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Circular and square slender concrete-filled tubular columns under large eccentricities and fire

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ABSTRACT

Previous investigations have revealed the unsafety of the current calculation methods in Eurocode 4 for evaluating the fire resistance of concrete-filled steel tubular (CFST) columns, which has given place to a movement in Europe for correcting the existing methods and developing new design rules. In order to support the development of new guidance, further experimental research is needed, especially concerning slender columns and large eccentricities. In this paper, the results of a series of fire tests on slender CFST columns of different section shape (circular and square) subjected to large eccentricities are presented. The influence of the cross-section shape, load eccentricity and percentage of reinforcement on the response of these columns at elevated temperatures is studied in this paper, focusing on the effect of large eccentricities combined with high slenderness. On the basis of the experimental results, the current design rules in Eurocode 4 are assessed, and a previous calculation method developed by the authors is also evaluated.

Notation

A_i	cross-sectional area of the of the part i of the composite section
A_m/V	section factor
B	width of the square section
CFST	concrete-filled steel tube
D	outer diameter of the circular section
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
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
$I_{i,\theta}$	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
$N_{fi,Rd,\delta}$	design axial buckling load in the fire situation in case of eccentric load
N_{Rd}	design axial buckling load at room temperature
$N_{Rd,\delta}$	design axial buckling load at room temperature in case of eccentric load
t	steel tube wall thickness
L	column length
$\varphi_{i,\theta}$	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
ρ	percentage of reinforcement
$\overline{\lambda}$	relative slenderness at room temperature

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

1. Introduction

Concrete-filled steel tubular (CFST) columns make use of the combined action of steel and concrete, showing an ideal structural performance. While the steel tube confines the concrete core enhancing its compressive strength, the concrete core prevents the steel tube wall from local buckling.

The fire resistance of CFST columns subjected to concentric axial loads has been widely studied through experimental testing in the framework of the research projects from CIDECT [1–3] and National Research Council of Canada [4–6], or those carried out at Fuzhou University (China) by Han and co-workers [7], researchers from the University of Seoul (Korea) [8] and the authors of this paper [9]. Nevertheless, the effect of eccentricity needs further evaluation, being a situation which can be commonly found in practice.

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Some of the main fire testing programs carried out worldwide have taken the load eccentricity into account (Grandjean et al. [2], Kordina and Klingsch [3], Lie and Chabot [4] or Han et al. [7]), but using only a limited number of column specimens. Also in previous tests from the authors of this paper [10], eccentric loads were used, although the load eccentricity ratio applied was reduced ($e/D = 0.13$ and 0.31). Thus, there is a need for investigating the effect of large eccentricities, which can occur in certain type of constructions such as industrial facilities.

Only one fire testing program focusing on slender CFST columns subjected to large eccentricities has been found in the literature, carried out at CTICM [11], where four CFST columns were tested under large eccentricities ($e/D = 0.75$ and 1.5), being two of them of circular section and another two of square shape. However, the results of this fire testing program are limited and need to be extended. Therefore, the reduced number of cases found considering large eccentricities motivates the need for carrying out new experimental programs, in order to increase the existing experimental database.

After a full review of the results of previous tests, an extensive experimental program has been designed in the framework of the European Project FRISCC (Fire resistance of innovative and slender concrete filled tubular composite columns). One of the aims of this project is to provide a full range of experimental evidence on the fire behaviour of CFST columns, a necessary basis for the development of numerical models and simple calculation rules. Four different section shapes are studied in this project: circular, elliptical, square and rectangular hollow section columns filled with concrete, although only the results of the circular and square columns are available at the moment.

The experimental investigation presented in this paper, which is part of the fire testing program being carried out in the mentioned project, focuses on slender CFST columns with circular and square cross-section subjected to large eccentricities. This experimental study will allow understanding the influence of the cross-section shape on the fire performance of CFST columns, as well as the effect of the load eccentricity and percentage of reinforcement.

Another aim of the experimental program presented in this paper is to serve as a basis for the development of safe design rules for the evaluation of the fire resistance of CFST columns. In Europe, different methods are available in Eurocode 4 Part 1.2 [12]. Clause 4.3.5.1 presents a simple calculation model for evaluating the design axial buckling load of composite columns in the fire situation based on the elastic buckling theory. A specific method for columns composed of unprotected concrete filled hollow sections can also be found in Annex H of the same code. Previous investigations have revealed that this method produces unsafe results for slender columns [13–15], which has led to the approval of an addenda to Eurocode 4 by the committee CEN/TC250/SC4 which limits the applicability of Annex H to columns with slenderness lower than 0.5.

Additionally, the evaluation of the effect of eccentricity by means of the current calculation methods in Eurocode 4 is not clearly solved and needs to be extended to large eccentricities, for which further experimental research is needed. Based on the results of the fire tests presented in this paper, the current calculation methods in Eurocode 4 Part 1.2 will be assessed and a new design proposal developed by the authors will be also evaluated for slender columns subjected to large eccentricities.

2. Experimental investigation

2.1. General

Despite a large amount of fire tests can be found in the literature on CFST columns of circular and square section subjected to concentric axial load or moderated eccentricities, it is uncommon to find test results which account for large eccentricities in CFST columns, only Renaud and Kruppa [11] having tested four columns subjected to large eccentricities.

The authors of this paper have performed several experimental campaigns [9,10], to study the fire resistance of slender CFST columns, although further experimental results are needed which include the effect of large eccentricities in slender CFST columns.

The experimental program which is presented in this paper consists of a total of 12 columns, six of them having circular section and the other six with square section. Two different cross-sectional dimensions were used for each shape, and large eccentricities were applied in most of the tests, with load eccentricity ratios (e/D or e/B) of 0.5 and 0.75. Two of the columns on each group were tested under concentric load, so as to have a reference for evaluating the effect of the load eccentricity. All the columns were bar-reinforced, using reinforcement ratios ranging between 2.4% and 5.15%. The columns were hinged at both ends, having a length of 3180 mm. The steel tubes had a nominal strength of 355 MPa, while the concrete used for filling the columns had a compressive strength of 30 MPa. The load level applied to the columns was a 20% of their load bearing capacity at room temperature, which had been calculated by means of a previously validated numerical model.

The square columns were designed to have approximately the same steel area as their circular counterparts, in order to be able to compare their effectiveness in the fire situation for the same steel usage.

The tested specimens, with their particular characteristics and resulting fire resistance measured in minutes, are listed in Table 1 (circular columns) and Table 2 (square columns). The cross-sectional dimensions and reinforcement arrangement of the tested columns can be seen in Fig. 1.

2.2. Test setup

The fire tests were performed in the facilities of AIDICO (Instituto Tecnológico de la Construcción) in Valencia (Spain), using a 5 × 3 m furnace equipped with a hydraulic jack with a maximum capacity of 1000 kN and a total of 16 gas burners, located at mid-height of the furnace chamber. Fig. 2a presents a schematic view of the experimental setup for the concentrically loaded tests, while the preparation of one of the specimens can be seen in Fig. 4a.

The load was applied to the top end of the columns through a knife-edge bearing (Fig. 4c and d), which permitted to introduce the desired eccentricity. The same eccentricity was applied at both column ends. Once the load was applied, it was kept constant while the standard ISO-834 [16] fire curve was prescribed, with unrestrained column elongation.

Table 1
Test properties and results, circular columns.

No.	D (mm)	t (mm)	Reinf.	ρ (%)	e/D	f_c (MPa)	f_y (MPa)	f_s (MPa)	$\overline{\lambda}$	Load (kN)	Time (min)
C1	193.7	8	6ϕ12	2.74	0.5	36.4	359.1	512.4	0.75	186.65	26
C2	273	10	6ϕ16	2.40	0.5	37.6	369.7	553.5	0.54	387.46	30
C3	193.7	8	6ϕ12	2.74	0	43.2	359.1	512.4	0.76	535.57	29
C4	273	10	6ϕ16	2.40	0	37.8	451.1	553.5	0.57	882.90	72
C5	193.7	8	6ϕ16	4.86	0.75	35.8	359.1	553.5	0.77	152.41	29
C6	273	10	8ϕ20	5.00	0.5	36.9	369.7	566.5	0.56	391.53	57