \Delta\theta_{g,t} \geq 0 if \theta_{g,t} \geq 0 \qquad (6)$$

where:
ξ of Equation 6 is calculated by Equation 7.

$$\xi = \frac{c_m \cdot \rho_m}{c_a \cdot \rho_a} \cdot t_m \cdot (u_m/A_g) \qquad (7)$$

where:

u_m/A_g is the massivity factor of structural elements involved by fire-resistant coating material, expressed in m^{-1}; c_m the specific heat of the fire-resistant coating material expressed in J kg^{-1} °C; t_m is the thickness of the fireproofing material, expressed in meters; λ_m the thermal conductivity of the fire coating material expressed in W m^{-1} °C; and ρ_m the specific mass of the fire coating material, expressed in kg m^{-3}.

Analyzed models and aspects of numerical modeling

Six welded profiles were studied, three profiles from the VS series usually intended to form beams, and three profiles from the CS series commonly intended to form pillars. The choice for these series of profiles takes into account the different proportions between the flanges and webs that the profiles of each series have. In addition, two fire exposure situations were investigated. For VS series profiles, the case of beams that serve as supports for slabs. For CS series profiles, internal columns are without contact with sealing elements. Table 3 describes the simulated numerical models. The same profiles with and without fire protection were analyzed analytically and numerically. It is noteworthy that the chosen profiles have a wide variation regarding the massivity factor. This allows assessing the influence of this geometric parameter on the thermal analysis.

Table 3. Numerical simulation plan (models analyzed).

Series	Profile	Mass factor (m^{-1})	Model*
VS	VS 150 x 15	308.74	VS 150 VS 150 (CP**)
	VS 450 x 71	164.72	VS 450 VS 450 (CP)
	VS 600 x 152	86.80	VS 600 VS 600 (CP)
CS	CS 250 x 108	107.12	CS 250 CS 250 (CP)
	CS 300 x 109	128.22	CS 300 CS 300 (CP)
	CS 400 x 106	175.59	CS 600 CS 600 (CP)

*In section 6, the numerical and analytical models are identified, respectively, with the suffixes FEM and NBR. **(CP) is the nomenclature for models with fire protection.

The thermal protection considered was of the contour type, constituted by Blaze Shield II designed mortar with constant thickness and, initially, equal to 20 mm for all the profiles studied. Subsequently, the influence of the thermal protection thickness on the temperature evolution in the profile was evaluated.

The ABAQUS® software, developed by Dassault Systemes (2016), was used to develop the numerical models for this research. Three-dimensional simulations of the structural elements were carried out considering a longitudinal length of 1.0 m. For the VS series profiles, it was considered that there is a slab protecting the upper face of the profile from fire. For the CS series profiles, the four faces exposed to the fire were considered. To demonstrate the results, the mid-section of the span, as it is the most critical, was analyzed.

For finite element mesh discretization, the DC3D8 element was used. It is an eight-node heat transfer element. Each node has a temperature degree of freedom and is applicable for transient analysis. The maximum dimension of the element was adopted as being equal to 6.0 mm. Furthermore, partitions were performed on the models to ensure at least 2 mesh elements along with the thinnest profile thickness. Figure 3 shows the mesh of the profiles with the smallest cross-section of the VS and CS series with and without fire protection, as well as an indication of the cross-section faces exposed to fire.

In all models, an initial ambient temperature equal to 20°C was considered. The convection coefficient used was 25.0 W m^{-2}·°C for the exposed face and 9.0 W m^{-2}·°C for the non-exposed face, as recommended by Eurocode 3. Following Jiang, Main, Weigand, and Sadek (2018), the emissivities of the steel surface and the fire protection material equal to 0.7 were considered. Perfect contact between the materials was assumed to allow thermal conduction between the elements.

The analysis was performed with a fire exposure time of 120 min. in all models. The control of time steps was performed by establishing the minimum increment equal to 0.001 seconds and the maximum equal to 60 s. The initial increment adopted was 1 s.

For structural steel, thermal properties were considered to be temperature-dependent. As for the fireproof coating material, in agreement with Silva (2005), constant thermal properties were considered. Subsequently, the differences in the thermal analysis were evaluated when considering the variable thermal properties indicated by Silva (2001).

To determine the non-uniform temperature distribution in the cross-section of the numerical models, four different points were chosen for the VS profiles and three points for the CS profiles. Figure 4 shows the location of the monitored points.

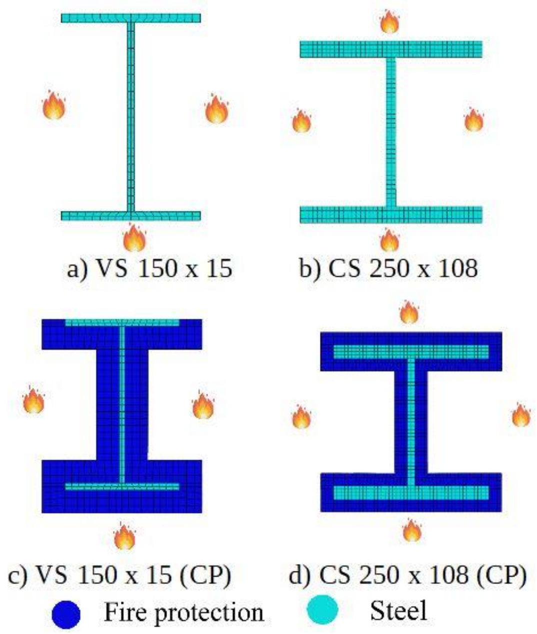

Figure 3. Finite element mesh and an indication of the surfaces exposed to the fire of the analyzed profiles: a) VS 150 x 15, b) CS 250 x 108, c) VS 150 x 15 (CP) and d) CS 250 x 108 (CP).

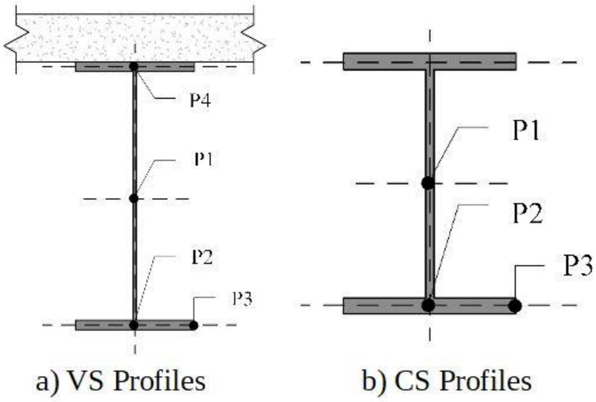

Figure 4. Location of monitoring points in the cross-section of profiles a) VS and b) CS.

Results and discussion

Steel profiles without fire-resistant coating

In this section, the objective was to compare the numerical method with the analytical method of NBR 14323 (ABNT, 2013), which considers a constant temperature distribution. Initially, to assess the variation in temperature distribution along the cross-section of the profiles, the study focused on analyzing the temperature evolution curves at the different nodal points monitored in the numerical models. Figure 5 and 6 present these results for the VS and CS profiles, respectively.

From Figure 5 and 6, it can be seen that the fire exposure situation significantly influences the temperature variation along the cross-section. For the VS profiles, which have the upper flange equipped with fire-resistant coating, it is noted that the smaller the profile's mass factor, the greater the variation in the temperature distribution along the section. For example, considering a time of 30 minutes, the highest temperature variations for profiles VS 150, VS 450 m and VS 600 were 26.2, 86.1, and 163.3°C, respectively. In turn, for CS profiles, it is noted that the curves of the nodal points rapidly converge to the same temperature. Therefore, in this case, the thermal gradients in the cross-section are of little significance. Furthermore, as observed for the VS profiles, it was possible to note that the variation in the distribution of temperatures along the section was inversely proportional to the profile massivity factor. For a fire lasting 30 minutes, the greatest temperature variation for profiles CS 250, CS 300, and CS 400 were 27.8, 23.8, and 6.6°C, respectively. It is noteworthy that for the VS series profiles, as the cross-section of the profile increases, the massivity factor decreases. As for the CS series profiles, as the cross-section of the profile increases, the massivity factor also increases (see Table 3).

Finally, it is observed that, from a certain time of exposure to fire, the thermal gradients in the cross-section tend to decrease, approaching a constant temperature distribution. Figure 7 demonstrates the temperature development of the profile that presented the highest thermal gradient along the cross-section (VS 600). The following fire exposure times were analyzed: 15, 30, 60, and 120 min.

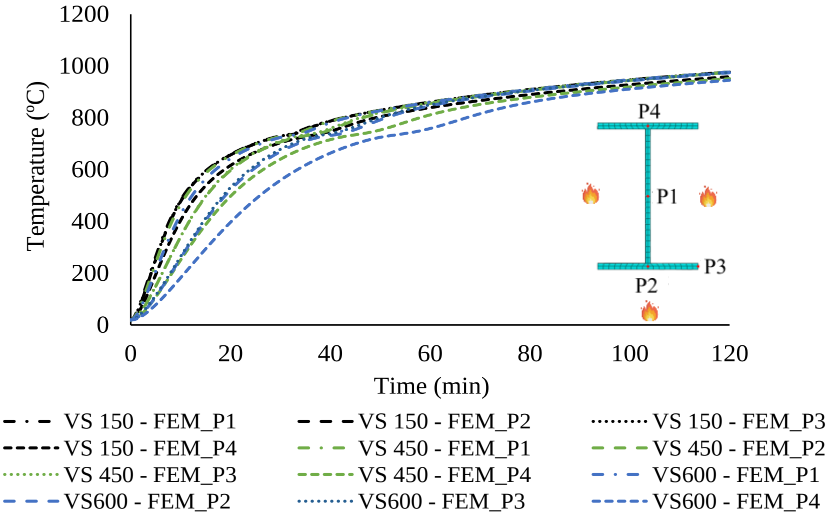

Figure 5. Temperature behavior at the numerically evaluated nodal points for the VS profiles without fire-resistant coating.

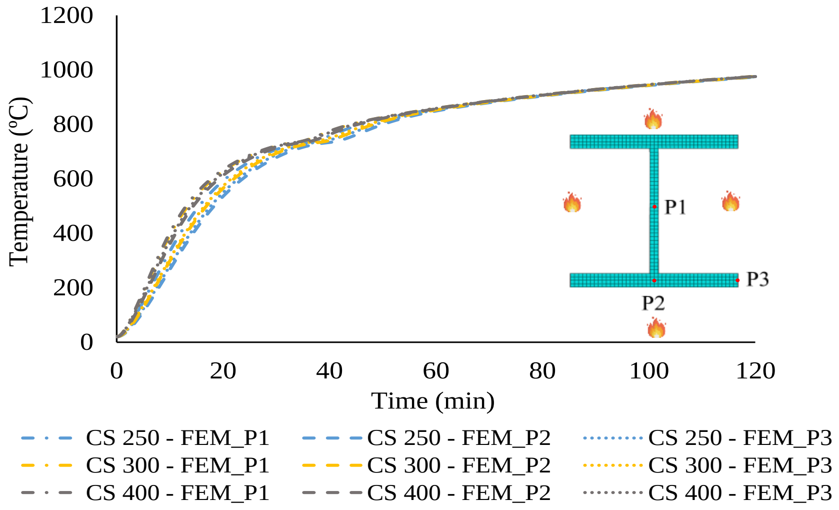

Figure 6. Temperature behavior at the numerically evaluated nodal points for the CS profiles without fire-resistant coating.

To compare the results obtained by the numerical method with the analytical method of NBR 14323 (ABNT, 2013), which assumes constant temperature distribution, the arithmetic mean of the studied nodal points was considered. Figure 8 and 9 show the temperature evolution curves for both methods, respectively, for the VS and CS profiles, respectively. Table 4 shows the temperature results and the relative error (RE) between the analytical and numerical methods for fire exposure times of 30, 60, and 120 min.

From Figures 8 and 9, it is possible to observe a good approximation between the temperature results obtained by both methods up to approximately 15 min. of exposure to fire. From then on, the analytical method starts to register higher temperature values in all the studied profiles, which shows a more conservative approach. From Table 4, it is possible to analyze the absolute values and the relative differences obtained between the methods. In all cases, the results obtained using the analytical method are superior to those obtained using numerical models. The greatest relative difference was obtained for the VS 150 profile in a time of 30 min., in which the temperature obtained by the analytical method was 13.7% higher compared to the numerical model. For this profile, there is a tendency to reduce the relative differences over time. However, this behavior was not standard. For the other profiles, the greatest relative differences were recorded for fires lasting 60 min.

Finally, the influence of the profile massivity factor on temperature development is highlighted. In both analyses, it was found that the increase in the profile's massivity factor implies a faster evolution of its temperature when exposed to fire.

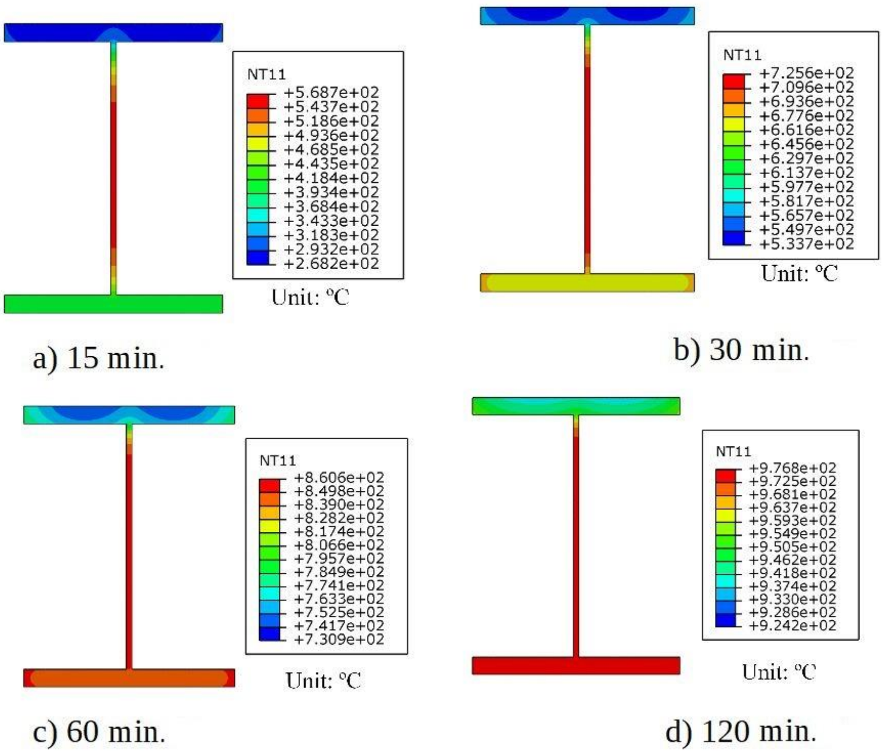

Figure 7. Temperature field in the cross-section of the VS 600 profile for fires with durations of a) 15, b) 30, c) 60, and d) 120 min.

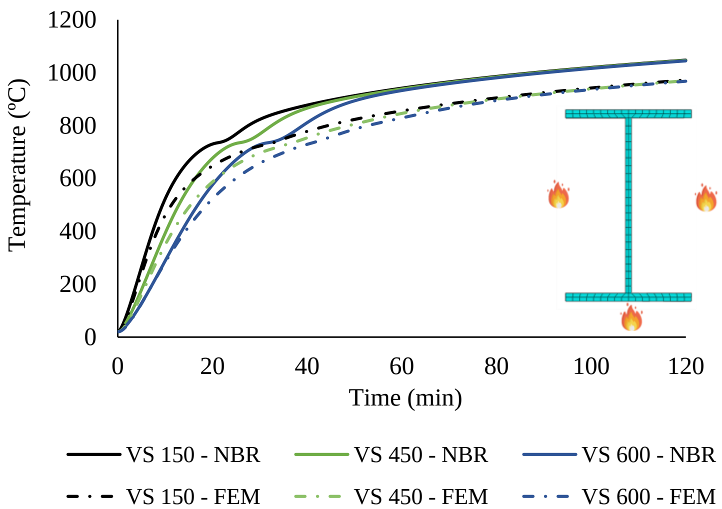

Figure 8. Comparison of temperature behavior between the analytical method and numerical analysis for the VS profiles.

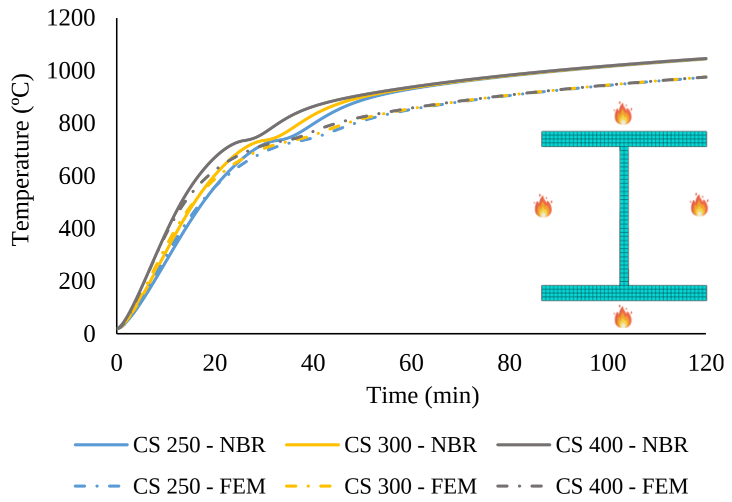

Figure 9. Comparison of temperature behavior between the analytical method and numerical analysis for the CS profiles.

Table 4. Relative differences between analytical method and numerical analysis results for profiles without fire-resistant coating.

Profile	Time (min.)								
	30			60			120		
	NBR (°C)	FEM (°C)	RE (%)	NBR (°C)	FEM (°C)	RE (%)	NBR (°C)	FEM (°C)	RE (%)
VS 150	823.4	724.1	13.7	941.5	856.4	9.9	1047.6	972.6	7.7
VS 450	768.1	698.2	10.0	938.3	847.2	10.8	1046.4	970.1	7.9
VS 600	727.8	659.8	10.3	932.5	829.8	12.4	1044.8	967.7	8.0
CS 250	720.9	699.1	3.1	931.0	855.9	8.8	1044.5	975.1	7.1
CS 300	734.9	710.9	3.4	934.6	858.6	8.9	1045.2	975.7	7.1
CS 400	763.5	722.5	5.7	938.0	861.0	8.9	1046.3	976.3	7.2

Steel profiles with a fire-resistant coating

In this section, the objective was to carry out a study on the influence of the use of thermal protection in thermal analysis. Specifically, the influence of the use of Blaze Shield II mortar with a thickness of 20.0 mm. Initially, the impact of considering the protective material thermal properties as variables or constants was verified. The variable thermal properties of specific heat and thermal conductivity adopted were indicated by Silva (2001). To compare the results, a profile of each series was chosen (VS 450 and CS 250) and the temperature curves evaluated at nodal point 1 were considered. These results are shown in Figure 10.

In Figure 10, up to the fire exposure time of approximately 55 min., it can be noted that the temperatures in the VS 450 (CP) profile, considering the variable thermal properties, are inferior concerning the consideration of constant properties. After 55 min. of fire, the results considering variable thermal properties surpassed those obtained when the thermal properties were assumed constant. As for the CS 250 (CP) profile, the temperature evolution of the model with variable properties registered lower values than those obtained with the use of constant properties during the entire exposure time. In general, the results presented in Figure 10 reveal high agreement between the thermal analysis models considering the variable and constant thermal properties, showing that the modeling considering the constant properties, despite being simpler, presents satisfactory results. For the other models presented in this research, the variable behavior of the thermal protection material properties was used.

In a similar way to the analysis of the profiles without fire coating, the temperature evolution curves at the different nodal points monitored in the numerical models were evaluated. Figure 11 and 12 present these results for the VS and CS profiles, respectively.

From Figure 11 and 12, it can be seen that the fire exposure situation significantly influences the temperature variation along the cross-section. For the VS profiles, which have the upper flange equipped with fire-resistant coating, there are high thermal gradients that tend to increase the profile's mass factor decreases. In addition, it is noteworthy that, contrary to what happens with profiles without thermal protection, the temperature variation in the cross-section of the profile increases with the fire time. In the VS 600 profile, for example, the maximum temperature variation in 30 min. is 127.7°C, whereas for 60 min. this value increases to 250.2°C. In turn, for the CS profiles, the thermal gradients in the cross-section were not significant throughout the fire exposure time, approaching a constant temperature distribution. However, it is noteworthy that, unlike the other analyses, the CS profile that presented the greatest variation in temperature distribution along the section was the CS 300, which has an intermediate massivity factor between CS 400 and CS 250. For a time of 30 min., the greatest temperature variation for profiles CS 250, CS 300, and CS 400 was 17.9, 37.9, and 27.2°C, respectively.

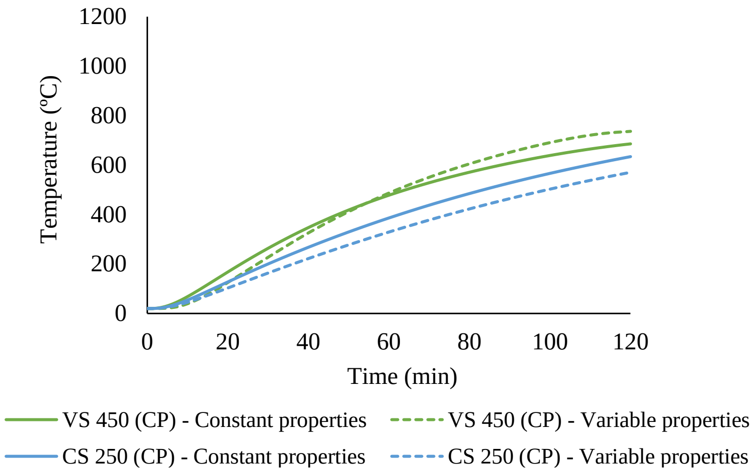

Figure 10. Comparison between the use of constant and variable thermal properties of fire protection on temperature evolution.

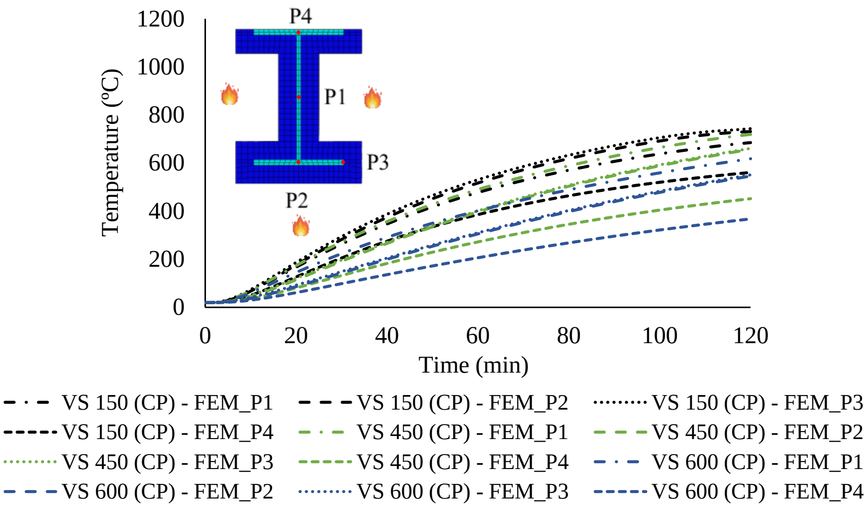

Figure 11. Temperature behavior at the numerically evaluated nodal points for the VS profiles with a fire-resistant coating.

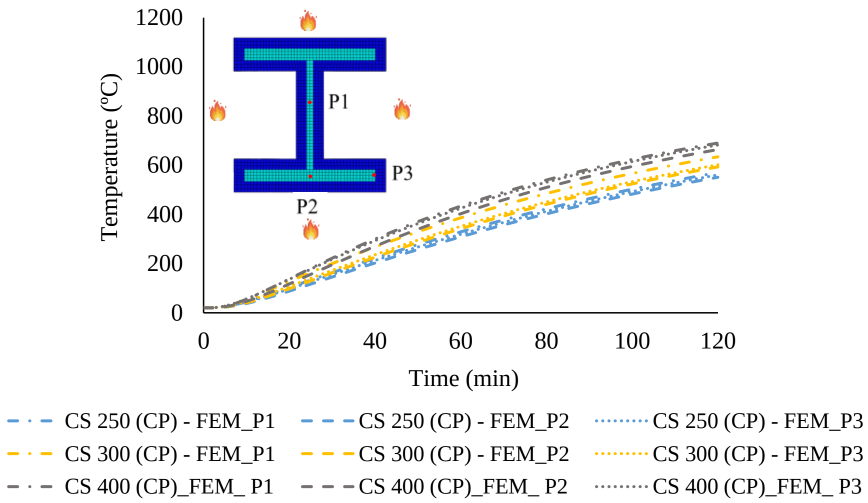

Figure 12. Temperature behavior at the numerically evaluated nodal points for the CS profiles with a fire-resistant coating.

Figure 13 demonstrates the temperature development of the profile with thermal protection that presented the highest thermal gradient along the cross-section (VS 600 CP). Again, the following fire exposure times were analyzed: 15, 30, 60, and 120 min.

Analogously to section 6.1, to compare the results obtained by the numerical method with the analytical method of NBR 14323 (ABNT, 2013), which assumes constant temperature distribution, the arithmetic mean of the monitored nodal points was considered. Figure 14 and 15 show the temperature evolution curves for both methods of analyzing the VS and CS profiles with thermal protection, respectively. Table 5 shows the temperature results and the relative differences between the analytical and numerical methods for fire exposure times of 30, 60, and 120 min.

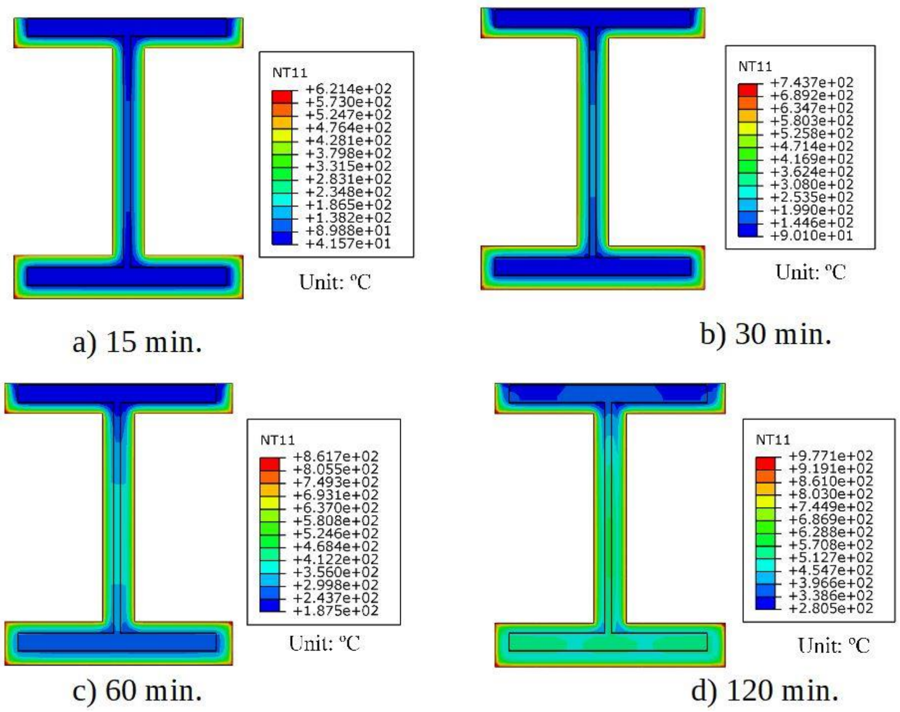

Figure 13. Temperature field in the cross-section of the VS 600 profile with fire-resistant coating for fires with durations of a) 15, b) 30, c) 60, and d) 120 min.

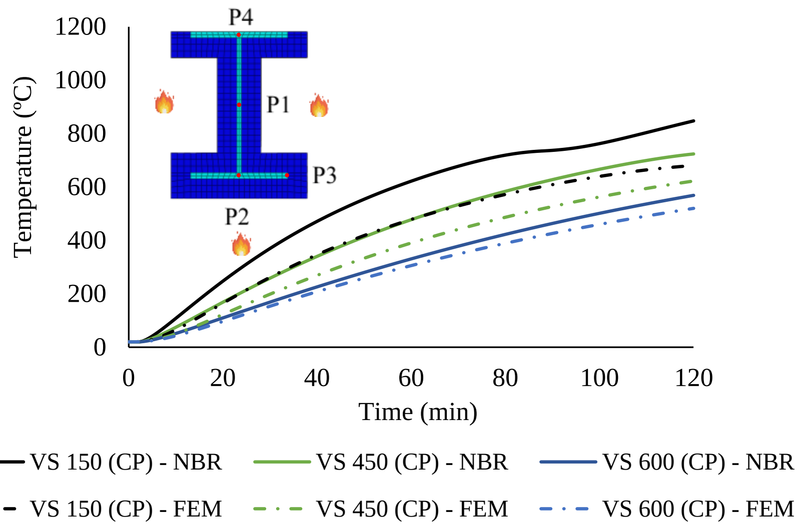

Figure 14. Comparison of temperature behavior between the analytical method and numerical analysis for the VS profiles with a fire-resistant coating.

Figure 14 and 15 show satisfactory agreement between the results obtained with the analytical method and the numerical models. In general, the temperatures obtained by the analytical method were slightly higher for the entire time interval of exposure to the fire. This fact confirms the safety of the analytical method.

From Table 5, it is possible to analyze the absolute values and the relative errors (RE) between the methods. The highest relative error was obtained for the VS 150 profile in a time of 30 min., in which the temperature obtained by the analytical method was 37% higher compared to the numerical model. In general, it was observed that the relative errors of the analytical method for profiles with thermal protection were higher than those obtained for the cases of profiles without fire-resistant coating. This can be explained by the increasing complexity of the numerical model.

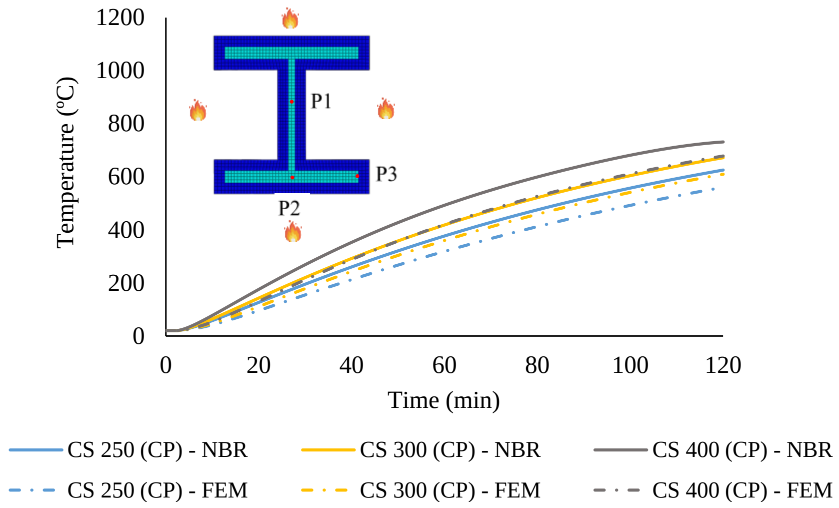

Figure 15. Comparison of temperature behavior between the analytical method and numerical analysis for the CS profiles with a fire-resistant coating.

Table 5. Relative differences between analytical method and numerical analysis results for profiles with a fire-resistant coating.

Profile	Time (min.)								
	30			60			120		
	NBR (°C)	FEM (°C)	RE (%)	NBR (°C)	FEM (°C)	RE (%)	NBR (°C)	FEM (°C)	RE (%)
VS 150 (CP)	369.4	269.6	37.0	621.7	483.0	28.7	847.6	680.4	24.6
VS 450 (CP)	258.1	205.1	25.9	477.4	395.2	20.8	723.6	622.5	16.2
VS 600 (CP)	168.8	158.7	6.4	330.8	309.9	6.7	568.8	520.4	9.3
CS 250 (CP)	195.0	160.1	21.8	376.6	323.5	16.4	625.0	560.7	11.5
CS 300 (CP)	219.8	184.4	19.2	418.0	364.6	14.6	671.3	609.5	10.1
CS 400 (CP)	268.6	218.8	22.7	492.6	425.8	15.7	731.2	678.3	7.8

In order to demonstrate the impact of thermal protection on the temperature field, Figure 16 shows the percentage reductions in temperatures, obtained from numerical models, of profiles with fire-resistant concerning the same profiles without protection.

From Figure 16, it can be seen that the use of the contour-type fire protection provides a significant improvement in the thermal fire resistance of the VS and CS profiles since the temperature values obtained significantly reduce protected profiles. The VS 150 x 15 profile, for example, has the lowest thermal resistance of the analyzed profiles. For a 30 min. exposure to fire, it appears that this profile without fire-resistant coating reaches an average temperature of 724.1°C, while in the same protected profile, the temperature reached is 269.6°C. It is a temperature reduction of 458.6°C, equivalent to a percentage reduction of 62.8%.

Furthermore, the influence of the fire-resistant coating thickness on the temperature evolution in the steel profile was evaluated. Figure 17 shows the evolution of temperatures at nodal point 1 of the VS 450 (CP) profile considering the following coating thicknesses: 10, 20, and 30 mm.

From Figure 17, it is possible to notice a significant influence on the temperature evolution in the steel structure as the thickness of the thermal protection coating increases. For example, for a 30 min. fire exposure time, there is an approximate temperature reduction, to the profile without thermal protection, of 38.8, 63.5, and 78.4% when considering fire-resistant coating with thicknesses of 10, 20 and 30 mm, respectively. Such results justify the use of a fire-resistant coating to be more and more frequent in steel structures, to protect them in fire situations.

Real (2003) describes that the effectiveness of thermal protection is directly related to the thermal properties of the constituent material, such as thermal conductivity and specific heat. In this context, the influence of these properties on the temperature evolution of the steel structure was evaluated. To demonstrate these results, the VS 450 (CP) profile was used. The results obtained are shown in Figure 18 and 19.

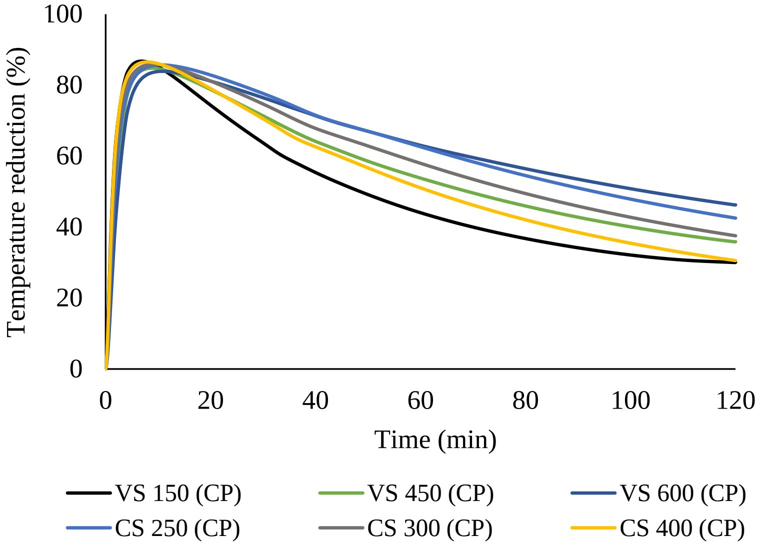

Figure 16. Temperature reduction of profiles with thermal protection.

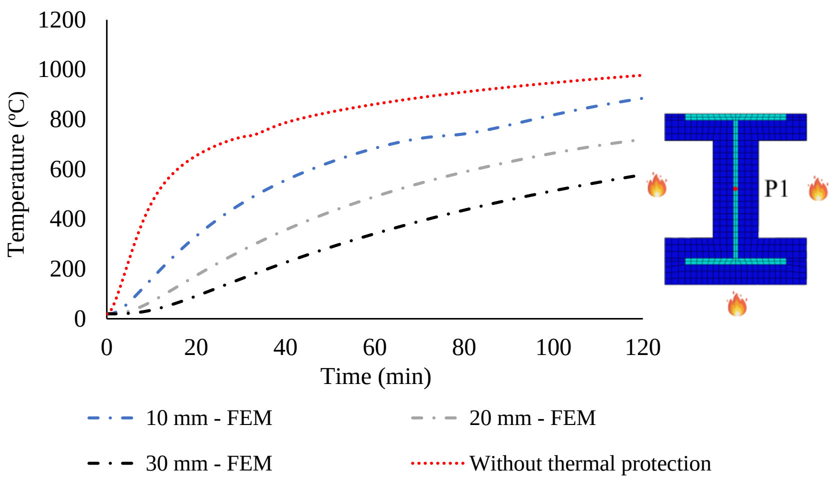

Figure 17. Influence of fire-resistant coating thickness on the temperature evolution.

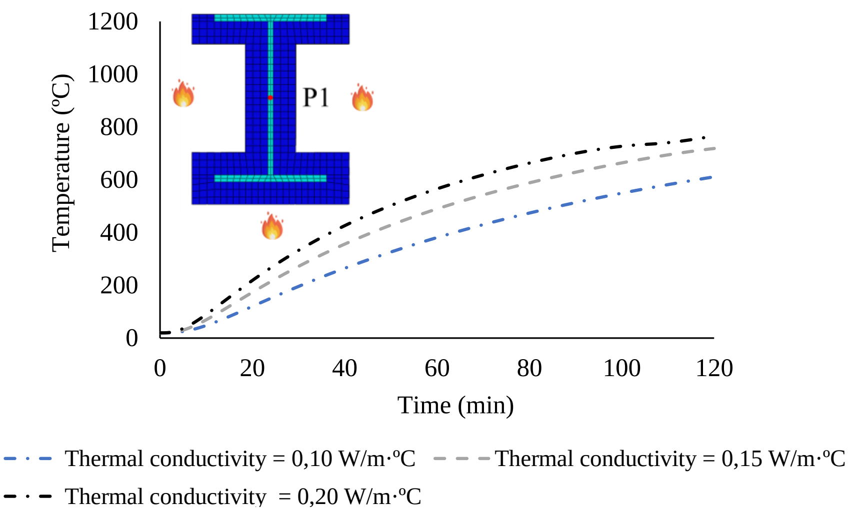

Figure 18. Influence of thermal conductivity on temperature evolution.

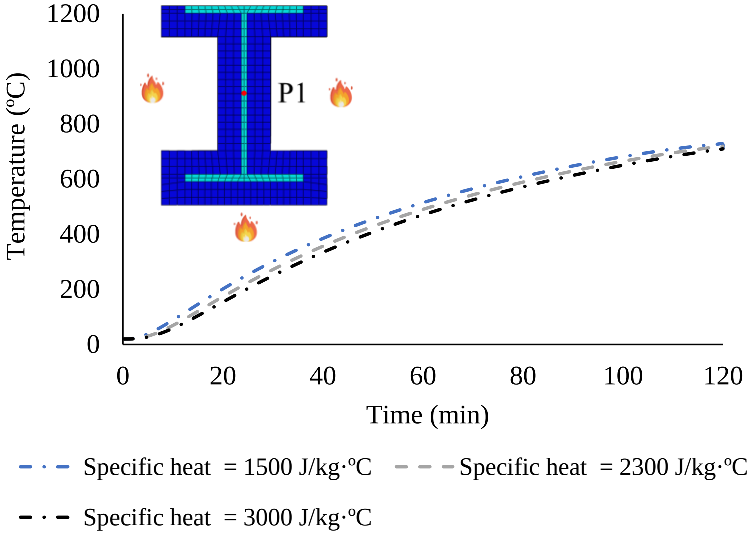

Figure 19. Influence of the thermal protection specific heat on the temperature evolution.

From Figure 18 and 19, it can be concluded that the reduction in thermal conductivity and the increase in specific heat provide a slower evolution of the temperature of the steel structure, which is favorable in a fire protection situation. These results can serve as subsidies for the development of new materials that combine these characteristics of thermal properties.

Conclusion

This article performed A thermal analysis of steel profiles with and without fireproof coating material. The arrangement of faces exposed to fire significantly influences the temperature variation along the cross-section. For the VS profiles, with thermally protected top flange, high thermal gradients were observed along the section. While for the CS profiles, with the four faces of the cross-section exposed, the thermal gradients showed little significance throughout the fire exposure time. In addition, increase in coating thickness and specific heat and the reduction in thermal conductivity, provide a slower evolution of the temperature of the steel structure.

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