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Fire resistance of concrete filled circular hollow columns with restrained thermal elongation

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ABSTRACT

The filling of circular hollow sections (CHS) with concrete is a good solution for strengthening columns since such procedure increase their load bearing capacity at room and high temperatures. However, in the event of a fire, restraining to thermal elongation may change their mechanical behavior. This paper presents the results of a large series of fire resistance tests on CHS columns with restrained thermal elongation. Parameters such as the slenderness of the column, its load level, the stiffness of the surrounding structure, the percentage of steel reinforcement and the degree of concrete filling inside the column, were tested. The results obtained show that the critical time of the columns was less than 46 min. The use of a concrete ring around the internal surface of the column's wall is of no advantage in terms of its behavior under fire conditions because this concrete ring suffers extensive spalling and cracking due to overheating of the steel tube. The main failure mode of the columns was global buckling. However in several cases local buckling also occurred.

Notation

EA_{eff}	Effective axial stiffness
EI_{eff}	Effective flexural stiffness
$f_{cu,j}$	Compressive cube strength of concrete at room temperature at “j” days
f_{sy}	Yield strength of construction steel at room temperature
f_{su}	Ultimate strength of construction steel at room temperature
f_y	Yield strength of reinforcing steel at room temperature
f_u	Ultimate strength of reinforcing steel at room temperature
K_{as}	Axial stiffness of the surrounding structure
K_{rsi}	Rotational stiffness of the surrounding in “i” direction
K_{ac}	Column's axial stiffness
K_{rc}	Column's rotational stiffness
L_e	Buckling length of the column
$N_{b,rd}$	Design value of the buckling load at room temperature
$N_{pl,Rk}$	Characteristic value of the plastic load to compression at room temperature
N_{cr}	Elastic critical load for the relevant buckling mode at room temperature
α	Degree of axial restraint
B_i	Degree of rotational restraint in “i” direction
$\bar{\lambda}$	Relative slenderness
η	Load level

1. Introduction

The use of circular hollow steel columns (CHS) filled with concrete in building construction is increasing due to several advantages, such as, for example, the higher load-bearing capacity, the possibility of using columns with smaller cross-sections, shorter erecting times due to avoiding formworks and good fire performance. Therefore, CHS columns seem to be an adequate construction solution in terms of load-bearing capacity at room and high temperatures.

The behavior of CHS columns when subjected to fire has been studied by several authors for years [1–16], but most of these studies do not consider the restraining to their thermal elongation. The response of these columns when inserted in a building structure is different than when isolated. Restraints on the thermal elongation of the column, provoked by the building surrounding structure, plays a key role on column's stability, since it induces different forms of interaction between the heated column and the cold adjacent structure. The increase in the stiffness of the surrounding structure to the column subjected to fire increases not only the axial but also the rotational restraining, while the former reduces the critical time (also the critical temperature) of the columns, the latter increase them [17–20].

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In 2000, Rodrigues et al. [19] published results obtained from a series of 168 fire resistance tests on compressed steel elements with restrained thermal elongation. Parameters were tested such as the slenderness of the elements, load eccentricity, stiffness of the surrounding structure and type of end supports. It was concluded that for the case of pin-ended elements with centered loading, the greater the stiffness of the surrounding structure, the lower is the critical temperature.

In 1999, Valente and Neves [20], presented the results of a numerical study on steel columns with axial and rotational restraining. It was concluded that the increasing on the axial restraining led to a reduction on the critical temperatures while the rotational restraining has the opposite effect.

In 1999 Kodur [7] presented the results of a series of 75 fire resistance tests on concrete filled hollow columns. Several types of concrete were tested such as, for example, plain concrete, steel reinforced concrete and fiber reinforced concrete. The parameters tested included the type and dimensions of the cross-section, thickness of the steel tube wall, strength of the concrete, type of aggregate, load level and end support conditions. The serviceability load applied to the columns varied between 10 and 45% of the design value of the buckling load of the columns at room temperature ($N_{b,rd}$). The failure criteria adopted corresponded to a speed of shortening of the columns of 76 mm/min (the columns were 3810 mm high). The fire resistance of the CHS columns filled with plain concrete was between 60 and 120 min, and higher than 180 min for those of reinforced concrete and steel fiber reinforced concrete. The failure mode of these columns occurred due to global buckling, especially for cross-sections with a diameter of less than 203 mm.

Han et al. (2002) and Han and Huo (2003) [2,3] presented the results of 18 load bearing capacity tests on CHS columns after fire. Several columns were tested: some with and others without fire protection. They evaluated parameters such as the cross-section type, the slenderness of the column, and the eccentricity of the loading. The unprotected columns were heated for 90 min and the protected ones for 180 min, as per the ISO 834 fire curve [21]. After reaching the cited levels of heating, the columns were then cooled and the tests were conducted at room temperature. The results showed a residual load bearing capacity of the unprotected circular CHS columns varying between 45% and 69% and the protected ones varying between 92% and 95% of the columns strength at room temperature.

In 2003 Han et al. [5] reported 13 fire resistance tests on protected and unprotected CHS columns. They tested parameters such as the cross-section dimensions, thickness of the steel tube wall and eccentricity of the loading. The load level adopted was 77% of the design value of the buckling load at room temperature ($N_{b,rd}$) calculated as per EN1994-1-1 [22]. The failure was considered when the column shortened by 38 mm or the shortening rate reached 11.4 mm/min as per EN1363-1 (1999) [23] criteria. The results showed fire resistances for the unprotected columns between 7 and 32 min and for the protected ones between 120 and 196 min.

In 2010 Leite et al. [9] tested in fire 24 circular CHS columns subjected to load levels of 30%, 50% and 70% of the design value of the buckling load at room temperature ($N_{b,rd}$). They had been filled with normal and high strength concrete, their cross-section diameters being 114.3 and 168.3 mm and the wall thickness of the steel tube, 6.4 mm. The failure criteria adopted was a rate of shortening of the column of 76 mm/min. The fire resistance varied between 32 and 44 min for the columns tested with a load level of 30% $N_{b,rd}$, between 21 and 28 min for those tested at 50% $N_{b,rd}$ and between 9 and 21 min for those tested at 70% $N_{b,rd}$.

Han et al. [4] and Espinos et al. [24] state that the concrete filling increases the fire resistance of the columns and their structural behavior becomes more ductile due to the composite action between concrete core and steel tube. At first, the steel tube expands more than the concrete core, due to the higher thermal expansion coefficient of the steel, which sustains the serviceability load applied to the column. In the latter stages the steel tube starts to buckle locally which transfers the load to the concrete core. Finally when the concrete core loses its strength, the column buckles.

In 2011 recent numerical studies were carried out on moment-resisting frames where the evolution of the bending moment and of the axial force were considered in thermal analyses as a function of time at various locations of the frame for the different fire scenarios [25].

In general, the major conclusions of these studies are that the loading level, cross-sectional dimensions, buckling length, slenderness, degree of concrete filling and type of concrete used to fill the column (i.e. plain concrete, reinforced concrete or fiber reinforced concrete) has a significant influence on the fire resistance of the columns. However, the influence of other parameters, such as the strength of the concrete and steel, the type of aggregates and the eccentricity of the loading is moderate. On the other hand, the ratio of steel reinforcement, the thickness of the steel tube wall and the axial distance from the reinforcing bars to the internal wall surface of the steel tube, have little influence on the fire resistance of the columns.

As the influence of the stiffness of the surrounding structure on the behavior of CHS columns subjected to fire is not very well clear in the previous works, a set of 40 fire resistance tests were performed at the Laboratory of Testing Materials and Structures of the University of Coimbra, in Portugal. The parameters considered on the series of tests carried out included the slenderness, cross-sectional diameter, loading level, stiffness of surrounding structure, steel reinforcement ratio and degree of concrete filling inside the steel tube (completely filled or with a ring around the internal surface of the steel tube's wall). The tests conducted and results are presented and discussed in the following sections.

2. Experimental programme

2.1. Test set-up

This section outlines the experimental programme performed in this study. Figs. 1 and 2 show respectively a general view and a scheme of the testing set-up, mounted at the Laboratory of Testing Materials and Structures of the University of Coimbra, in Portugal, for fire resistance tests on building columns with restrained thermal elongation [26,27]. A 3D restraining steel frame (1), consisting of four columns, two upper and two lower beams, arranged orthogonally, simulates the stiffness of the structure surrounding the column subjected to fire. Different positions for the columns of this restraining frame allowed different values for the stiffness of the surrounding structure to the column in test. Values of axial stiffness (K_{as}) between 13 and 128kN/mm and of rotational stiffness (K_{rs}) between 4091 and 5079kN·m/rad in direction X1 and between 1992 and 2536kN·m/rad in direction X2 may be achieved by this restraining frame. M24 bolts, grade 8.8, were used for the connections of the restraining frame, except the ones between its peripheral columns and the upper beams, where M27 threaded rods (2), steel grade 8.8, were used.

During all tests, a constant compressive load was applied to the test column in order to simulate its serviceability load when in a real building structure. This load was applied using a hydraulic jack with a total capacity of 3 MN (3). The applied load was controlled by a load cell (4), placed between the upper beam of the 3D restraining frame and the head of the piston of the hydraulic jack. The hydraulic jack was fixed in a 2D reaction frame (5), in which a safety structure (6) was also mounted to prevent damage to the experimental setup in case of sudden collapse of the column.

The thermal action was applied by a modular electric furnace (7) comprising two modules of 1.5 m x 1.5 m x 1.0 m and one module of 1.5 m x 1.5 m x 0.5 m, placed on top of each other, thus forming a 2.5 m high chamber around the column.