Evaluation of Internal Forces in Cold-Formed Steel Truss exposed to Fire

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Abstract. The use of cold-formed steel structural elements is evident in recent decades and motivated by their structural efficiency as a function of the relationship between strength and weight. Its application is wide ranging in buildings or hangars. However, due to the slenderness of the elements, projects involving cold-formed steel are governed by the instability phenomena. In a fire situation, it is known that the physical and mechanical characteristics of materials deteriorate during exposure to fire and the resistant capacity decreases with increasing temperature. Thus, this work aims to analyze a truss subjected to the action of fire. The CS-ASA/FA program defines the temperature field of the cold-formed steel cross-sections without fire protection and the simplified method of NBR 14323 is used to obtain the temperature in the truss section with hollow encasement fire protection material. Additionally, the behavior of normal force on the most requested bar due to temperature increase is evaluated. The results showed the importance of using fire protection material in reducing the temperature of steel elements and showed that the magnitude of normal force increases with increasing temperature, which contributes to the loss of structural strength.

Keywords: cold-formed steel, thermal analysis, fire, CS-ASA/FA.

1 Introduction

The popularization of cold-formed steel structural elements is evident in the last decades. The use of this type of structural elements began mainly in hangars and nowadays it is also present in residential constructions with the new construction method on the rise, the Light Steel Frame. The spread of cold-formed steel can be justified by advantages such as weight. A lighter structure generates less robust foundations. Transport is also facilitated, which reduces the amount and complexity of equipment required and can result in a lower final cost when compared to welded or hot-rolled structural elements. The execution time is another positive point because, as it is a pre-molded, mountable and light structure, its execution is can be faster and more practical. The wide variety of cross-sections guarantees the cold-formed steel good versatility in civil construction. However, associated with the increased diversification in the use of cold-formed steel, comes the need to verify safety in fire situations. This is due to the fact that their behavior at elevated temperatures is different from that at room temperature. Although the chances of fire occurrence are small, in general, they have catastrophic consequences.

Following this same line, the present study has as objective to evaluate the behavior of the internal forces of a cold-formed steel truss. More specifically, the computational module CS-ASA/FA (Computational System for Advanced Structural Analysis/Fire Analysis; [1,2]) is used to obtain the temperature field in the different cross-sections that make up the truss bars through a thermal analysis in transient regime. Then, the Ftool software is used to evaluate the behavior of normal internal forces considering the temperature rise. Additionally, a fire protection material protecting the truss is adopted and the simplified method for obtaining the temperature of the structural element presented in NBR 14323 [3] is used. The truss is covered with plasterboard, in order to verify the influence on the behavior of the internal forces of this structural system.

2 Cold-formed steel in a fire situation

All structural materials commonly used in civil construction such as concrete, steel, wood or aluminum show profound changes in their properties when subjected to high temperatures. A steel structure subjected to 600°C can lose up to 50% of its relative strength and collapse rapidly [1]. In the case of cold-formed steel, the slenderness of the element is a factor that contributes to the rapid heating of the structural element, especially when unprotected. Currently, as alternatives for passive fire protection, steel elements can be coated in fire protection material. Most protections use low density designed mortars, presenting lower cost and higher application speed to achieve the objective. However, the application of this material makes it difficult, or may even make it unfeasible, to use cold-formed steel, since they are made of thin plates (maximum 8 mm thick), while the projected material needs thicknesses ranging from 5 to 20 mm, resulting in a very high final weight [4]. As an alternative, there are plasterboards with glass fibers and vermiculite in their composition, ensuring specific characteristics for fire protection.

Some studies involving the application of fire protection on cold-formed steel can be highlighted: Soares and Rodrigues [5] presented the design of a box-type beam composed of two cold-formed steel Ue sections that were subjected to simple bending without and with gypsum mortar, plasterboards, mineral fiber mortar and projected mineral fiber as fire protection materials. Feng et al. [6] studied, experimentally and numerically, the thermal behavior of panels composed of cold-formed steel U sections and plasterboards. Mendes et al. [4] proposed the use of plasterboard for the fire protection of floor support trusses composed of cold-formed steel elements.

3 Fire analysis

For the simplified methods and for the advanced calculation methods, the verification of structural elements in a fire situation requires, the determination of the temperature distribution in these elements. The thermal analysis of a structural element subjected to a fire situation consists in determining the temperature variation or the temperature field in the element of interest, based on the boundary conditions of the adopted fire model. In the problems of structures in a fire situation, the thermal analysis basically involves two parts: the determination of the heat transferred by convection and radiation, originating from the fire, in the contour of the element of interest; and, the determination of heat transfer by conduction inside the structural elements [7].

In the simplified calculation models, the temperature rise is considered homogeneously for the entire cross-section and along the length of the structural element of interest, using simple analytical equations in the case of steel. In the advanced calculation models, numerical methods such as finite differences and finite elements are applied to obtain the temperature field in the structural element in a more realistic way throughout the heating process.

It is important to highlight that the temperature in the structural element depends on the temperature caused by the fire, that is, the temperature of the gases present in a certain compartment. The fire curve adopted in the present work, standard fire of ISO 834-1 [8], for the thermal analysis is given by Eq. (1):

$$T_{gases} = T_0 + 345\log\left(8t + 1\right) \qquad ()$$

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

3.1 CS-ASA/FA [1,2]

In the present study, the computational module CS-ASA/FA [1,2] is used to perform the thermal analysis in transient regime in the different cross-sections that make up the bars of the studied truss. This module was developed based on the Finite Element Method (FEM) [9] and is part of a large computational system called

CS-ASA [10]. Within CS-ASA, CS-ASA/FA is capable of performing the thermal analysis of cross-sections in steady and transient conditions, as well as the thermo-structural analysis of structures when coupled to the CS-ASA/FSA (Fire Structural Analysis; [11,12]) module.

It is worth noting that it is important to properly understand the mechanisms of heat transfer, by convection, radiation and conduction, which make it possible to determine the transfer of energy to any element/body. Furthermore, for the correct determination of heat transfer within the structural elements, it is necessary to consider the variation of the thermal properties of the constituent materials as a function of temperature. It is assumed that the temperature distribution along each structural element is uniform and equal to that estimated for the cross-section. Thermal analysis is then carried out exclusively in the cross-sectional plane through numerical models of heat transfer that make it possible to determine the temperature distribution at different points in the section. The numerical simulation of thermal analysis consists of solving the differential heat conduction equation for solid bodies. The formulation present in CS-ASA/FA and further details regarding the computational module can be found in Pires et al. [1,2].

3.2 The steel temperature according to NBR 14323 [3]

By the simplified thermal model presented in NBR 14323 [6], the temperature rise in steel structural elements, subjected to a uniform temperature distribution in the cross-section and located inside the building, is given by Eq. (2), considering structural elements without or with thermal protection, respectively:

a) $$\Delta T_{steel,t} = k_{sh} \frac{(u/A)}{c_{steel}\rho_{steel}} \varphi \Delta t$$ b) $$\Delta T_{steel,t} = \frac{\lambda_m (u_m/A)}{t_m c_{steel}\rho_{steel}} \frac{(T_{gases,t} - T_{steel,t})\Delta t}{1+(\xi/4)} - \frac{\Delta T_{gases,t}}{(4/\xi)+1} \quad ()$$

but $\Delta T_{steel,t} \geq 0$ if $\Delta T_{gases,t} > 0$, and has: $$\xi = \frac{c_m \rho_m}{c_{steel}\rho_{steel}} t_m (u_m/A) \quad ()$$

where, in Eq. (2a), k_{sh} is a correction factor for the shading effect, which can be taken as equal to 1; c_{steel} is the specific heat of steel; ρ_{steel} is the specific mass of steel considered independent of temperature equal to 7850 kg/m³; Δt is the time interval in seconds and cannot be taken as greater than 5; u is the perimeter exposed to fire of the structural element, in meters (m); and A is the cross-section area of the steel structural element, in m². The relationship between the perimeter exposed to fire and the cross-section area (u/A), for prismatic bars of length L, defines the massivity factor. It is clearly seen that, for structural elements with a cross-section of the same area, the temperature increase will occur faster for those with a larger surface exposed to fire. Still from Eq. (2a), ϕ is the heat flux per unit area, expressed in Watts per m² (W/m²). In Eq. (2b), λ_m, t_m, c_m and ρ_m are the thermal conductivity, thickness, specific heat, and specific mass of the fire protection material, respectively; $T_{steel,t}$, is the temperature of the steel structural element, in the current time step; $\Delta T_{gases,t}$ is the temperature variation of the gases, in the current time step; u_m is the effective perimeter of the fire coating material in m; the u_m/A ratio defines the massity factor of the protected structural element; Δt, in this case, cannot be adopted longer than 30 seconds. Thus, for both cases treated, the temperature in the steel structural element, at the current instant of time, is given as follows:

$$T_{steel,t} = T_{steel,t\text{-}\Delta t} + \Delta T_{steel,t} \quad ()$$

The procedure presented for determining the temperature rise in steel structural elements, with and without thermal protection, is of the simple incremental type for any fire curve.

4 Numerical example

This section aims to obtain the temperature field in the different cross-sections that make up the bars of a truss considering the situations: without and with fire protection material. The analysis without fire protection is performed in a transient regime using the CS-ASA/FA computational module [1,2]. For the consideration of the fire protection, the simplified method for obtaining the temperature of the structural element presented in NBR 14323 [3] described by Eq. (2b) is adopted. With the temperature field established for the two situations (without and with fire protection), the normal internal forces in the truss bars are evaluated using the Ftool software. The truss analyzed in this study (Figure 1) is intended for the roofing of industrial buildings and composes the Central Events pavilion of Ceará (CEC), located in Fortaleza (CE).

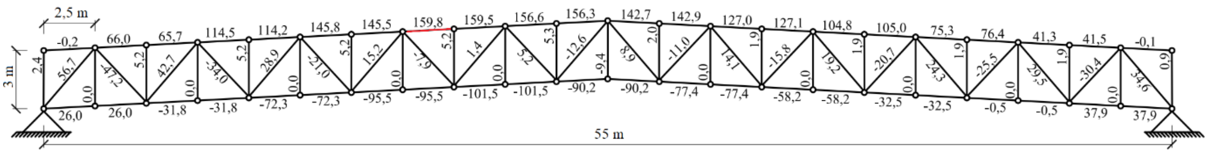
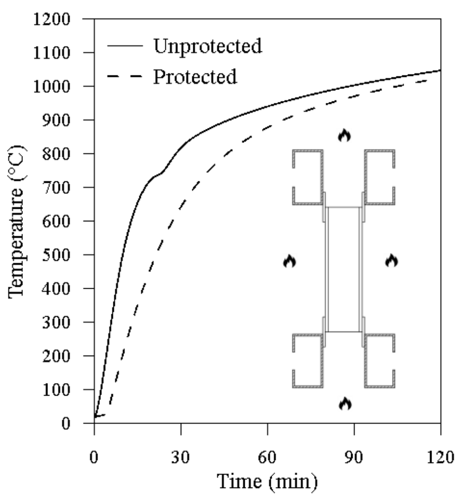


Figure 1. Analyzed truss: geometry and normal forces at room temperature

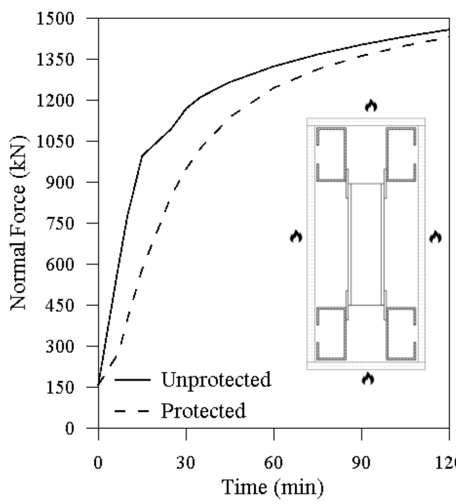
This truss is part of a study carried out by Pillar [13]. The pavilion is 260 m long and its roof is composed of a 3º inclination, supported by the truss under analysis, with a free span of 55 m, as illustrated in Figure 1. The adopted cross-sections are cold-formed steel Ue 300x100x60x6.3 for the flanges and Ue 200x100x50x6.3 for uprights and diagonals. The steel is of the ASTM A-572 Grade 50 type, with a yield strength equivalent to 345 MPa and a modulus of elasticity of 200 GPa at room temperature.

A load of 0.27 kN/m is considered, which corresponds to the self-weight, overload and the wind load according to NBR 6123 [14]. To determine the influence of temperature on the structural elements studied, exposure to fire on all sides was considered. For the analysis considering the fire protection, plasterboard plates with 12.5 mm thickness are used, based on the study by Mendes et al. [4]. The thermal properties of the material used are: density equal to 800 kg/m³, specific heat equal to 1700 J/kg°C and thermal conductivity equal to 0.20 W/m°C.

The graphs in Figure 2 show the temperature versus time curves considering the truss unprotected, considering the truss with hollow encasement fire protection (Figure 2a) and the curves of the behavior of normal force in the most stressed bar of the truss as a function of the exposure time to fire also considering the situations of without and with thermal protection (Figure 2b).



a) Temperature versus time



b) Normal Force versus time

Figure 2. Thermal analysis and normal force behavior

Even considering the cold-formed steel Ue in isolation in the thermal analysis without fire protection, a significant difference can be seen in the graph in Figure 2a in relation to the curve with fire protection. It is possible to see that the fire protection material promotes a considerable reduction in the temperature of the cross-section of the truss, showing an efficient alternative in the analysis in a fire situation. Regarding the behavior of the normal force on the most stressed bar, it is observed from the graph in Figure 2b that the magnitude of this force increases with the time of exposure to fire, that is, internal forces due to temperature arise in the truss due to restrictions on the expansion which significantly contributes to the loss of structural strength.

5 Conclusion

In the development of the present study, an analysis of a truss subjected to the action of fire was carried out. Through the CS-ASA/FA program [1,2], the temperature range of cold-formed steel elements without fire protection was defined. By the simplified method of NBR 14323 [3], it was possible to obtain the temperature in the truss section with hollow encasement fire protection. Once the temperature of the structural elements was established, the behavior of the normal force in the most requested bar was evaluated as a function of the temperature increase (or the time of exposure to fire). Given the results achieved, it can first be concluded that the use of fire protection material in the structure is effective and important because it considerably reduces the temperature of the steel structural elements. Furthermore, it is also concluded that additional internal forces due to temperature rise in the truss due to expansion restrictions. This is an important conclusion because it reinforces the attention that must be paid to the analysis of fire situations, since additional requests not foreseen in projects at room temperature can significantly compromise the strength of the structural system.

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