The Influence of Slenderness in Steel and Composite Columns under Fire Conditions

Farid Boursas
Laboratory of Applied Civil Engineering (LGCA), Department of Civil Engineering, University of Tebessa, Algeria
farid.boursas@univ-tebessa.dz
(corresponding author)

Rafik Boufarh
Laboratory of Applied Civil Engineering (LGCA), Department of Civil Engineering, University of Tebessa, Algeria
rafik.boufarh@univ-tebessa.dz

Bilal Maghaghi
Department of Civil Engineering, Mohamed Boudiaf University of M'sila, Algeria
bilal.maghaghi@univ-msila.dz

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ABSTRACT

This study simulated two columns using the finite element software SAFIR. The first was a steel profile column and the second was a steel profile partially encased in a concrete column (SPPEC). Both columns were heated on four sides for one hour using the ISO834 standard fire curve. Two boundary conditions were considered for both columns, simply and doubly supported and loaded utilizing eccentric loading. A parametric analysis aimed to identify a thermal analysis of unprotected and protected steel columns in terms of temperature field distribution, and time-temperature curves of a few selected nodes were drawn from the SAFIR software. A thermomechanical study was also carried out using the results of the thermal analysis to determine the influence of slenderness on the resistance of the steel and the partially encased profile in concrete columns under fire solicitation. Finally, a comparison of the fire resistance of the two columns was made. The results proved that the slenderness negatively influences the fire resistance of the steel and composite columns and that the behavior of the composite columns is significantly better than the steel ones.

Keywords-steel profile column; SPPEC column; fire curve ISO834; slenderness; thermomechanical study

I. INTRODUCTION

Nowadays, modeling of structures under fire conditions allows the evaluation of a structure's behavior and its resistance to fire without resorting to tests. Columns are structural elements that ensure structural stability. A fire can severely affect the structural performance of columns [1], and several theoretical approaches and tests have been proposed to examine the fire resistance of columns. A simplified method was proposed in [2] to examine the resistance of an element to fire conditions, specifying that the resistance to fire (uniform temperature) is ensured if the temperature of the element after a fire is lower than its critical temperature. A procedure to determine the critical temperature was proposed according to the EN 1993-1-2 standard [3] and presented according to different stresses on the element (element bent without risk of overturning, element compressed or bent with risk of overturning, compressed element bent). This approach made it possible to check bare or protected elements, while if the element is protected, this procedure evaluated the thickness of the protective layer. In [4], the virtual work principle was used to establish a reinforced concrete beam element model under the influence of high temperature. The proposed model was evaluated under experimental tests on a frame. This configuration was chosen for parametric analysis, including the time factor. The study noted that the axial stress induces an axially compressive force which increases the deflection at the mid-span of the beam when the temperature increases, and the more the axial stress increases, the more the deflection increases. On the other hand, the deflection decreases if torsional rigidity increases. The experimental study presented in [5] investigated the influence of the circular shape on the behavior under fire conditions, describing the test procedure, observations, and the obtained fire resistance values.

Several theoretical methods have been developed and successfully applied for the rapid, safe, and efficient design of reinforced concrete columns under fire conditions. In [6], an experimental study was presented for the influence of spacing on the fire resistance of HSC circular columns under axial loading. The tested columns were modeled in the axis of symmetry with integrated reinforcements. The applied material model considered the influence of transient temperatures on the mechanical properties of concrete and steel, and a parametric study was carried out on the effect of cracking, the development of transient creep deformations, and plastic deformations for concrete. The results indicated that during the entire heating period, high thermal gradients generated tensile stresses in the section plane of the columns. The effects of axial and rotational stresses on the fire response of Concrete-Filled Tubular (CFT) columns were investigated in [7], using the fiber model to simulate the fire behavior of CFT columns in portal frames. A parametric study was carried out to analyze the influence of the retaining frame's adverse effects on the reaction to fire of CFT columns. The restraint thermal elongation induced restraint forces that negatively affected the column, however, a beneficial effect was produced by maintaining rotation which positively modified the boundary conditions of the heated column. In addition, another favorable effect came from the progressive redistribution of the internal forces as the heated column lost its mechanical capacity. In a second step, the current provisions given by Eurocode 4 Part 1.2 [8] were analyzed together with those given in the UK National Annex to Eurocode 4. The behavior of Concrete-Filled Steel Tubes (CFSTs) for slender columns subjected to eccentric loading under fire conditions was investigated in [9], simulating the destruction process of CFST slender columns under an ISO-834 standardized fire, and comparing the numerical to the experimental results. The comparison showed that the proposed model predicted the fire resistance of CFST slender columns subjected to a eccentric load. A parametric study was carried out to investigate the effect of load centering ratio, steel yield strength, concrete compressive strength, and CFST column reinforcement ratio under fire conditions.

The fire resistance of columns with double-filling concrete CFDST was studied in [10], using Finite Element Analysis (FEA) models and comparing the results with the experimental ones from the literature. Based on the developed numerical model, a study of the parameters affecting the resistance design of CFDST columns was carried out, using the experimental data to validate the accuracy of the proposed method and showing that it can predict the resistance of CFDST columns with reasonable accuracy. A three-dimensional Finite Element Model was proposed in [11] to predict the fire resistance of steel tubes filled with CFST cast-in-place concrete with preload, and was validated by experimental tests. The model was used to predict the fire resistance time of CFST columns with different slenderness, load, and preload ratios. The results showed that the preload of the steel tube had little influence on the fire resistance of short CFST columns, while the influence of the preload on the fire resistance can be significant on larger slenderness ratios and a further increase in slenderness ratio exceeding a certain range can reduce the effect of preload. In [12], a mathematical model using the fiber approach was presented to calculate the resistance of eccentrically loaded Concrete-Filled thin Steel Tubes (CFST) under fire stress. The model used thermal simulation to determine the temperature distribution in the cross sections and nonlinear global buckling analysis. This model included the initial geometry imperfection, air space between the concrete and the steel tube, tensile strength of the concrete, deformations caused by preloads, and the behavior of materials as a function of temperature and it was examined against experimental tests and existing numerical results.

In [13], a study on the fire performance of square-section steel tubes filled with reinforced concrete columns (SRCFST) was presented, using ABAQUS to establish the numerical models of the members of the SRCFST to simulate fire behavior. The models were validated against the results of experimental tests in terms of temperature field, axial strain versus time curves, fire resistance, and failure modes. The fire performance of the SRCFST columns, including temperature distributions, axial strain-time (Δ-t) curves, axial force distribution, and deformation, were investigated and compared with common CFST columns. The results showed that the fire behavior of SRCFST columns can be further improved with the integrated steel profile. Finally, the influences of various parameters on fire resistance, including fire load ratio, material strength, steel tube ratio, profile steel ratio, and slenderness ratio, were examined. In [14], eight full-scale Concrete-Encased Steel (CES) columns made of C120 concrete and an S500/S690 high-strength steel section were tested under concentrated load and heated under an ISO834 fire to failure, evaluating the fire resistance of each CES column. The axial displacement-time curve, the temperature-time curve, the angle of rotation of the end support, the post-fire conditions of the concrete surface, and the mode of rupture were examined. The experimental study showed that the addition of polypropylene fiber was effective in minimizing the explosive concrete spalling in high-strength CES columns to achieve a fire resistance time comparable to normal-strength CES columns. Furthermore, recommendations were provided for modifying the current methods for the fire-resistant design of high-strength concrete CES columns.

This study focused on the thermal and mechanical behavior of structural elements idealized by a steel column or partially encased with a concrete column (SPPEC) in the nonlinear domain. As composite columns differ from steel due to the combined action between concrete and steel that gives higher strength and more realistic behavior [15], the SPPEC column is challenging due to its sensitivity to parameters such as the cross-section size, material modeling, and boundary conditions [16]. To study the response of structures under the influence of fire, the SAFIR finite element program [17] developed at the University of Liège in Belgium solves the general Fourier heat transfer equation:

$$\left(k\frac{\partial^2 T}{\partial X^2}+K\frac{\partial^2 T}{\partial Y^2}\right)+Q=\rho c\frac{\partial T}{\partial t} \quad (1)$$

Several methods can be used to transform the heat transfer equation into a form suitable for finite element analysis. The most common is the weighted residual method which requires that the weighted averages of the residuals is equal to zero:

$$\int_x w_i(x)e(x)d_x = 0 \quad (2)$$

where $w_i(x)$ is a set of weighting functions. To take convection into account, a modification must be made to the basic formulation already developed. Convection is quantitatively described by Newton's law of cooling:

$$q = h(T_s - T_\infty) \quad (3)$$

Applying it to this problem produces:

$$\sum_{i=1}^{n}\left[\int_A k\left(\frac{\partial N_i}{\partial x}\frac{\partial N_j}{\partial x}+\frac{\partial N_i}{\partial y}\frac{\partial N_j}{\partial y}\right)dA\right]T_i + \sum_{i=1}^{n}\left[\int_S hN_iN_j dS\right]T = \int_A QN_j dA - \int_S qN_j dS + \int_S hT_\infty N_j dS \quad (4)$$

as structural response analysis. The bar element is used to model the columns, and the stiffness matrix is:

$$K = Ks + Ku \quad (5)$$

Different deformations (mechanical and thermal) were considered in the numerical simulation. The total strain rate is the sum of the elastic strain rate, the plastic strain rate, the thermal strain rate, and the thermo-mechanical interaction rate:

$$\dot{\varepsilon} = \dot{\varepsilon}^{\theta} + \dot{\varepsilon}^{P} + \dot{\varepsilon}^{\theta} + \dot{\varepsilon}^{tm} \quad (6)$$

II. THERMAL STUDY OF STEEL COLUMNS

For this study, an unprotected IPE120 steel column was solicited by eccentric loading of 5KN, according to different heights. Figure 1 shows the dimensions of the studied IPE120.

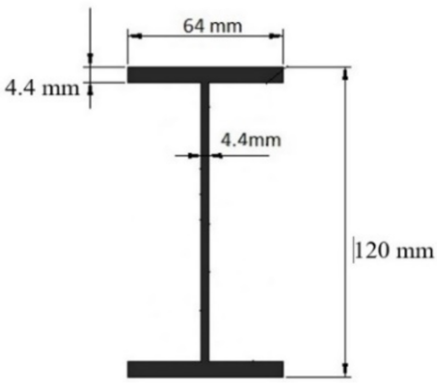

Fig. 1. Steel profile dimensions.

The discretization was based on a triangular meshing; which allowed to obtain 282 elements composed of 226 nodes for the steel section, as shown in Figure 2. Figure 3 shows the temperature evolution within the cross-section of the IPE120 exposed to an ISO-834 fire in the four accessible faces. This flow distribution shows a decreasing temperature towards the center of the web. For this purpose, three points were targeted:

- Node 1 on the solicited side of the upper flange
- Node 33 in terms of joint web-flange
- Node 109 in the center of the web

Figure 4 shows the representative curves of these points. The unprotected IPE 120 element reached a temperature of 60°C in 85s on the three nodes. Its temperature increased parabolically up to 1600s, and then rose linearly up to 940°C until 3600s. It can be noted that the three nodes take the same temperature assessment in the cross-section of the column solicited according to the four faces and that comes back to the finesse of the flange thickness and the chosen web.

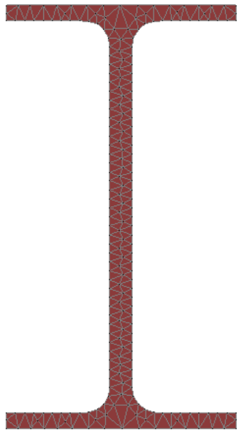

Fig. 2. Discretization of steel profile.

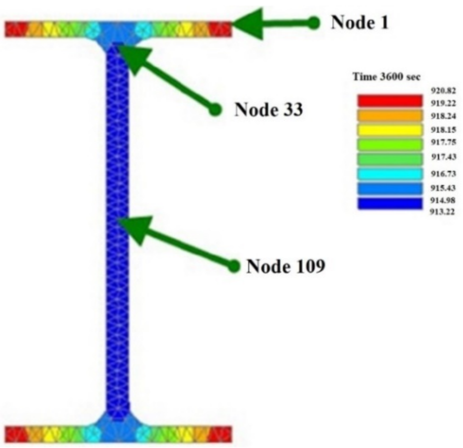

Fig. 3. Temperature distribution after 3600 sec of exposition.

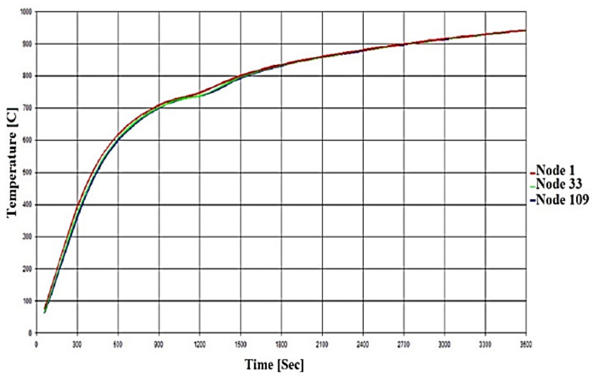

Fig. 4. Obtained temperatures vs time for nodes 1, 33, and 109.

III. THERMAL STUDY OF COMPOSITE COLUMNS

A steel profile was partially encased with a concrete column (SPPEC) and solicited by eccentric loading of 45KN according to different heights, as shown in Figure 5.

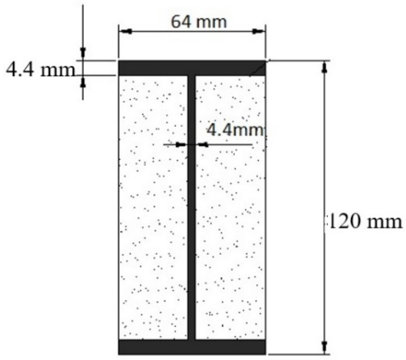

Fig. 5. SPPEC column dimensions.

The discretization was based on a triangular mesh, allowing to obtain the steel section partially coated with concrete, and consisted of 608 nodes or 1112 elements, as shown in Figure 6.

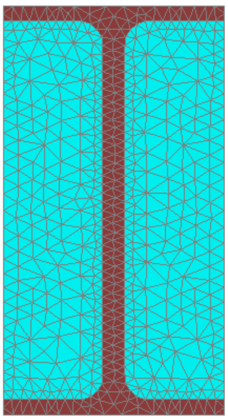

Fig. 6. Discretization of SPPEC column.

Similarly, as with the IPE120 column, the studied column was exposed to fire on four sides. The heat flow shows the formation of a symmetrical evolution compared to IPE120, and the temperatures varied between 932.7°C and 853.40°C. For this purpose, three points were targeted and their representative curves are shown in Figures 6 and 7. These chosen points were:

- Node 241 on the solicited face of the lower flange
- Node 33 on the exposed face of concrete
- Node 450 in the center of the cross-section

As shown in Figure 8, the temperature increased parabolically from 90s, where node 33 reached a temperature of 70°C, node 241 reached 40°C, and node 450 reached 20°C. After 3600s, the center of the section reached a temperature of 853.40°C, the side of the lower flange reached a temperature of 922.79°C, and the third node of the solicited face of concrete reached a temperature of 932.70°C.

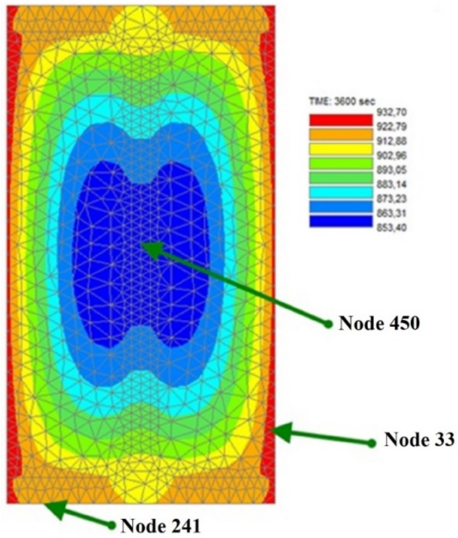

Fig. 7. Temperature distribution after 3600s of exposition.

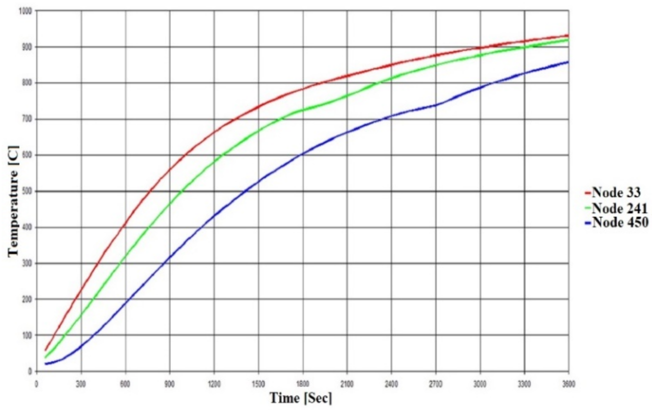

Fig. 8. Obtained temperatures vs time for nodes 33, 241, and 450.

IV. MECHANICAL ANALYSIS

The mechanical behavior of a steel column and another composite bi-articulated with varied height (5m to 9m) was examined. The steel column was subjected to an eccentric load of 5kN, and the steel profile partially encased with the concrete column (SPPEC) was subjected to an eccentric load of 45kN. With:

$$F = \frac{\text{load applied}}{\text{limit load at room temperature}} = 50\%$$

The studied columns were discretized in 21 nodes and 10 elements, as shown in Figure 9. The slenderness parameter was evaluated to analyze its influence on the fire behavior of steel and composite columns.

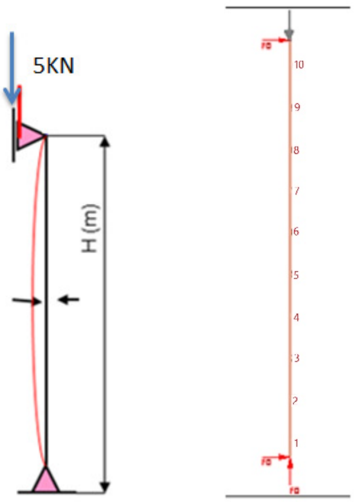

Fig. 9. Considered columns scheme.

TABLE I. FIRE RESISTANCE OF THE COLUMNS AS FUNCTION OF HEIGHT

Section type Steel profile Mixed	Fire resistance (Ref/s)				
	H=5m	**H=6m**	**H=7m**	**H=8m**	**H=9m**
Steel column	187	100	30.5	16.25	13.75
Composite column	2621	1989	1739	1580	1446

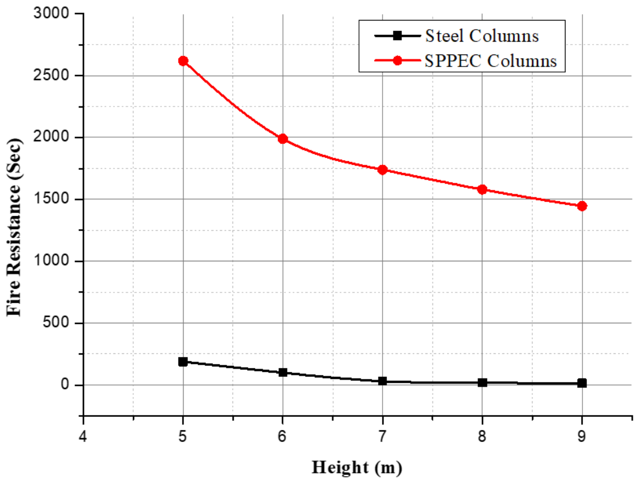

Fig. 10. Influence of columns' height for IPE120 protected in concrete and unprotected on fire resistance.

Figure 10 shows the fire resistance of IPE120 in both cases as a function of the height of the columns. Increasing the height of the columns hurts their resistance to fire. When the height of a column is increased, the fire resistance decreases for the two studied sections. Similarly, the temperature variation for the IPE120 profile has a low variation compared to the composite section. The influence of the protection of the steel profiles is very important in the mechanical behavior in terms of fire resistance.

V. CONCLUSION

This study performed a numerical analysis of a steel profile column and a steel profile partially encased with concrete column (SPPEC) under fire conditions, using the SAFIR software based on the finite element method. The results showed the impact of the slenderness parameter on the fire resistance of this kind of column. From the results of this study, the following conclusions may be drawn:

- The numerical investigation indicated that the variation of temperature in the steel profile exposed to fire on the four sides is very minimal, and it undergoes a degradation of its mechanical characteristics abruptly and can reach failure.
- The protection of the steel profile with concrete in SPPEC columns creates a significant temperature difference within the cross-section after exposure to fire and causes the failure of the element to not be sudden.
- The increase in the height of the steel profile column significantly affects its fire resistance.
- The protection of steel profile columns with concrete has a positive and considerable influence on the fire resistance of IPE120 partially coated with concrete, and its resistance is 2621s.
- The increase in the height of the two types of columns harms their fire resistance. Increasing the height of the column results in a decrease in the fire resistance in the two section columns.

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