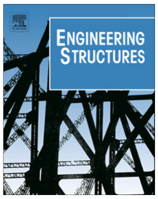
Engineering Structures 141 (2017) 83–96

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct



Fire response of restrained composite columns made with concrete filled hollow sections under different end-support conditions

João Paulo C. Rodrigues [*], Luís Laim

ISISE – Institute Sustainability and Innovation on Structural Engineering, University of Coimbra, Portugal

ARTICLE INFO

Article history:
Received 13 November 2016
Revised 8 February 2017
Accepted 22 February 2017

Keywords:
Fire resistance
Hollow section
Steel
Concrete
Column
Thermal restraining
Boundary conditions

ABSTRACT

The fire behaviour of composite columns made with concrete filled hollow sections under different structural boundary conditions was experimentally investigated and their results are presented and discussed in this paper. The main objectives of this research were therefore to investigate the influence of the section geometry, slenderness, section factor, boundary conditions, and stiffness of the surrounding structure to the thermal elongation of the columns on the structural performance of such columns exposed to fire. The critical time (fire resistance), the failure temperature distribution and the respective failure modes of the columns were then assessed. These experimental results were still compared with predictions from the currently European design rules (EN 1994-1-2:2005) in order to observe how unsafe they might be. Finally, results of this research study showed that circular composite tubular columns presented an enhanced fire performance, comparing to other sections (square and rectangular sections for instance). As the difference between the principal moments of inertia for the cross-section of a column increases, the effect of the boundary conditions in their fire resistance increases.

1. Introduction

The strength and ductility of composite steel and concrete tubular columns are enhanced by the continuous confining stress provided by the steel tube [1–3]. Their excellent structural performance makes them particularly suitable for applications in high-rise buildings. Extensive research has been conducted on the behaviour of concrete-filled steel tubular (CFST) columns at ambient temperature. From some of those studies, it can be observed that rectangular CFST columns with slenderness ratio (given by $2\sqrt{3}L/b$) of 20 and with the long side of the cross-section two times higher than the short side are prone to local buckling either close to the end or near the quarter height of the columns. For columns with slenderness ratio of 50 the failure loads may be reached with local buckling near mid height [4]. Another main feature of this type of columns is the effect of the depth-to-thickness ratio of the steel component on the structural response of the composite column. The effects of local buckling may be ignored in the calculation of the contribution of the steel component in concrete-filled tubes for relative depth-to-thickness ratios less than 50. On the other hand, for ratios greater than 120, there may be significant reserve in capacity in post-local buckling range which evidently increases the load-bearing capacity [5]. In addition, it was also concluded that when the strength of concrete is low (about 30 MPa), steel fibres can replace the reinforcement but not in the case of high or ultra-high performance concrete (about 90 or 130 MPa) [6]. As well as that the reinforcing bars do not improve the load-bearing capacity of the columns when eccentricity is applied about the weak axis. Another important point to note is that the concave corners should be restricted with stiffeners to avoid concrete premature brittle failure [7].

Since fire safety is also one of the key aspects of structural design, it is still essential to develop a full understanding of the fire performance of composite tubular columns. Some experimental and numerical research has been carried out to investigate the fire performance of these columns in the last decades. Examples of this are the research works of Kodur (1999) [8], Romero et al. (2011) [9] and Yao et al. (2016) [10]. Concrete filling offers an attractive practical solution for providing fire protection to steel hollow columns without any external protection. The fire resistance of concrete-filled steel square hollow section (SHS) columns may be between 50 and 100 min, depending on the type of concrete filling (plain concrete, steel bar-reinforced concrete or steel fibre-reinforced concrete) [8], whereas the fire resistance of common steel tube columns is much less than 30 min [11]. This increase is due to the

---

[*] Corresponding author.
E-mail address: jpaulocr@dec.uc.pt (J.P.C. Rodrigues).

http://dx.doi.org/10.1016/j.engstruct.2017.02.073

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
A_m/V	section factor
D	external diameter of the CHS
L	effective buckling length of a column in the plane of bending
$N_{b,Rd}$	design buckling resistance of a compression member
N_{cr}	minimum elastic critical force for flexural buckling of a compression member with semi-rigid end support conditions
$N_{fi,cr}$	elastic critical axial load
$N_{fi,pl,Rd}$	design cross-sectional plastic resistance to axial compression in fire situation
$N_{fi,Rd}$	design axial buckling load in fire situation
$N_{pt,Rd}$	design resistance to axial compression of the composite section
P	axial compression force in the column
P_{max}	maximum axial compression force in the column
P_0	initial applied service load on the column
T_C	thermocouple in concrete
T_S	thermocouple on steel
k_a	axial restraint imposed by a surrounding structure to the thermal elongation of the column
$k_{a,c}$	axial stiffness of the column
K_r	rotational restraint imposed by a surrounding structure to the rotation of the column ends subjected to fire (about both principal axes)
$K_{r,c}$	rotational stiffness of the column about the minor axis
b	short dimension of the cross-section (width of the cross-section)
d	long dimension of the cross-section (depth of the cross-section)
f_c	compressive strength of the concrete at normal temperature
f_y	yield strength of the steel at normal temperature
t_{cr}	critical time
t_{P_max}	time at the maximum axial compression force in the column
t_s	wall thickness of steel tube
$\bar{\lambda}$	non-dimensional slenderness of the column at normal temperature
ρ_s	longitudinal steel reinforcement ratio
κ	axial restraint level

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 [12,13].

From results of other fire resistance tests, it was found that, for the same steel usage, circular columns present a better fire performance than square columns, because of the corner effect in relation to the temperature distribution. Additionally, for the same (circular and elliptical) column dimensions and percentage of steel reinforcement, the fire resistance is significantly reduced when introducing eccentricity [14,15], since it is not taken advantage of the contribution of the concrete core. Furthermore, both the simple calculation model in clause 4.3.5.1 and the method in Annex H of EN 1994-1-2:2005 [16] – which use is not permitted in some European countries – lead to unsafe predictions for both axially and eccentrically loaded columns [17]. The buckling behaviour of elliptical CFST columns (generally used in wide open spaces) is also sensitive to both steel tube thickness and concrete strength, with higher tube thickness resulting in higher load-carrying capacity and enhanced ductility, and higher concrete strengths improving load-carrying capacity but reducing ductility. The degree of concrete confinement still depends on the eccentricity of applied loading. Columns which are predominantly loaded in compression provide a greater amount of confinement than columns 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 [18].

Most of these studies on columns made of concrete-filled steel hollow sections at high temperatures addressed the effect of the depth-to-thickness ratio, the column slenderness, the initial applied load level, the load eccentricity and the local buckling in the concrete-filled steel tube on their fire resistance. This is why the study on the separate and combined effects of the axial and rotational restraint on the buckling behaviour of this type of columns subjected to fire is important and required. Special attention should be drawn to the boundary conditions of the columns. Restraints to the thermal elongation of the column, plays an important role on column's stability, since it induces different forms of interaction between the heated column and the cold adjacent 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 [19–22].

Therefore, the results of a series of fire resistance tests on composite tubular columns inserted in a three-dimensional frame are presented and discussed in this paper, in order to investigate the separate and combined effects of the axial and rotational restraint imposed by the surrounding structure to the thermal elongation of the column when subjected to fire. Different structural boundary conditions were provided both by positioning the peripheral columns of the 3D restraining frame at different positions and by changing the connection configuration between the restraining frame and the column in fire. Other important goals of this research work were also to evaluate the influence of the section geometry, slenderness and section factor on the critical time (fire resistance), failure temperature distribution and failure modes of this kind of columns. These results were still compared with the predictions from available design 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 calibration of numerical models, which may help to develop a suitable analytical guidance in the design of composite tubular columns subjected to fire, which is dependent on all studied parameters in this research work.