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Fire resistance of restrained composite columns made of concrete filled hollow sections

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ABSTRACT

Most of the previous studies on composite columns made of concrete-filled hollow sections in case of fire have addressed the effect of the depth-to-thickness ratio, column slenderness, initial applied load level, load eccentricity and local buckling in the steel tube on the fire resistance of these columns. However these studies have not analysed the influence of the axial and rotational restraint on the buckling behaviour of these columns in case of fire. So, a series of fire resistance tests on this type of columns are presented and discussed in this paper. The primary test parameters taken into account were the column slenderness, type of cross-section, and axial and rotational restraining of the surrounding structure to the testing columns. The specimens were uniformly exposed to a fire curve and the critical times (fire resistance), failure temperatures and respective failure modes were assessed. The experimental results were still compared with the predictions from available analytical models in order to check if these are safe and consistent for fire design. Finally, results of this research study showed that the fire resistance of the columns may be not significantly affected by the stiffness of the surrounding structure and that the simplified calculation method for fire design of concrete filled hollow sections exposed to fire all around the column presented in Annex H of EN 1994-1-2:2005 is unsafe, except for the elliptical columns.

1. Introduction

Concrete-filled steel tubular (CFST) columns are gaining increasing usage in practice owing to their excellent structural performance and ease of construction. Extensive research has been carried out on the behaviour of composite columns made of concrete-filled circular (CHS), square (SHS), rectangular (RHS) and elliptical (EHS) hollow sections at normal temperature [1–6]. Several and important observations are reported in these studies. For instance, when the concrete strength increases the effects of the bond between the concrete and the steel tube may become more critical. In other words, for normal concrete strength, the reduction on the loadbearing capacity of CFST columns due to reduction of the bonding strength may be negligible, but for high-strength concrete, the variation between CFST columns with the inner surface of the steel tube non-greased and greased may be 17% [7]. Other interesting point to note is that EN 1994-1-1:2004 [8] predictions for circular axially and eccentrically loaded CFST columns with single curvature bending may be on the safe side whereas for columns with double curvature bending may be on the unsafe side [9]. In addition, in columns which fail essentially by local buckling, the confinement effect of the concrete core decreases when the concrete strength increases, as well as when the steel tube diameter to wall thickness ratio increases [1]. Note that, the diameter of the steel tube has the most significant effect on both the ultimate axial load and the corresponding axial shortening of the circular CFST columns [2]. The buckling behaviour of elliptical CFST columns is also sensitive to both the steel tube thickness and the concrete strength, higher steel tube thicknesses resulting in higher loadbearing capacities and enhanced ductility, and higher concrete strengths improving also the loadbearing capacity but reduce the ductility [10]. Lastly, the degree of concrete confinement still depends on the eccentricity of the applied loading. Columns which are predominantly loaded in compression provide a higher amount of confinement than the ones which are mostly in bending. Therefore, distinct loading eccentricity limits have been proposed for major and minor axis bending in order to define and model the concrete constitutive behaviour [6].

Since fire safety is also one of the key aspects of structural design, it is essential to develop a full understanding of the fire performance of CFST columns. Some experimental and numerical research works have been carried out to investigate the fire performance of these columns in the last years. Examples of this are the works of Han et al. (2003) [11], Moliner et al. (2013) [12] and Pagoulatou et al. (2014) [13]. The most important outcome to be stressed from the literature is that the EN 1994-1-2:2005 [14] simple calculation model may lead to unsafe results for pinned-pinned columns under concentric axial loads and to highly conservative results for eccentric loads [12,15,16]. This simple calculation model may produce large errors for columns which do not make use of reinforcing bars, but it may give accurate predictions for steel

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Notation

CC	circular column
CFST	concrete-filled steel tubular
CHS	circular hollow section
EC	elliptical column
EHS	elliptical hollow section
LWT	linear wire transducer
RC	rectangular column
RHS	rectangular hollow section
SC	square column
SHS	square hollow section
A	cross-sectional area of the column
D	external diameter of the CHS
$N_{b,Rd}$	design axial buckling load at normal temperature
N_{cr}	elastic critical load at normal temperature
$N_{fi,cr}$	elastic critical load in the fire situation
$N_{fi,pl,Rd}$	design value of the plastic resistance to axial compression of the total cross-section in the fire situation
$N_{fi,Rd}$	design axial buckling load in the fire situation
$N_{pl,Rd}$	design value of the plastic resistance to axial compression of the total cross-section at normal temperature
P	axial compression force in the column
P_{max}	maximum axial compression force in the column
P_0	initial applied load in the column
T_C	thermocouple in concrete
T_S	thermocouple in the steel tube
k_a	axial stiffness of the surrounding structure
$k_{a,c}$	axial stiffness of the column
K_r	rotational stiffness of the surrounding structure to the rotation of the ends of the column in the fire situation (about both principal axes)
$K_{r,c}$	rotational stiffness of the column about the minor axis
b	smaller dimension of the cross-section
d	bigger dimension of the cross-section
t_{cr}	critical time
t_{P_max}	time at the maximum axial compression force in the column
t_s	wall thickness of the steel tube
$\overline{\lambda}$	relative slenderness
ρ_s	longitudinal steel reinforcement ratio

bar reinforced columns [12]. Note that the concrete filling offers an attractive practical solution for providing fire protection to CFST columns since fire resistance of this type of columns may be between 30 and 60 min when the load level is 20% of the respective design value of the buckling load at normal temperature [17], in contrast to the steel tube columns where their fire resistance is commonly less than 30 min [18]. This increase is due to the composite action between the concrete core and steel tube. At first, the steel tube expands more than the concrete core, due to the higher thermal elongation 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 [15]. Besides, comparing the fire resistance of circular and elliptical columns, it was observed that the former may have higher fire resistance than the latter. This is due to the lower section factor that the circular section presents, which delays the heating of the column, thus providing a longer fire resistance. The difference in performance between elliptical and circular columns is less evident for slender columns, since the cross-section shape has a lower influence [19]. With regard to the concrete strength, it was found that the fire resistance of circular CFST columns was lower in the ones filled with high strength concrete than in the ones with normal strength concrete, this for the higher load levels (40%), while for the smaller load levels (20%) the columns with high strength concrete presented the same or higher fire resistance [12]. Lastly, the addition of steel reinforcing bars still has a favourable effect on the response of the CFST columns, although only small increments in terms of fire resistance are occasionally obtained [16].

On the other hand, most of the studies have not taken into account the interaction between the column and the surrounding building structure. The response of these columns when inserted in a building structure is different than when isolated. Restraints to the thermal elongation of the column, plays an important role on its stability, since it induces different forms of interaction between the heated column and the cold adjacent building structure. Whereas the axial restraint to thermal elongation of the columns may play a detrimental effect the rotational restraint may have a beneficial effect on the fire resistance [20–25].

Therefore, this research work presents and discuss the results of fire resistance tests on axially loaded CFST columns with restrained thermal elongation provided by a three-dimensional (3D) steel frame in order to investigate the effect of the axial and rotational stiffness of the surrounding structure to the column. Different values of restraint to thermal elongation of the columns were provided by positioning the peripheral columns of the 3D restraining frame in different positions. Other important goals of this research work were to evaluate the structural response of columns with different cross-section shapes (circular, square, rectangular and elliptical sections) and the influence of the slenderness of the columns on their fire resistance. In each experimental fire resistance test, temperatures in the furnace and at several points of the specimens, as well as, vertical and horizontal displacements, rotations and forces resulting from the restraining on the thermal elongation of the columns, were measured to achieve those objectives. These results were thereby compared with the predictions from available analytical models, in order to establish their accuracy and applicability for providing economical CFST structures in case of fire. Finally, another purpose of this experimental research was to provide valuable data for the validation of numerical models, which may help to develop a suitable analytical guidance in the design of CFST columns subjected to fire, which is dependent on all studied parameters in this research work.

2. Experimental Tests

2.1. Test plan

The experimental tests on axially loaded CFST columns with restrained thermal elongation were conducted at the Laboratory of Testing Materials and Structures of the University of Coimbra, in Portugal. The experimental programme consisted on fourteen fire resistance tests, seven of which were performed on columns under both a 30 kN/mm axial restraint to their thermal elongation and a 94,615 kN·m/rad rotational restraint (about both principal axes), and seven others under both a 110 kN/mm axial restraint and a 131,340 kN·m/rad rotational restraint. These values were similar to those previously used in this Laboratory for analogous studies [22,23] to facilitate comparisons between their results. The values of the axial and rotational stiffness of the surrounding structure to the columns were determined using numerical simulations and experimental tests, as mentioned in [22,23]. The lower value of stiffness means practically absence of thermal restraint, whereas the higher tried to simulate a common two-storey building of 3 × 4 bays of 6 m span.

This experimental programme is summarised in Table 1. As an example the reference SC150-30 ka indicates a fire resistance test on a square column (SC) with a 150 mm side under a 30 kN/mm axial restraint (k_a).

2.2. Specimens

Four different types of cross-section shapes were selected for the composite columns in this study: circular, square, rectangular and