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Ambient and fire behavior of eccentrically loaded elliptical slender concrete-filled tubular columns

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ABSTRACT

This paper presents the results of an experimental program carried out on slender elliptical hollow section columns filled with concrete. Given the reduced number of experimental results found in the literature on concrete filled tubular columns with elliptical cross-section, the main objective of this paper is to compare the behavior of such innovative cross-sections under ambient and high temperatures. The test parameters covered in this experimental program were the load eccentricity (0, 20 and 50 mm) and the type of infill (plain concrete or bar-reinforced concrete). Six room temperature tests were performed, while other six tests were carried out at elevated temperatures, under both concentric and eccentric axial loads. Using the results of these tests, the current provisions of Eurocode 4 for room temperature and fire design were assessed, and a specific design proposal developed by the authors was evaluated.

Notation

A_i	Cross-sectional area of the part *i* of the composite section
A_{sn}	Area of the reinforcing bars within the region of depth h_n
A_m/V	Section factor
a	Half larger outer dimension of an elliptical section
b	Half smaller outer dimension of an elliptical section
CFEHS	Concrete filled elliptical hollow section
CFT	Concrete filled tube
e	Load eccentricity
$E_{a,\theta}$	Modulus of elasticity of structural steel at the temperature θ
$E_{c,sec,\theta}$	Secant modulus of concrete at the temperature θ
$E_{s,\theta}$	Modulus of elasticity of reinforcing steel at the temperature θ
$(EI)_{fi,eff}$	Effective flexural stiffness in the fire situation
EC4	Eurocode 4
EHS	Elliptical hollow section
f_c	Compressive cylinder strength of concrete at room temperature (test date)
f_s	Yield strength of reinforcing steel at room temperature
f_y	Yield strength of structural steel at room temperature
h_n	Distance of the neutral axis to the center-line of the cross-section
$I_{i,\theta}$	Second moment of area of the part *i* of the cross-section at the temperature θ
ℓ_θ	Buckling length of the column in the fire situation
N	Test load
$N_{fi,Rd}$	Design axial buckling load in the fire situation
N_u	Ultimate axial load at room temperature
P	Perimeter of the section
R	Fire resistance time
t	Steel tube wall thickness
L	Column length
W_{pa}	Plastic section modulus of steel
W_{pc}	Plastic section modulus of concrete
W_{ps}	Plastic section modulus of the reinforcing bars
W_{pan}	Plastic section modulus of the steel region of depth $2h_n$
W_{pcn}	Plastic section modulus of the concrete region of depth $2h_n$
W_{psn}	Plastic section modulus of the reinforcing bars within the region of depth $2h_n$
$\varphi_{i,\theta}$	Reduction coefficient depending on the effect of thermal stresses
φ_s	Reduction coefficient depending on the percentage of reinforcement
φ_δ	Reduction coefficient depending on the eccentricity
$\mu = N/N_u$	Axial load level
$\bar{\lambda}$	Relative slenderness at room temperature

$$\bar{\lambda} = \sqrt{N_{pl}/N_{cr}} = \sqrt{\left(A_c f_c + A_a f_y + A_s f_s\right)/\left[\left(\pi^2 EI\right)/L^2\right]}$$

$\theta_{i,eq}$	Equivalent temperature of the part *i* of the cross-section

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1. Introduction

The structural behavior of elliptical hollow sections (EHS) has been deeply studied in recent years by Gardner and co-workers, covering cross-section classification [1] and the evaluation of the response in compression [2], shear [3], bending [4] and flexural buckling [5]. Furthermore, the elastic buckling response of elliptical hollow sections in compression was studied by Ruiz-Teran and Gardner [6] and Silvestre [7]. A review article was published by Chan et al. [8] on the structural design of EHS, which brought together the previous developments. In a more recent work, Gardner et al. [9] studied the structural behavior of EHS under combined compression and uniaxial bending. Additionally, Law and Gardner [10] investigated the lateral instability of EHS members in bending.

The effect of filling EHS columns with concrete was examined by Yang et al. [11] and Zhao and Packer [12], through testing stub columns under compressive axial load at room temperature. Also concrete filled stainless steel elliptical stub columns were experimentally investigated by Lam et al. [13].

Dai and Lam [14] developed a numerical model to represent the axial compressive behavior of elliptical concrete filled steel tubular stub columns. These authors studied the differences in the degree of concrete confinement between circular and elliptical hollow sections, observing that the circular sections provided higher confinement than the elliptical shapes, due to the different contact stress distribution around the perimeter of the section. Based on this study, Dai and Lam [14] developed a stress–strain model for concrete confined by elliptical steel hollow sections.

Recently, Sheehan et al. [15] examined the structural response of concrete filled elliptical hollow section (CFEHS) stub columns under eccentric compression through both experimental and numerical studies. Analytical compression–bending moment interaction curves were derived from the results of this investigation.

Jamaluddin et al. [16] presented the results of a series of experiments on elliptical concrete filled tubular (CFT) columns subjected to axial compressive load. In this experimental program, a total of twenty-six specimens were tested, including both stub and slender columns.

Considering the reduced number of experimental results available on CFEHS columns, new experiments are presented in this paper. Differently from previous experimental studies, this paper focuses on slender columns subjected to eccentric loads. The test results are used as a basis to evaluate the current design rules in EN 1994-1-1 [17] for CFT columns.

Regarding the fire response of elliptical columns, the number of investigations is very limited. Some recent work on unfilled EHS columns subjected to fire carried out by Scullion et al. [18–20] can be found in the literature, but no experimental studies have been carried out so far on elliptical concrete filled steel tubular columns exposed to fire. The only work developed in this field can be found in previous numerical investigations from the authors [21] and the studies from Dai and Lam [22], who discussed the effect of the sectional shape on the structural fire behavior of axially loaded CFT stub columns, showing that the best fire performance is obtained with circular sections, followed by columns with elliptical, square and rectangular sections. It is worth noting that no experimental studies on slender CFEHS columns at elevated temperatures have been presented yet, nor any design method for the calculation of the fire resistance of these composite columns has been developed to date.

In previous work from the authors of this paper [21], a non-linear three-dimensional finite element model for CFEHS columns exposed to fire was presented. In the absence of fire tests on elliptical columns to validate the model, the values of the modelling parameters from a previously validated model for circular columns [23] were adopted. Based on the results of parametric studies, it was observed that, as expected, the fire resistance of the columns decreased with an increase in member slenderness and load level, as well as with an increase of the section factor. The existing design guidance in EN 1994-1-2 [24] for the calculation of the buckling resistance of CFT columns in fire was assessed. It was observed that neglecting the effect of thermal stresses (i.e. assuming flexural stiffness reduction coefficients equal to unity) led to unsafe results when applying the simple calculation model to slender CFEHS columns in axial compression. In the absence of specific guidance, it was recommended to use the flexural stiffness reduction coefficients from the French National Annex to EC4 [25] using an equivalent diameter of $D = P/\pi$. In more recent investigations [26, 27], the authors developed a specific method for calculating the design axial buckling load in the fire situation of bar-reinforced circular and elliptical CFT columns subjected to concentric axial load, based on the guidelines of Clause 4.3.5.1 in EN 1994-1-2 for the fire design of composite columns.

One of the aims of this paper is to support with experimental evidence the previous findings from the authors, and to serve as a basis for the development of future design rules for elliptical CFT columns both in fire and at room temperature.

2. Experimental study on concrete filled elliptical steel columns at room temperature

2.1. General

The authors have performed several experimental campaigns, [28–31], to study the buckling resistance at room temperature of slender CFST columns with circular, square and rectangular cross-sections. However, no tests can be found in the literature which study the influence of eccentricity in slender elliptical CFST columns, only Jamaluddin et al. [16] have investigated concentrically loaded columns of such typology.

The tests presented in this paper were designed for investigating the effects of two parameters on the behavior of slender elliptical CFST columns subjected to compressive axial load: type of infill (plain concrete or bar-reinforced concrete) and eccentricity (e). In this experimental program, six CFEHS columns of cross-sectional dimensions 220 × 110 × 12 mm were tested at room temperature, under both concentric and eccentric loads, using eccentricities of 20 and 50 mm. Three of the column specimens were unreinforced, while the other three made use of reinforcing bars. The dimensions of the typical cross-section of an unreinforced and a bar-reinforced column can be seen in Fig. 1.

All the column specimens had a buckling length of 2135 mm and were tested under pinned–pinned (P–P) end conditions on their minor axis. Plain and bar-reinforced C30 grade concrete was used in this experimental program. Table 1 summarizes the experimental data.

It can be observed in Table 1 that two slenderness can be defined, for buckling of the columns about their strong axis ($\overline{\lambda_y}$) and weak axis ($\overline{\lambda_z}$), which have been calculated as defined in Eurocode 4 (see Notation section). All the specimens presented obviously a higher slenderness in their weak axis ($\overline{\lambda_z}>\overline{\lambda_y}$), this slenderness being always higher than 0.5. In order to avoid any interaction between the strong and weak axes, the eccentricities were applied in all cases about the weak axis. This interaction should be studied in a future research, where a larger number of tests must be performed.

2.2. Column specimen and test setup

All the specimens were manufactured at Universitat Politècnica de València (Spain) and tested later at Universitat Jaume I in Castellón (Spain). The buckling length of the columns was 2135 mm in all tests as, despite the steel tubes were cut with a length of 2000 mm, the distance between the hinges of the loading frame required the addition of a special assembly with a length of 135 mm.

A 300 × 300 × 15 mm steel plate was welded to the bottom end of the columns. The columns were then put in an upright position and filled with concrete, and afterwards shaken by means of an external