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NUMERICAL ANALYSIS OF STEEL COLUMNS CONSIDERING THE WALLS ON FIRE CONDITION

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Abstract. *Steel columns are structural elements widely used in multi-storey buildings, industrial, commercial warehouse, among others. However, the reduction of stiffness and strength of steel in response to a temperature raise imposes the need to predict the critical time of exposure of the structure in fire, looking for safety and economic design structures. The presence of walls introduces change in gradient temperature at the steel cross section. In those circumstances, this paper aims to present a numerical study of steel columns with open section of type I, whereas the compartment of the environment in fire. The buckling of the compressed element will be marked by a reduction factor obtained using the relationship between the buckling load in a fire situation, characterized by asymptotic displacement, and buckling load identified at room temperature.*

1 INTRODUCTION

Fire is one of the natural phenomenon which, if it is not properly considered in the design of structures, can cause devastating consequences. Among the main materials used in the structures of the buildings it can be mentioned the steel structural, which has severe behavior changes on fire condition. The behavior of steel structures on fire condition, including the composite structure, for a long time it has been seen as dominated by the effects of the resistance loss from the material caused by the temperature rise, and large deformation through the load imposed to a weakened structure. To overcome this disadvantage it can be considered the application of fire protection to ensure that the steel can be exposed to fire for more time so it can reach similar temperatures to those that would be reached without the use of this protection. However, this procedure involves costs that, generally, make the steel structures less competitive related to the use of other structural material.

Regarding to the requirements of fire resistance from steel and composite structures elements on a fire condition, most of the standards and main normative codes of the world are still based on isolated elements in furnace experiments. This is because of the difficulty, both economic and technical, to perform experiments with complex structures, which would represent better the real structures behavior. The current international standards show simplified procedures to determine the critical time of fire resistance of steel structure. However, these simplifications are restricted to few cases and show approximated results; usually those results are not what really happen. In this way the numerical models in finite elements help to explain, in a more coherent way, the structural behavior of these elements on fire condition.

In this research [1] performed at the University of Sao Paulo was made structural numerical analysis at room temperature and thermo-structural analysis using the finite element method with the computational package Ansys [2], whose intent was to show the structural materials behave under high temperatures considering many situations and configurations, checking if the standards requirements provide with safe this behavior. However, on that study, due to uncertainties relative to the analysis procedure when using different types of elements simultaneously, it was used only the finite element type SOLID, with 8-nodes, for the modeling of steel cross section and compartment walls, but this element requires large computational effort. The aim of this paper is to demonstrate these numerical models now performed with finite element type SHELL, more appropriate for modeling of structures in thin walls, like steel cross sections. The advantage of using the element SHELL, whose geometry has only 4 nodes, is to allow large displacements, and also to allow coarse mesh for the numerical models of finite element, still obtaining very similar results to those achieved by the SOLID elements. This way this element requires much lower computational effort than that required by the SOLID element. The processing time is about 10 to 20 times lower.

2 NUMERICAL MODELING ASPECTS

Numerical models are built on this paper using the Ansys package, which provides to the researcher necessaries tools to obtain the results interesting to the thermal, structural and thermo-structural analysis. With this code is possible to consider the three primary modes of heat transfer: *conduction*, *convection* and *radiation*. The analysis of interest will be a *transient thermal analysis* type, which considers the evolution of the temperature over the time, allowing to determine the distribution of the temperature in the model at any instant. After made this thermal analysis for the definition of the thermal gradient in the cross section of the columns for each layout among columns and walls, simulating fire compartment, it will be realized thermo-structural analysis where it will apply a constant load with the thermal gradient in the cross section being varied along the time according to the previous analysis. A prior analysis at room temperature is going to be used to determine the ultimate load of the resistant capacity of the column so ratios of this will be used at each thermo-structural analysis.

2.1 About the thermal analysis

Thermal analysis is realized previously to obtain the thermal gradient in the cross section for determined time, since t = 0 to 150 minutes, with intervals of whole minutes. Consideration of masonry occurs in that first analysis and has, as main function, the heat exchange with the steel cross section and to isolate the fire environment, allowing the heat loss on the opposite side of the masonry and the steel. Masonry does not have structural function, being eliminated from the next analysis (thermo-structural). Because of a better coupling of the wall to the steel cross section. The _masonry, differently from the steel cross sections, was modeled with SOLID.

The *heat flow* by convection is produced by the difference of the density among the gas from the fire environment. For the numerical model it will be used the value for the heat transfer coefficient by convection α_c equals 25 W/m².ºC, according to item 8.5.1.1.2 from Brazilian standard [3].

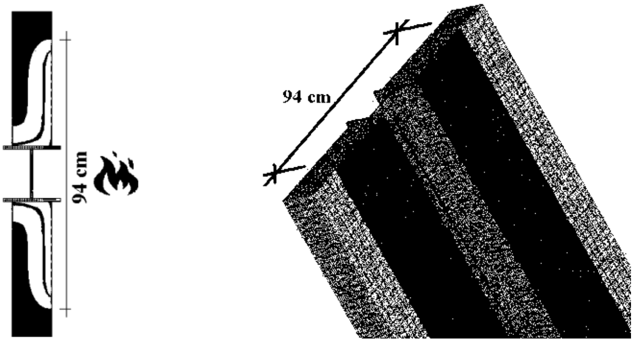
Radiation is the process where the heat flows like waves. Among the parameters to be considered in the numerical models proposed in this paper regard to the radiation will be attributed: emissivity coefficient with a value of 0.5 (at first), Stefan-Boltzmann constant with a value equals to $5.67\text{x}10^{-8}$ W/m².K^4, both according to the Brazilian standard [3] and configuration factor with a value equals 1.0 according to [4].

For the emissivity, the European standard [5] in its section 2.2, suggests the value 0.7, but emphasizes that is necessary to consider the *shadow effect*. However, for reasons of comparison to previous results and processing times, the value of 0.5 will be used in this paper. Furthermore, future works will use the value 0.7 coefficient and will consider the heat loss on the other side of the fire compartment with radiation and convection coefficients according to [5], also the axial restraint.

The application of the thermal effect was considered using the surface element SURF152, both for convection and radiation, being one element for each effect. Each element has only one degree of freedom per node, in this case, corresponding to the temperature. For gases heating from compartment fire was used the standard fire curve ISO 834-1:1999 and described in Equation 1, where ºC is the temperature of the gases and *t* represents the time in minutes [6]. The area considered for application of the thermal effect was 94 cm, as it is shown in Figure 1, being according to the strategy used in the experimental and numerical models [7].

$$\theta_g = 345\log_{10}(8t+1) + 20°\text{C} \tag{1}$$

The mechanical and physical properties of steel as function of temperature were used according to [5]. The thermal properties adopted for the masonry (compartment), according to the computational code Ozone v2.0 [8] were: density equals 1600 kg/m^3, specific heat equals 840 J/g.K and thermal conductivity equal to 0.7 W/m.K.



(a) (b)

Figure 1: (a) Thermal gradient in the whole cross section and masonry and (b) part exposed to fire.

Efficiency tests were made with three meshes with different densities of finite elements for the model with 2 walls reaching the flanges. The numbers of elements used in each mesh are shown in Table 1, as well as the number of nodes and the approximate dimensions of the elements.

Table 1: Dimensional details of the elements and nodes for each mesh.

	ref1	**ref2**	**ref3**
Elements of the column (shell)	2040	8160	18360
Nodes	2135	8349	18643
Width x Height (mm x mm)	17x53	8.5x26.5	5.6x17.6
Elements of the end plate (shell)	240	960	2160
Elements of the masonry (solid)	3840	7680	11520
Width x height x thickness (mm x mm x mm)	31.3x26.5x8.8	62.5x53.0x17.5	20.8x17. 7x5.8

2.2 About the analysis thermo-structural

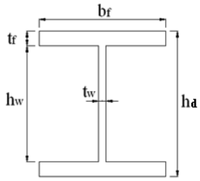
For the numerical model of the structural analysis were adopted the following mechanical properties at room temperature: yield strength equals 275 MPa and elasticity modulus equals 210,000 MPa. In the structural analysis made with the code Ansys, considering high temperature, was adopted the constitutive relation proposed by Eurocode 3 [5], that takes into account the penalty of the yield strength and elasticity modulus with the temperature.

The mesh density of referring to the models in thermal analysis, eigenvalue and thermo-structural must be identical, allowing the thermal gradients in the cross section from thermal analysis and global imperfection from eigenvalue analysis to be transferred correctly to thermo-structural analysis. Also were tested the 3 meshes density described above and their differences will be explained later.

Just like [1], the thermo-structural analysis was performed under open cross section, from type I laminate subjected to the effects of geometric imperfections of the global kind. The cross section used in the models was UC 203 x 203 x 46 (English series). Their geometrical characteristics are shown in Table

2. The local and distortional buckling modes, have not been considered because it is a cross section where the local slenderness is not predominant.

Table 2: Cross section UC 203 x 203 x 46.

Dimension	Value (mm)	Figure
h_w	181.2	
h_d	203.2	
t_w	7.2	
b_f	203.6	
t_f	11.0	
L	3170.0	

The columns were considerate with both extremity pin-ended, according to Figure 3, considering end plate with 20 mm of thickness, whose elasticity modulus was considered 1000 times higher than that adopted for the cross section (at room temperature), in order to avoid local effects.

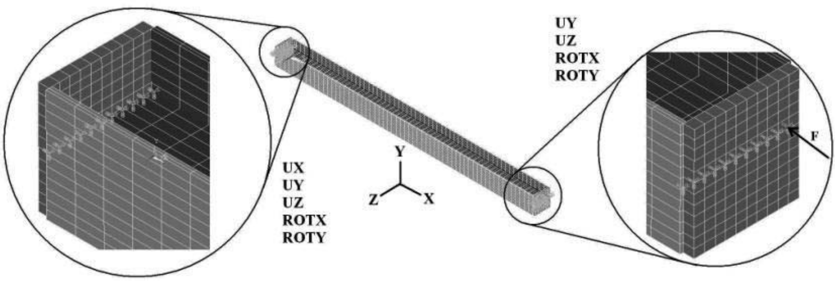
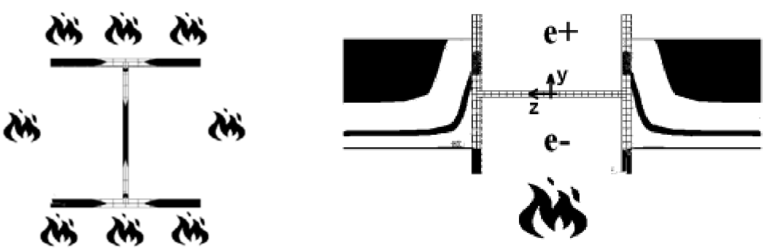


Figure 3: Detail of the column extremity, application of axial force and degrees of freedom restricted.

Thermo-structural analysis is performed by applying a static load lower and proportional to the buckling load at room temperature considering the global geometric imperfection obtained through eigenvalue analysis, according to [9]. After that, the thermal gradient is applied as a body load with the results of transient thermal analysis. The critical time is evaluated at the instant when the column loses the stability due to the temperature elevation. This procedure was performed both with the single column with thermal action on all sides, as shown in Figure 4a, also with the masonry at the flanges from Figure 4b and Figure 4c, in this case the thermal action was applied only in one of the sides.



(a) (b)

Figure 4: (a) Single column with thermal effects on all sides; (b) configuration of the walls reaching the flanges and way of initial global imperfection positive and negative.

3 RESULTS

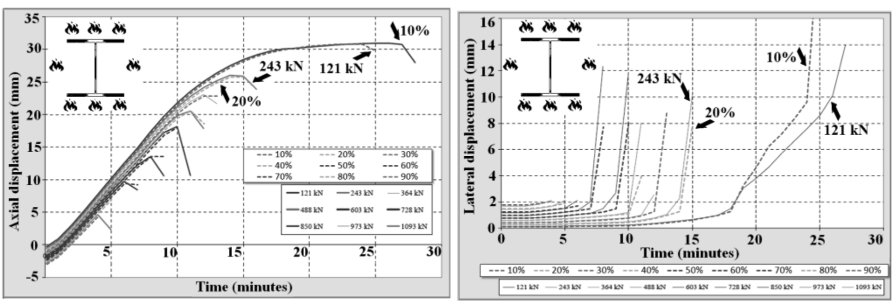
In this section will be presented the results obtained through the thermal analysis and thermo-structural analysis, those models were compared with other researchers for their validation.

3.1 Thermal models

The results of thermal model built with walls in contact with the flanges were compared with results from the other researchers [7] and showed good agreement when using the same emissivity values and heat loss like the reference. Thermo-structural models compared with [1] using the results of the thermal analysis with 0.5 emissivity coefficient, adiabatic model and standard fire curve ISO834-1:1999 in order to make the comparison possible.

3.2 Thermo-structural model with single column

The results of the axial displacement at the top and the lateral displacement at midspan presented good concordance with those shown in [1]. Figure 5 shows with solid curve the previous results with SOLID elements and, with dashed curve, the results with SHELL elements from this paper. It was identified significant differences at the processing time from both finite elements used: for SHELL elements the thermo-structural analysis took 1.1 to 2.8 hours depending on the ratios of the buckling load applied, while for those SOLID elements the time of the processing took about 24 hours to complete the analysis.

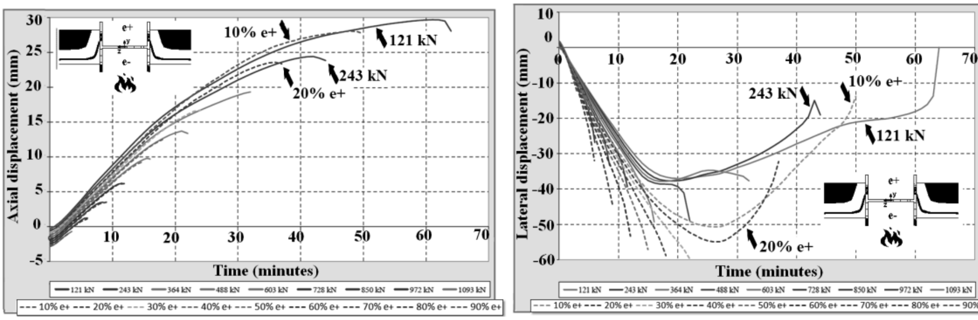


(a) (b)

Figure 5: Results from (a) axial displacement at the top and (b) lateral displacement at midspan for single column without walls and heat source in all directions by comparing SOLID elements, with solid curve, and SHELL elements, with dashed curve.

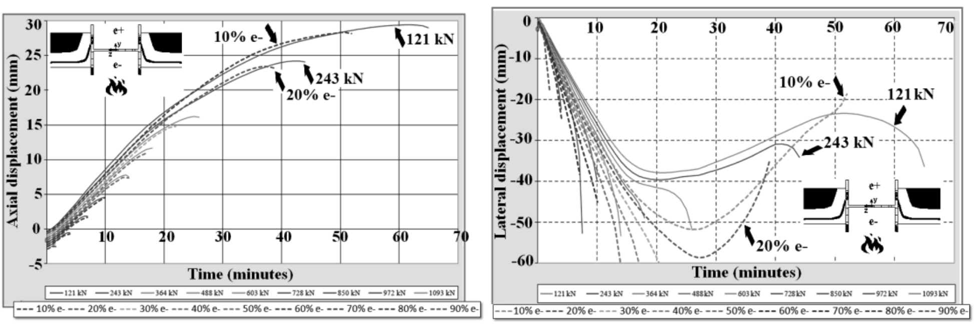
3.3 Thermo-structural models with masonry reaching the flanges of the cross section

For the model with masonry reaching the flanges the processing time was longer than that identified to the single column. This is because the walls keep the fire in only one room, in a way that the thermal action occurs only in one side of the steel cross section. Such aspect, also with the fact that they change the thermal gradient of the cross section, stealing steel heat, makes the average temperature of the columns becomes less than those identified for the single columns without walls. With the lower average temperature will be necessary a larger number of loading steps to lose stability, in other words, minutes of fire. Beside this, the thermal gradient will develop an element bowing, increasing the lateral displacement at midspan related to the single column. The results obtained in this research, compared with the results of [1], are shown in Figure 6a, with the axial displacement at the top of the column, and in Figure 6b the lateral displacement at midspan of them. The Figure 7a and Figure 7b show the axial and lateral displacement, respectively, considering the global initial imperfection negative, as already shown in Figure 4. In all figures below, the solid curve are with SOLID elements [1], while the dashed curves represent the results of the SHELL element used in this paper.



(a) (b)

Figure 6: Global initial geometric imperfection positive related to the heat source with (a) axial displacement at the top; and (b) lateral displacement at midspan comparing SOLID elements, solid curves, with SHELL elements, dashed curves.



(a) (b)

Figure 7: Global initial geometric imperfection negative related to the heat source with (a) axial displacement at the top; and (b) lateral displacement at midspan.

It is noticed good concordance between the model built in SHELL and the one built in SOLID for the axial displacement. The lateral displacement at midspan, however, was larger for all the cases with the element SHELL. It is believed that this is due to the fact that these elements allow larger displacement and because it has rotation degrees of freedom, not present in the SOLID element.

The critical times for this model were slightly lower, this is because the largest displacement at midspan increases the distance between the load action line and the longitudinal column axis, increasing and concentrating the internal efforts. The processing time for the mesh named *ref2* took about 6 to 12 times less time to complete the process related to the model in SOLID, that took 2 to 3 days.

In the three meshes tested the processing times were calculated and placed in chart form in Figure 8. Meshes *ref2* and *ref3* had results close to each other and also close from the reference curves, in SOLID element. The results of mesh *ref1* were slightly below of the reference curve. Noticing the big difference in the processing time and the good quality of the results, it was chosen the mesh named *ref2*.

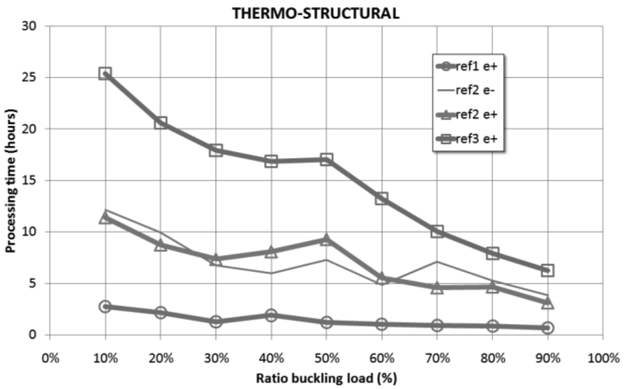


Figure 8: Tested meshes and processing times.

Because each load step receives small increments and each substep requires numerical convergence, the final time of processing becomes higher always when the buckling load ratio gets lower, in other words, reaches a higher critical time. The critical time will be equal to that load step where the numerical convergence is lost, what means, the internal efforts no longer balance with the external loads applied. In the search for numerical convergence can happen high distortions in the elements resulting in shapes often incoherent with reality, while some other times can demonstrate local or global buckling as it is supposed to happen in a real situation. Figure 9 shows some of these shapes from the elements, but remembering that this occurs in the loss of convergence, being a numerical answer many times incoherent. The quality of the results is not affected, because what is interesting for us is the behavior of the structural element until the load step of the convergence loss, such as the minute of exposure to the fire where it occurs.

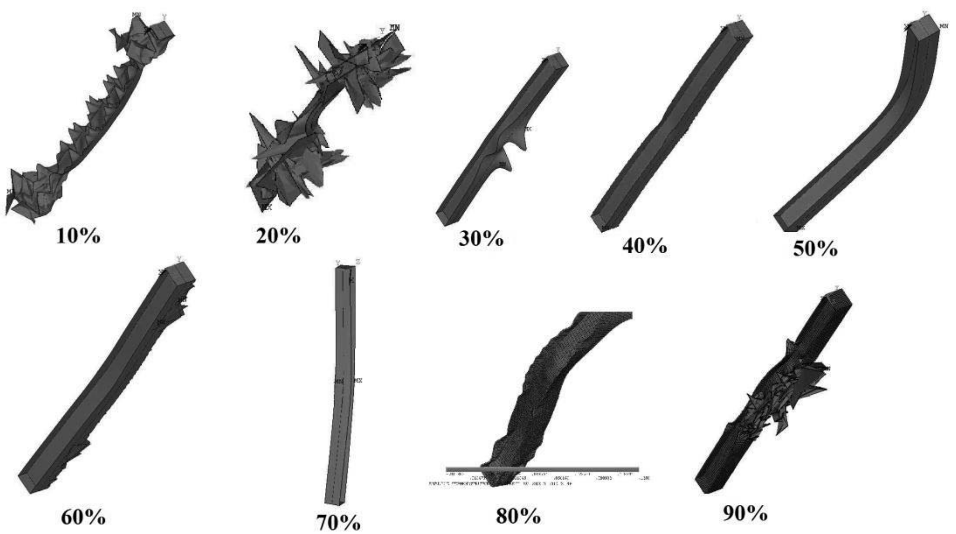


Figure 9: Structural element buckling during the numerical convergence loss from the models with walls reaching flanges for each buckling load ratio.

4 FURTHER WORKS

Further works following in this same research line will study the heat incidence of the fire by radiation with emissivity 0.7, and also will consider heat loss in the unexposed side and the axial restraint.

5 CONCLUSION

It can be concluded that the element SHELL is more appropriate to represent thin structures like steel cross sections in both analysis at room temperature and in thermo-structural analysis. These elements seem to be adequate in thermal analysis and make possible the transference of the thermal gradient in the cross section obtained previously for the thermo-structural analysis.

Since the methodology used in the model developed in SHELL was similar to that applied to the SOLID model, it is possible to say that the results of the *displacement x time* show coherence. This way, it is observable that the models studied in this paper have great efficiency because they need less processing time, i.e., they have a lower computational cost. Because of this the model enable the realization of a large number of analysis in short time.

For thermal analysis, the transfer of nodal temperatures, following the numeric strategy adopted, shown coherence even in the SOLID x SHELL interface, or it is same them say, in the contact between the cross section and the masonry.

Finally, it is necessary to remember that the numerical analysis presented in this paper still represents one preliminary phase of the study, other compartment walls layouts will be studied. For further studies will be performed new tests trying to turn the strategy even more comprehensive and closer to real situations.

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