Numerical study of steel trusses in fire conditions

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Abstract. A structural system under fire is subject to loss of strength and stiffness and may eventually collapse. In this context, the need for studies to investigate the structural behavior under high temperatures is necessary. Therefore, the present study proposes to perform numerical analyses of steel trusses in a simplified way, considering the physical non-linear effects from the deterioration of the material at high temperatures, as described in NBR 14323. Thus, a methodology was adopted that considers the effects caused by temperature on the stiffness of the structural element. The calculation of displacements and internal forces is done through the Fool Software. With the reduction of the stiffness parameter, the results show that the structure displacements increase with the rise in temperature, and the more accentuated this steel deterioration, the greater the influence of the external load on the displacement.

Keywords: planar truss analysis, inelastic analysis, thermal loads, Ftool software

1 Introduction

Controlling fire became necessary for the human societies advancement, since this technology was essential in everyday life, especially in primitive societies. Throughout history, the loss of life and material damage caused by fire has reinforced the importance of fire safety in civil engineering projects [1]. However, the topic "fire safety" would only gain deserved attention after fatal disasters, as it is possible to highlight, in Brazil: the fires of the Andraus buildings, on February 24, 1972 and Joelma, on February 1, 1974; the fire in the Andorinhas Building, in Rio de Janeiro, in February 1996; the fire at the Kiss nightclub in Santa Maria, at dawn on January 27, 2013; and the incident that hit the Museum of the Portuguese Language in São Paulo, on December 21, 2015. The most recent events are: the fires at the National Museum of Brazil in Rio de Janeiro, on September 2, 2018, the Flamengo training center, on February 2, 2019, the Bonsucesso Federal Hospital in Rio de Janeiro, on October 27, 2020, and the fire that hit the Cinemateca Brasileira in São Paulo, on July 29, 2021.

The main objective of fire safety, therefore, is to minimize the risk to life and property loss. This objective directly depends on the integrity of the building in fire situation, ensuring the time necessary for the people who occupy it to be saved [2]. To ensure that there is this minimum period, the parameters that involve fire must be taken into account when analyzing structures. This is of fundamental importance, especially the assessment of how the physical and mechanical resistance characteristics of materials are affected. Currently, increasingly sophisticated analytical, numerical, and experimental models allow a better understanding of the behavior of these parameters under high temperatures [2-4].

Thus, this article seeks to verify the structural behavior of steel trusses subjected to fire conditions, with emphasis on displacements caused by loading and temperature. The numerical methodology adopted, which will be better explained in the next section, basically consists of taking into account the heating of the structural element as described in NBR 14323 [5], as well as the material change properties as the temperature increases.

2 Numerical Methodology Adopted

Because the loss of strength and stiffness are two of the main aspects in a structural analysis of fire situation, this analysis consists of determining the temperature distribution in the elements and simulating the structural displacements of interest. Thus, it is possible to determine and measure the impact of fire on the behavior and structural equilibrium, for certain time intervals of exposure to fire and temperature range.

This study proposes to perform numerical analyses that consider the physical nonlinear effect in a simplified way, considering the deterioration of the material at high temperatures, as described in NBR 14323 [5]. To this end, a simplified methodology was adopted that proposes to consider the effects caused by the structural element temperature on its stiffness, where the parameter to be reduced will be the steel's modulus of elasticity.

This method basically consists of varying the temperature in increments of 5 seconds, and at each time interval a linear elastic analysis is performed to calculate the displacements generated by the temperature and the external load applied, taking into account the material's deterioration and, consequently, the effects on structural stiffness. At each temperature increment, then, the displacement portions related to the external load and the temperature gradient are calculated, thus determining the equilibrium path of the structure. The algorithm presented in Table 1 describes this procedure in general and in the next subsections, the main steps of the method will be described in more detail.

Table 1. Algorithm for the displacement calculation of structural systems under thermal load

T**emperature increase over time (s)**: t = 0, 5, 10,... t_{max}

a. Define the truss geometry and its boundary conditions

b. Calculates the temperature of gases: $T_{gases} = T_0 + 345\log(8t+1)$

c. Calculates the steel temperature variation: $\Delta T_{steel,t} = k_{sh} \dfrac{\left(d\,/\,A\right)}{c_{steel}\rho_{steel}}\varphi\Delta t$

d. Update Young's modulus for each temperature: $E_T = E_a \cdot k_{Ea,T}$

e. Determines the normal efforts through a linear elastic analysis (Software Ftool [6])

f. Calculates displacement caused by temperature variation: $\Delta u_t^T = \sum n(\alpha \cdot \Delta T \cdot L) + \Delta u_{t-\Delta t}^T$

g. Calculates displacement caused by external load: $\Delta u_t^c = \sum n\left(\dfrac{NL}{AE_T}\right)$

h. Calculates final displacement: $\Delta u_t^{total} = \Delta u_t^T + \Delta u_t^c$

2.1 PVW for structural displacement calculation

For the calculation of displacements in the structure, the Principle of Virtual Work (PVW), also known as the Unit-Load Method (ULM), was used. Therefore, from the equation presented below, it is possible to calculate the displacement at any point of the structure, caused both by the acting external loading and that caused by the temperature change, that is:

$$1 \cdot \Delta u = \sum n\left(\frac{NL}{AE}\right) + \sum n\left(\alpha \cdot \Delta T \cdot L\right) \tag{1}$$

where Δu is the displacement caused by external forces and temperature change; the number "1" represents the unitary virtual external force applied in the direction of the displacement to be calculated; n are the virtual normal internal forces acting on the bars caused by the unit force; N are the actual normal internal forces acting on the bars caused by the actual external forces; L is the length of the bar; A is the cross-sectional area of the bar; E is the Young's modulus of the bar; α is the coefficient of thermal expansion of steel; ΔT is the temperature variation that the bar underwent between time t and time *t*-Δ*t*. Note that the first sum corresponds to the displacement caused by the external load applied to the truss, while the second, to that caused by the temperature change in a bar, some bars or even in the entire structure (all bars).

2.2 Temperature of the gases according to ISO 834-1 [7]

The temperature that the steel reaches in fire situation depends on the gases present in the compartment where the fire takes place. The gases' temperature determination in a burning compartment depends on several parameters. However, the current regulations allow the use of standardized curves, constructed as a function of the fire exposure time only. The fire curve adopted herein is the standard fire curve of ISO 834-1 [7], given by the expression:

$$T_{gases} = T_0 + 345\log(8t + 1) \tag{2}$$

where, T_{gases} is the temperature of the hot gases in the burning compartment in °C, T_0 is the initial ambient temperature, generally assumed to be 20 °C, and t is the fire exposure time in minutes.

2.3 Temperature of structural steel according to NBR 14323 [5]

The structural steel bar that is subjected to a uniform temperature distribution in the cross section, does not have a fire protection and is located inside a building, having its temperature variation provided for by NBR 14323 [5], which is given by the following expression:

$$\Delta T_{steel,t} = k_{sh}\frac{\left(d / A\right)}{c_{steel}\rho_{steel}}\varphi\Delta t \tag{3}$$

where k_{sh} is a correction factor for the shading effect, which can be taken to equal 1.0 [5]; *d* is the fire-exposed perimeter of the steel structural element; *A* is the structural element cross-sectional area; the *d/A* ratio provides the bulk factor for uncoated steel structural elements; c_{steel} is the specific heat capacity of steel; ρ_{steel} is the density of steel, adopted regardless of temperature as 7850 km/m^3; φ is the heat flux per unit area; and Δ*t* is the time interval. Regarding this last parameter, the value of Δ*t* cannot be taken as greater than 5 [5].

Thus, the temperature in the steel structural element at the current instant of time is given by:

$$T_{steel,t} = T_{steel,t-\Delta t} + \Delta T_{steel,t} \tag{4}$$

2.4 Properties of steel exposted to high temperatures according to NBR 14212 [5]

The steel mechanical properties degradation is also provided for by NBR 14323 [5], which brings the reduction factor of the Young's modulus of rolled steel, given by:

$$k_{Ea,T} = \frac{E_T}{E_a} \tag{5}$$

where, E_T is the Young's modulus at a temperature *T*, and E_a is the Young's modulus at 20 °C. Figure 1 illustrates the behavior of this property as a function of temperature increase.

3 Example studied

The truss (or tri-pinned frame) shown in Fig. 2 was initially analyzed at room temperature by Papadrakis [8] and later by Torkamani and Shieh [9], who performed geometrically nonlinear studies. The supports are pinned, the external load P adopted was 200 kN and a thermal load was added to both bars. For this structural system, the displacement to be analyzed is the vertical at the central node of the truss, as represented in the figure.

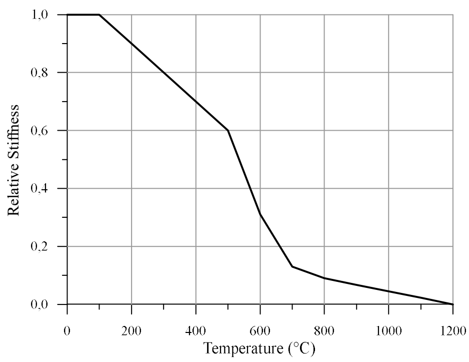


Figure 1. Relative variation of the steel's elasticity module in function of temperature

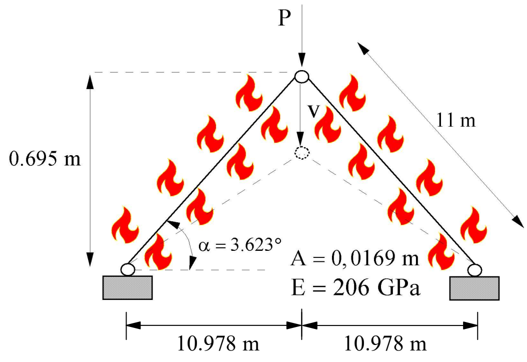


Figure 2. The steel truss analyzed

3.1 External load and temperature contributions

With the adopted numerical strategy, it is possible to separately analyze the effect of the two loads that influence the vertical displacement at the top of the structure: external force "P" and thermal load. Figure 3 illustrates the behavior of the truss when analyzing the variation of the vertical displacement with the temperature under these loads and considering the degradation of the material.

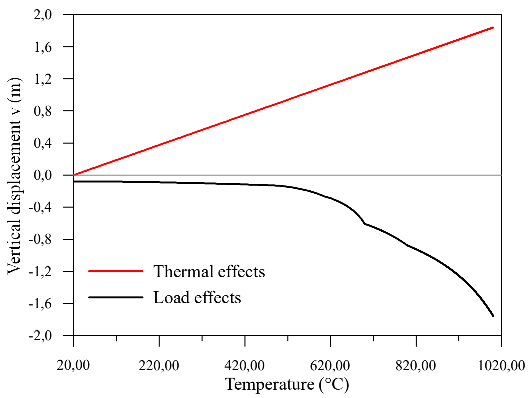


Figure 3. Truss' vertical displacement: external load "P" and thermal load

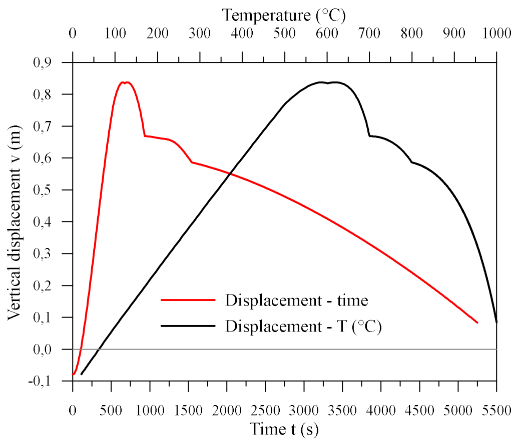
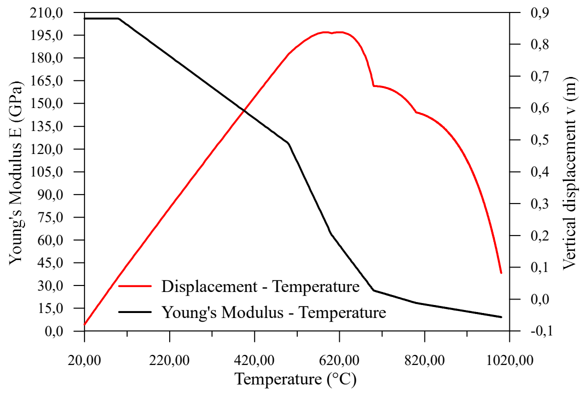


Figure 4. Truss' total vertical displacement in function of temperature and time

While the external force "P" causes the central point of the truss to move vertically downwards, the thermal effect causes this point to move vertically upwards. At first, the displacement caused by external forces is practically constant, and only when the structure reaches temperatures close to 600°C does this displacement become more significant, reaching and surpassing the displacement caused by the temperature variation, which acts in the direction contrary. This variation is due to the sharp drop in the Young's modulus that also occurs at a temperature close to 600°C, which compromises the stiffness of the structure.

3.2 Total vertical displacement and its relationship with the Young's modulus

The curves shown in Fig. 4 show the variation of the total vertical displacement (combined effects) at the central point with the increase in temperature and the passage of time. As highlighted above, from 600 °C onwards, with the sharp drop in the Young's modulus, the influence of external forces predominates in the behavior of the structure, causing the analyzed point to suffer a greater downward vertical displacement. In Figure 5 it is possible to see how the curves' points of variance shown in the graph follow the points where there is a reduction in the Young's modulus.



Figue 5. Truss' final vertical displacement and the variation of the Young's modulus

4 Final Considerations

In the development of the present research, the structural behavior of a steel truss (or tri-pinned frame) under fire was evaluated, with emphasis on the vertical displacement of the system caused by external loading and thermal load. The fire behavior was adopted as proposed by ISO 834-1 [7], while the heating of the structural element was considered as described in NBR 14323 [5]. The analysis was performed with the aid of the Ftool software [6], used to find the real and virtual normal forces acting on the structure, through a linear elastic analysis, both necessary for the PVW. Initially, the vertical displacement of the truss caused by the temperature variation and the external load was considered individually, and later together. Given the results achieved, it can be concluded that the rise in temperature and the consequent degradation of the stiffness parameter contributes to the loss of stability of the system. In addition, the results also demonstrate that at temperatures where there is an accentuated degradation of the Young's modulus, there will also be a greater displacement caused by the external load. Therefore, the importance of considering the degradation of the strength of the structure in the analysis is evident.

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