PAPER • **OPEN ACCESS**

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To cite this article: J P Rojas Suárez *et al* 2022 *J. Phys.: Conf. Ser.* **2153** 012005

Journal of Physics: Conference Series **2153** (2022) 012005 doi:10.1088/1742-6596/2153/1/012005

Evaluation of the fire resistance of steel-reinforced concrete-filled steel tubular columns with a circular cross-section

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Abstract. In the present investigation, an analysis of the fire resistance of the steel-reinforced concrete-filled steel tubular columns with circular cross-sections was carried out by means of numerical simulation. The development of the study was carried out by means of numerical simulation to predict the behavior of the column against fire. The results of the numerical model are validated by comparing the temperature levels obtained through experimental tests. From the results obtained, it is shown that the increase in the contact area between the steel and the concrete reduces the average temperature of the column, which implies a greater resistance to fire. The fire resistance of the columns with the steel profile designs are between 3.4 - 3.6 times higher compared to the column only made of concrete, which is an indication of the excellent performance of the steel-reinforced concrete-filled steel tubular columns with circular cross-sections columns. In general, the methodology proposed in this research allows the analysis of the thermal physical phenomena of the different columns used for the construction of buildings.

1. Introduction

Due to accelerated economic growth globally, there has been an increase in the construction of large-scale structures. The columns are the main elements used to support compression and bending loads. Since the importance of this element, it is necessary to guarantee the load capacity and ductility of the material. Among the existing column types, steel-concrete composite columns have high profitability and various advantages [1]. In this type of columns, there are the steel-reinforced concrete columns (SRC), concrete-filled steel tubular columns (CFST), concrete-filled double skin steel tubular columns (CFDST), steel-reinforced concrete-filled steel tubular columns (SRCFST), among others [2-5].

Steel reinforced concrete-filled steel tubular columns (SRCFST) are comprised of an outer steel tube, an embedded steel profile, and concrete. The above allows combining the advantages of the CFST and SRC columns. This type of column has been extensively investigated through experimental studies and numerical simulation to evaluate its behavior when subjected to static and dynamic loads [6-8]. The results obtained show that the steel profile embedded in the SRCFST columns significantly improves the load capacity, reduces the formation of cracks, presents greater seismic resistance, and improves the ductility of the column. Due to the above, SRCFST columns are widely used for building structures.

One of the main causes of massive disasters in buildings is the presence of fire [8]. Therefore, interest has been awakened to analyze the impact on the structure of the columns when they are subjected to high temperatures. Espinos, *et al*. [9] performed an evaluation of the fire resistance between CFST and CFDST columns by means of numerical simulation. Zhu, *et al*. [10] experimentally investigated the heating rate and fire resistance between SRCFST and CFST type columns. Tan, *et al*. [11] investigated the parameters of fire resistance, failure modes, internal force distribution and temperature distribution in CFST columns. Meng, *et al*. [12] experimentally studied SRCFST columns under different fire conditions, which include uniform fire and non-uniform fire.

Despite the various studies available in the literature, few studies have focused on SRCFST type columns under fire conditions. Due to the economic cost of creating experimental test facilities for the study of SRCFST columns and the difficulty of measuring variables such as deformation and temperature distribution, it is necessary to use other strategies to improve the understanding of the physical phenomena of SRCFST columns under the presence of fire.

The present research aims to study cross-section SRCFST columns that circulate under the presence of fire. The analysis is performed by finite element methods using OpenFOAM software [13]. The study involves the analysis of the temperature distribution variables and axial deformation under different types of steel profile designs and fire load ratios.

2. Methodology

This section describes the mathematical models, the properties of the materials and the computer-aided design (CAD) models of each type of column to be investigated.

The specific heat capacity of concrete is determined as a function of the temperature (T) range, as shown in Equation (1) [14].

$$\overline{\rho_c}\overline{s_c} = \begin{Bmatrix} \frac{19\rho_c s_c}{20} + \frac{\rho_w s_w}{20} & T \leq 100°C \\ \rho_c s_c & T > 100°C \end{Bmatrix}, \quad (1)$$

where ρ_w is the density of the moisture, $\overline{\rho_c}$ is the density considering the effect of water vapor, ρ_c is the density without considering the effect of water vapor, s_w is the specific heat capacity of the moisture, $\overline{s_c}$ is the specific heat capacity considering the effect of water vapor and s_c is the specific heat capacity without considering the effect of water vapor. The transitory thermal strain of concrete (ε_{th}) is determined by Equation (2) and Equation (3) [15].

$$\varepsilon_{th} = \kappa \cdot \varepsilon_e \frac{\sigma}{f_c} \quad T \leq 550\ °C, \quad (2)$$

$$\frac{\varepsilon_{th}}{\partial T} = -0.0001 \frac{\sigma}{f_c} \quad T > 550\ °C, \quad (3)$$

where ε_e is the thermal expansion strain of concrete, f_c is the cylinder strength of concrete, and κ is a constant of the model ($\kappa = 2$). To consider the effect of concrete softening due to tensile loads, the stress-deformation model proposed by Hon and Varma was used [16], as shown in Equation (4); where E_c is the concrete modulus of elasticity, ε is the strain, and σ is the stress, respectively.

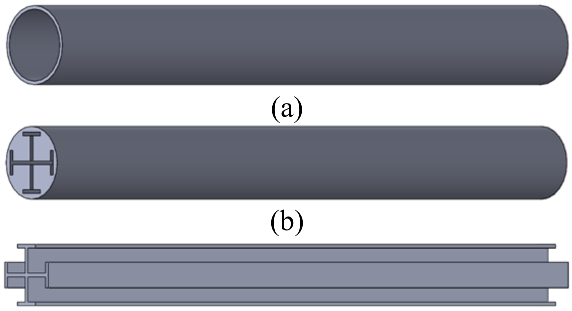
$$\sigma = \begin{Bmatrix} E_c \cdot \varepsilon & \varepsilon < 0.09 \frac{f_c}{E_c} \\ 0.099 f_c - 0.1\varepsilon \cdot E_c & 0.09 \frac{f_c}{E_c} \leq \varepsilon \leq 0.18 \frac{f_c}{E_c} \\ 0.081 f_c & \varepsilon > 0.18 \frac{f_c}{E_c} \end{Bmatrix}, \quad (4)$$

The thermal properties for steel and concrete of the SRCFST column were based on the structural fire design rules EN 1992-1-2 [17] and EN 1993-1-2 [18], described by the European Committee for Standardization. A convection coefficient of 25 W/m^2K and an emissivity factor of 0.7 are established. The coefficient of thermal expansion for concrete was defined as $6 \times 10^{-6}\ K^{-1}$. The ambient temperature is set at a value of 27 °C. The emissivity of the fire was determined at a value of 1.

Journal of Physics: Conference Series **2153** (2022) 012005 doi:10.1088/1742-6596/2153/1/012005

The behavior of the SRCFST columns in the presence of fire was a finite element analyzed with OpenFOAM software [13]. The geometric parameters defined for the construction of the SRCFST column were the external diameter, length of the column, the thickness of the steel tube, and support conditions. Additionally, the thermal and mechanical properties of the materials are established: concrete, steel profile, and steel tube. The load plates are modeled as perfectly elastic elements. The geometric shape of the components of the SRCFST columns are shown in Figure 1.

The development of the experimental tests was carried out in an electric oven. The length of the manufactured column was 1000 mm. For the validation of the results obtained by simulation, temperature sensors were installed inside the column.



(a)

(b)

(c)

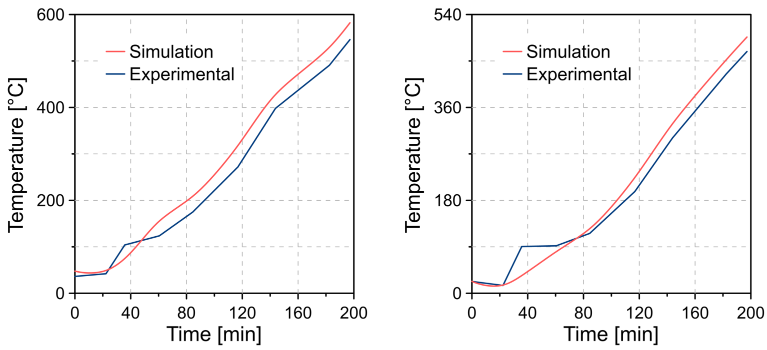
Figure 1. Components of the SRCFST columns; (a) steel tube; (b) concrete; (c) steel profile.

3. Results

This section presents the results and discussions obtained from the investigation, which include the predictive capacity of the model and the analysis of the temperature distribution and axial deformation of the columns.

3.1. Experimental setup

To guarantee the reliability of the results predicted by the simulation, a comparison was made with the temperature obtained by the experimental tests in two locations of the column cross section: location A (outer surface of the column) and location B (geometric center of column). The results of the comparison are shown in Figure 2.



(a) (b)

Figure 2. Comparison between the temperature obtained. experimentally and simulated; (a) location A; (b) location B.

From the results obtained in Figure 2 it was evidenced that the trend reported by the simulations describes the same behavior as the experimental measurements. An average relative error of 18% and 14% was observed for location A and location B, respectively. The largest deviation at location A is attributed to its proximity to the outer surface of the column, which may be exposed to uneven heat flow. Despite the above, the deviations obtained are considered adequate to study the physical behavior of SRCFST columns in the presence of fire.

3.2. Temperature distribution analysis

To analyze the effect of the embedded steel profile in SRCFST columns, different types of profile designs are analyzed. The types of simulated profile designs are shown in Figure 3. The results of the temperature analysis are described in Figure 4.

Figure 4 shows the temperature distribution of the cross-section of the three-column designs. In all designs, it was evidenced that the temperature decreases gradually from the outer surface to the geometric center of the column. In general, the presence of the steel profiles inside the column produces a greater temperature zone below 200 °C compared to the column formed only of concrete. Similar results are reported in the literature. This is attributed to the low thermal conductivity between steel and concrete. Comparing the designs of profiles type B and type C, it was evidenced that the latter presents a slightly lower temperature distribution compared to the design of profile type B. The above is a consequence of the greater contact area between the steel profile and the concrete. The previous results show that the zones of higher temperatures are considerably reduced when the steel profiles are embedded in the column, which is a significant benefit to improve fire resistance.

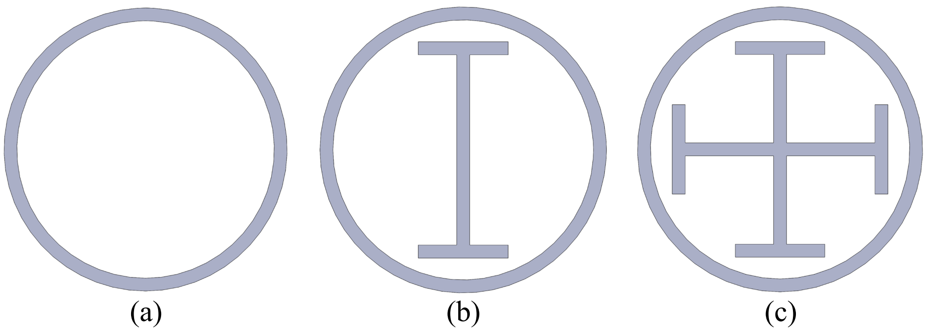


Figure 3. Column design; (a) type A; (b) type B; (c) type C.

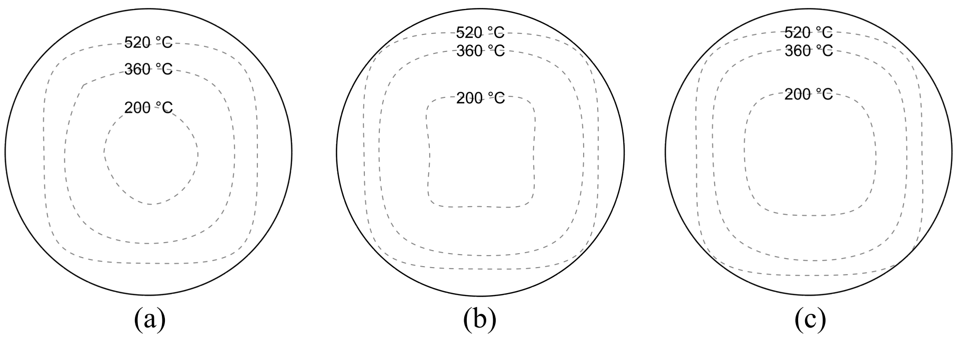


Figure 4. Temperature distribution for columns; (a) type A; (b) type B; (c) type C.

3.3. Analysis of axial deformation

Figure 5 shows the axial deformation of the column for the different types of columns (see Figure 3). In the case of type B and type C column designs, it was evidenced that these have a considerably higher fire resistance compared to columns only made of concrete (type A). This is demonstrated by considering the rapid drop in the deformation curve. This accelerated fall is a consequence of the deterioration of the rigidity of the column as it is in the presence of fire.

For type B and type C designs, it was observed that column failure occurs for an approximate time of 105 minutes and 111 minutes, respectively. This failure occurs as a consequence of the progressive buckling of the steel tube, which reduces the confining effect of the column. The higher fire resistance of type C column design compared to type B, is attributed to the regions of lower temperature in the cross-section of the column, as reported in the previous section. Additionally, the moment of inertia of the type C column is higher, which is another factor that contributes to the fire resistance of the column.

Figure 6 shows the axial deformation curve for different fire load ratios for the type C column. It was observed that the increase in the fire load ratio causes a considerable decrease in the fire resistance of the column. In the cases analyzed, a 40% and 60% decrease in catastrophic failure time was evidenced for a load ratio of 0.5 and 0.6 compared to a load ratio of 0.4, respectively. This is a consequence of the more accelerated loss of the stability and load capacity of the column.

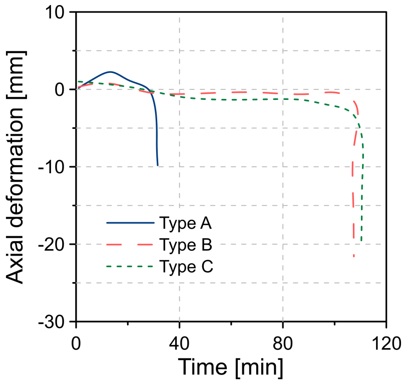


Figure 5. Axial deformation for different column designs.

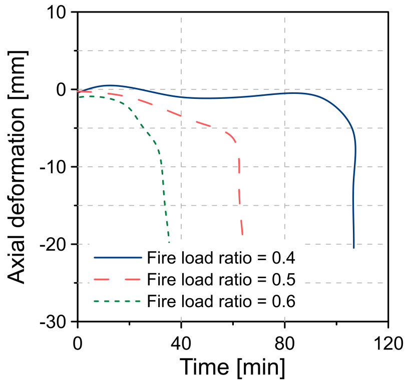


Figure 6. Axial deformation for different fire load ratios.

4. Conclusions

In the present investigation, an analysis was carried out by means of numerical simulation of the thermal behavior of the steel-reinforced concrete-filled steel tubular columns. The study involves the analysis of the temperature distribution variables and axial deformation under different types of steel profile designs and fire load ratios. The results obtained show that the thermal resistance between the steel profile and the concrete affects the temperature distribution in the cross-section of the column. In general, increasing the contact area between these two materials reduces the average column temperature, which implies greater resistance to fire.

The analysis of the axial deformation curve as a function of time shows that the embedding of the steel profiles in the columns considerably retards the accelerated failure. The fire resistance of the columns with the steel profile designs are between 3.4-3.6 times higher compared to the column only made of concrete, which is an indication of the excellent performance of the steel-reinforced concrete-filled steel tubular columns.

In general, the methodology proposed in this research allows the analysis of the thermal behavior of the different columns used for the construction of buildings. In this way, it contributes to the search and evaluation of new column designs, with the aim of improving their performance in the presence of fire.

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