XLIII CILAMCE
21-25, November, 2022
FOZ DO IGUAÇU - PR - BRAZIL

Thermal And Structural Behavior of Cold-Formed Steel Frame Under Fire Condition

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Abstract. The Light Steel Frame building system is composed of structures manufactured in cold-formed profiles of light and galvanized steel. With the union of these profiles structural and non-structural frames are assembled, such as floor and wall beams, slabs, among other components. Over the metallic structure, a coating is applied by cement boards, drywall, smartsid, or vinyl siding. These plates can contain acoustic, thermal and fire-resistant coating layers. Because it has a metal support structure, LSF buildings receive great influence in fire situations, since high temperatures modify the physical and mechanical properties of steel. The present paper aimed to evaluate the behavior of a structural panel of the steel frame type, covered with gypsum plasterboards, in a fire condition, analyzing the influence of temperature increase on the mechanical properties of the structural profiles that constitute it. To achieve this objective, numerical analyses were performed with the commercial software ANSYS, where the instability modes, the loadbearing capacity and the influence of the thermal action on the frame were evaluated. With the result of the analyses, it was possible to obtain the fire resistance of the structure.

Keywords: LSF structures. Fire. Finite Elements Method.

1 Introduction

Rethinking civil construction in an optimized way, Sustainable Energy Construction appears as an alternative to the high material cost of conventional methods. One of the main methods of these constructions is steel frame. This construction system is made up of light profiles in galvanized steel, which form structural frames that later receive closing layers The main benefits presented by this system are the speed of execution and the reduction of waste, which leads to a better sizing of materials and consequently reduces the cost of the construction. [1]

One of the main destructive agents of civil structures is fire. A fire when uncontrolled can represent the catastrophic collapse of a construction. However, even when controlled, a fire can irreparably damage structural elements submitted to high temperature, condemning the use of the building. When compared to brickwork, steel has a disadvantage in a fire situation, since this material has high thermal conductivity, which occasionally affects its resistant properties with the increase of temperature. Steel immersed in a homogeneous temperature environment of 550 °C, under the influence of the total load, will lose its safety margin defined in the design, initiating a localized buckling process in the structure. In addition, the temperature difference between the flanges of the structural profile generates a bending of the upright in relation to the axis of greater inertia and the displacement of the center of rigidity towards the coldest flange, since the modulus of elasticity, in this region, is less reduced [2].

The behavior of cold formed profiles, especially at high temperatures, presents a high level of geometric and material nonlinearity. Thus, an analytical analysis of the thermal and structural behavior becomes costly and unfeasible, requiring that its rigorous determination is made with the aid of standards or computational numerical tools, as is the case of finite element methods. This method is based on the discretization of a continuous system and a finite number of elements with simple geometry, which make it possible to evaluate the global behavior of the structure through the behavior of each of its elements. [3]

This paper aims to evaluate the behavior of a structural steel frame panel in a fire condition, analyzing the influence of temperature increase on the mechanical properties of structural profiles. For this, the elastic buckling will be analyzed to determine the critical load and the instability modes, the loadbearing of the structure, the thermal gradient for one hour of fire exposure, and finally the fire resistance will be determined.

2 Numerical Analysis

The model analyzed consists of a structural frame formed by two horizontal U93x43x1.5 track profiles, fixing three vertical studs in UE90x43x15x1.5 profiles. 12.5 mm thick, 975 mm wide, and 1000 mm high gypsum boards are fixed on the studs, as shown in figure 1.

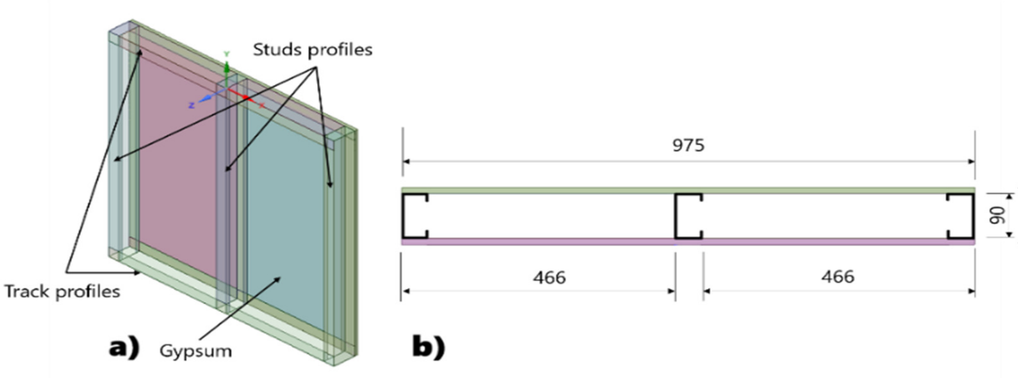

Figure 1. Schematic representation of the analyzed structure

For the development of the analyses, a finite element model was created as shown in figure 2. Where the cold formed profiles were modeled by rectangular plate elements, discretized with height and width of 5 mm. The gypsum plates were discretized into solid elements with 15 mm edges, because for thermal transient analysis a very refined discretization is not necessary [4].

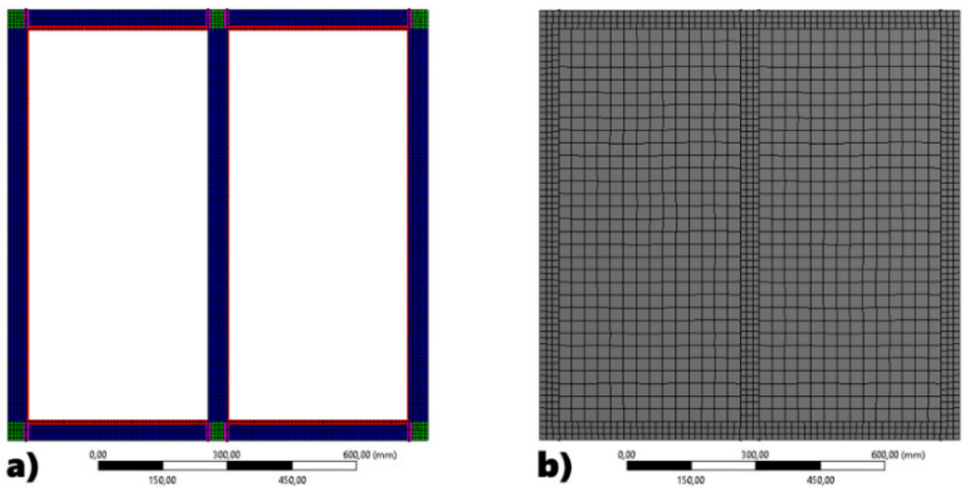

Figure 2a: Internal structure in plate elements, Figure 2b: Gypsum in solid elements

The joints between the U-profiles and the UE studs were considered as perfectly rigid and with elements double the thickness, as shown in the green regions in figure 2a. To represent the junction between the gypsum boards and the profiles a bonded contact condition was used.

After defining the geometric model, cold-formed EN10326 S280GD steel was used as the material for the profiles; its physical, mechanical and thermal properties at room temperature are presented in Table 1. The properties of the gypsum plates at room temperature were not configured because only the instability and loadbearing analyses were performed in this condition, since the plates do not have a structural function. [5]

Table 1. Physical, Mechanical and Thermal Properties for S280GD Cold Rolled Steel – EN10326 (2004)

Proprieties S280GD Cold rolled - Room temperature	
Ultimate strength [MPa]	360
Yield strength [MPa]	280
Young's Modulus [GPa]	210
Shear Modulus [GPa]	81
Poisson's ratio	0.29
Elongation (80 mm) [%]	18
Density [kg/m³]	7800
Specific heat [J/kgK]	465
Thermal conductivity [W/mK]	59
Coefficient of thermal expansion [1/K]	1.04E-5

2.1 Critical load and mode of instability

The first analysis performed consists in a verification of the critical load of the structure and its respective instability mode. For this, a fixed constraint was applied at the base of the frame, and three unit loads of 1 N were applied to the upper U-profile, divided in the middle positions between the studs and at the upper end of the intermediate stud. To represent a load distribution, the web thickness of the upper U-profile was considered to be 20 times the real thickness, thus avoiding localized deformation. The thicknesses of the profiles are represented in figure 3a, where the blue regions have 1.5 mm, the green regions 3.0 mm, and the red region 30 mm.

As the analysis performed represents a linear buckling, the Lanczos method was used to obtain the first instability mode, which is represented in figure 3b

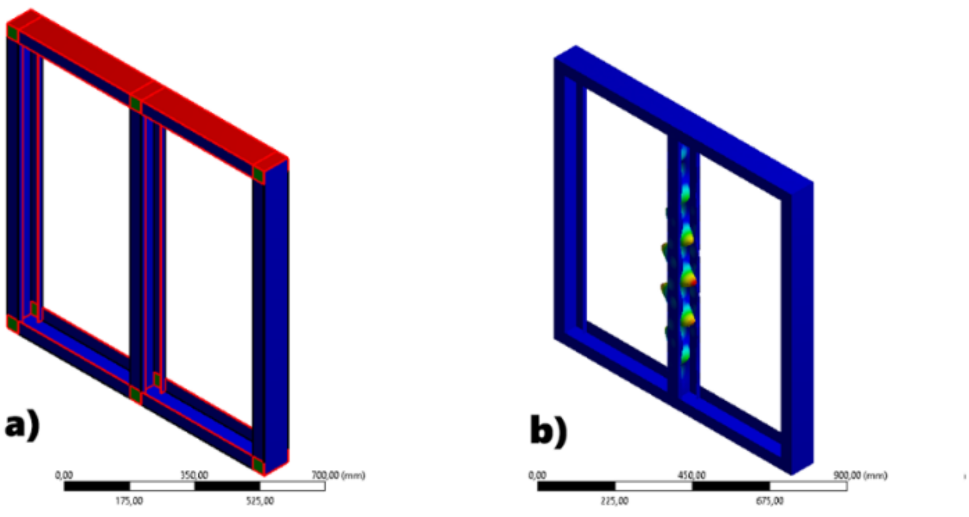

Figure 3a: Structure submitted for analysis 1, Figure 3b: Mode of instability acting on the structure

The instability verified is of the localized type, acting in the web of the intermediate column. This instability mode presents deformations in the profile walls maintaining its straight axis, being caused mainly by the high slenderness of the cold formed profile walls.

2.2 Loadbearing capacity

With the instability mode obtained through analysis 1, a nonlinear analysis was performed as to geometry and material, possessing initial geometric imperfection. The initial deformations applied to the geometry of analysis 2 were obtained by importing the finite element mesh deformed in analysis 1, with the application of a multiplicative factor of the displacements. This factor was obtained by equation 1, which relates the length that can be displaced in the web of the profile (w) by the maximum displacement generated in the instability mode ($u_x max$) [6].

$$factor = \frac{w}{u_x max} \tag{1}$$

To determine the loadbearing capacity, only the structural profiles were considered, without the gypsum plasterboards. The material of the profiles was modeled as Elastic-Perfectly Plastic.

With the definition of the material and the geometric model, three nodal loads were applied to the web of the upper profile and a lateral constraint condition to the frame, representing the gypsum board fasteners. Finally, a nonlinear analysis by the Arc Length Method was developed. This numerical solution method is very efficient for systems of nonlinear equations with critical points in their curve, because it models Snap-Through and Snap-Back behaviors. The first case occurs when there is a decrease in applied force with an increase in displacement, and the second case is when both force and displacement decrease and then increase.

The convergence criterion was used based on the displacement, with a value calculated by the solver, a tolerance of 5% and a reference value equal to 0 mm. With this a maximum loadbearing capacity of 37,570 N was obtained. Figure 4 represents the equivalent Von Mises stress obtained with analysis 2.

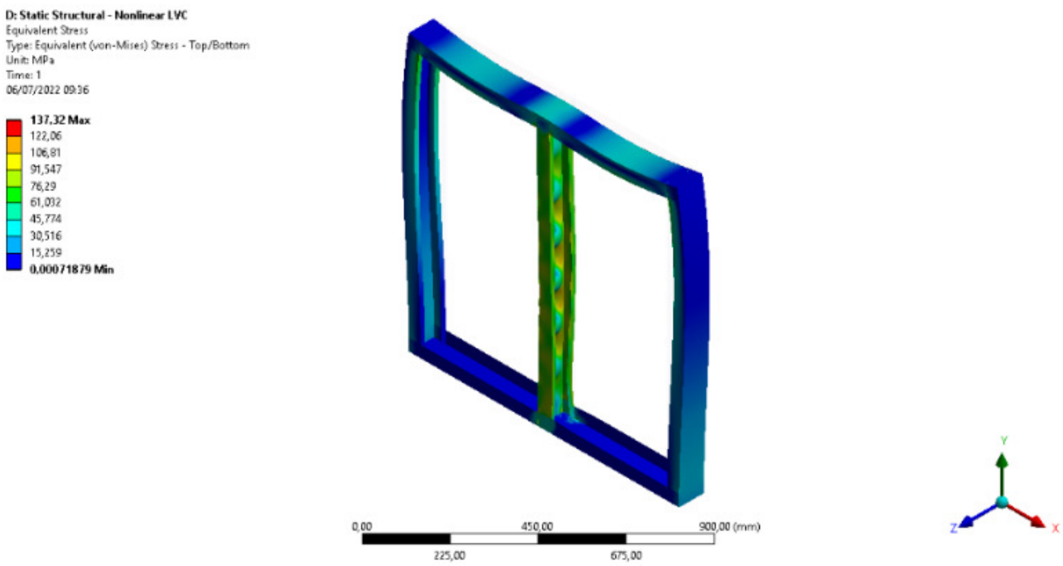

Figure 4. Deformed condition and Von-Mises stresses obtained by analysis 2

Analyzing Figure 4 it is possible to observe that the deformed condition is consistent with the instability mode obtained in analysis 1, presenting the localized instability in the web of the intermediate stud.

2.3 Nonlinear transient thermal analysis

After performing the instability and loadbearing capacity analyses for room temperature, a transient thermal analysis was developed. The finite element model used consists of a steel frame structure in rectangular plate elements, with gypsum plates modeled as solid elements, fixed by contact. The thermal properties, as a function of temperature, of specific heat, thermal conductivity and elongation for the steel used are presented in figure 5a, 5b and 5c respectively, based on EN1991-1-2. [7]

To perform this analysis, it was necessary to configure the thermal properties of gypsum plates as a function of temperature. These data are presented in Table 2 and were obtained based on studies by Alves and Batista (2007) [4] from data by Feng et al (2003) [8].

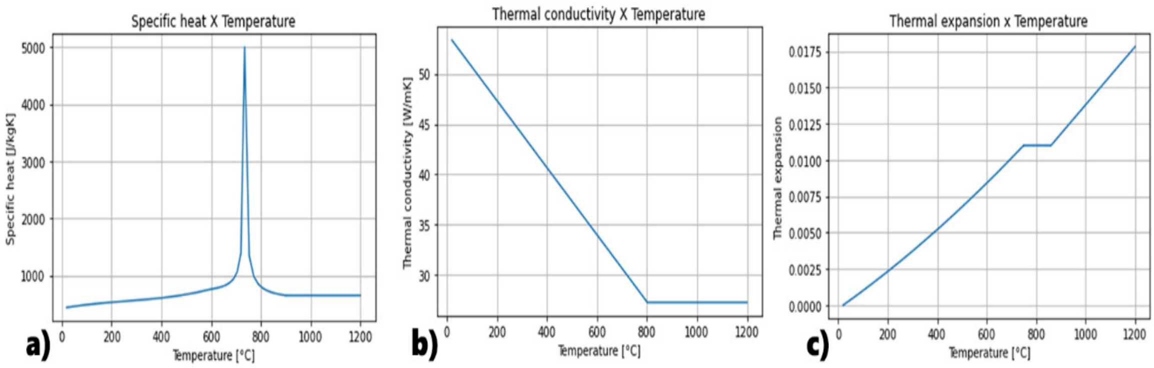

Figure 5a. Specific heat. Figure 5b. Thermal conductivity. Figure 5c. Thermal expansion

Table 2. Thermal proprieties of gypsum by Alves and Batista (2007) in" Feng et al (2003)

Density [kg/m³]	Temperature [°C]	Thermal conductivity [W/m°C]	Specific heat [JKg °C]
727	10	0.2	925.04
	95	0.21092	941.54
	125	0.21478	24572.32
	155	0.103	953.14
	900	0.25734	1097.5
	1200	0.3195	1097.5

The cavities were considered with thermal insulation, disregarding the transfer effects through them. This simplification admits that the transfer will be performed only by conduction between the profiles. As a boundary condition, three forms of heat transfer were applied: conduction, convection, and radiation.

- Conduction: Conduction occurs in both solid and liquid states. This behavior occurs due to the propagation of energy between more energetic particles to less energetic particles, where the flow of energy follows particles with higher temperatures colliding and stirring the molecules of a body with lower temperatures. Conduction in the analyzed model takes place between the faces by means of the internal structure, which has its thermal properties as a function of temperature, as shown in figure 5. [9]

- Convection: The convection process is given by the transfer of thermal energy due to fluid displacement. This process encompasses the diffusion energy transfer mechanism of random molecular motion, and also the mechanism of global macroscopic fluid motion. Thus, this physical behavior is created by the temperature difference of the gases in the region between the gypsum board and the heat source, as well as in the cavities between the boards when there is no insulation. To define the heat flux generated by this transfer mechanism on the face exposed to the fire, a convection heat transfer coefficient equal to 25 W/m²K was adopted, while on the unexposed face it was adopted as 9 W/m²K, to thus include the radiation effects. [9]

- Radiation: Radiation occurs through thermal energy emitted or absorbed by the matter of a body that has a non-zero temperature, regardless of the form of the matter. This emission occurs through electromagnetic waves (photons), not requiring a material environment to propagate. In the model analyzed we observe radiations from the emitting source (fire) and the plasterboard surface, in the cavities, all surfaces radiate heat, however, as there is the presence of insulation, these effects are insignificant. On the face not exposed to fire there is radiation only from the plasterboard surface to the external environment, which is at room temperature and does not emit heat. The emissivity of the radiation generated by the flames was adopted equal to 1 on the exposed face. On the unexposed face, radiation effects were considered in the transfer coefficient due to convection. [9]

The temperature curve applied in the model is defined by ISO834 [10]. With the applied boundary conditions, an incremental nonlinear thermal transient analysis in time was performed, with a split in 60s and minimum split in 1s. For the convergence criterion a heat flux condition with a tolerance of 0.1% and a minimum reference value equal to 1E-06 [6] was used.

With this analysis it was possible to obtain the times for the average and maximum temperatures, these which are defined by Equation 2. [6]

$$\begin{aligned} T_{max} &= \overline{T}_0 + 180 \\ T_{ave} &= \overline{T}_0 + 140 \end{aligned} \tag{2}$$

The times to reach the maximum and average temperature on the unexposed side were approximately 35 minutes and 33 minutes respectively.

2.4 Fire resistance analysis

With the temperature gradient history, a nonlinear analysis was performed regarding the material and geometry, applying different load percentages in 40,50,60,70 and 80% as developed by Piloto (2017) [6]. This percentage of load refers to the maximum loadbearing capacity for room temperature obtained with analysis 2.

The constraint conditions for this analysis were the same as for analysis 2, with a fixation at the base and a lateral fixation at the point of the fasteners, however the temperature gradient history obtained in analysis 3 was applied. In addition, the gypsum plasterboards were removed, as they have no structural function for loadbearing capacity analysis. For the solution the Newton-Raphson method was used, because according to Alves (2012) [3] this is one of the most efficient methods for the numerical solution of problems of the type f(x) = 0. The parameters of the solution were defined with a time division in 60 s and minimum division of 1s. The convergence criterion was used based on the displacement, with a value calculated by the solver, a tolerance of 5% and a reference value equal to 0 mm. Figure 6 demonstrates the deformed condition of the structure for this analysis.

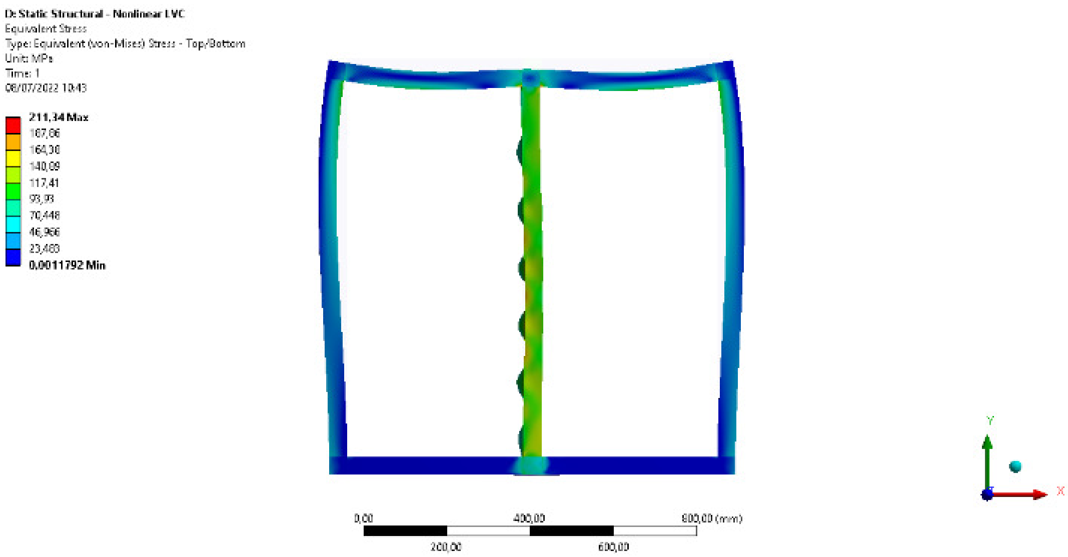

Figure 6. Deformed condition and Von-Mises stresses obtained by analysis 4.

For this model the minimum, average and maximum temperatures were evaluated, as well as the fire resistance in minutes, for different percentages of the load obtained in analysis 2. The results obtained are presented in Table 3.

Table 3. Fire resistance for each percentage of the structure's loadbearing capacity

Load Level [%]	Steel min. Temperature [ºC]	Steel ave. Temperature [ºC]	Steel max. Temperature [ºC]]	Fire Resistance (R) [min]
40	527	559	590	48
50	472	512	552	45
60	406	461	516	40
70	310	377	443	34
80	214	300	385	30

With the results obtained it is possible to verify a decrease in the critical temperature and in the fire resistance of the structure as there is an increase in the percentage of applied load.

3 Conclusions

Through analysis 1 was obtained the critical load and the instability mode of the structure, serving as a basis for defining the geometric imperfections applied in analysis 2. With this analysis was obtained the bearing capacity for room temperature, which applied along with the temperature history of analysis 3, provided the fire resistance through analysis 4. With the fire resistance obtained, it is possible to determine the time of exposure to fire that the structure takes to lose its physical characteristics, being this information of extreme importance for the control of a fire. Finally, it is worth noting the importance of future work considering different types of insulation, and a model that evaluates the effects of convection in the empty cavities of the analyzed structure.

Acknowledgements. The authors thank Araucária Foundation for the financial incentive to the research and the Federal Technological University of Paraná for the support provided.

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