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Experimental investigation on the fire behaviour of rectangular and elliptical slender concrete-filled tubular columns

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ABSTRACT

While the fire behaviour of concrete-filled steel tubular (CFST) columns with circular and square cross-section has been well established based on experimental programs and numerical investigations, the information about the fire behaviour of CFST columns with rectangular or elliptical cross-section is very scarce. Therefore, further research is needed in order to establish the structural behaviour of concrete-filled elliptical and rectangular hollow sections at elevated temperatures as a basis for the future development of new design guidance. In this paper, a series of slender CFST columns of rectangular and elliptical cross-section are tested at elevated temperatures under both concentric and eccentric loads, reaching large eccentricities. The effect of the load eccentricity and percentage of reinforcement is studied, considering both major and minor axis buckling. The influence of the cross-section shape, load eccentricity and percentage of reinforcement on the fire behaviour of these columns is investigated. The experimental results are subsequently used to assess the current design rules in Eurocode 4 Part 1.2 for these new section shapes.

1. Introduction

The use of circular and square hollow sections in composite construction has been widely documented, and the behaviour of such hollow sections filled with concrete has been extensively investigated, both at room temperature and in the fire situation. Many examples of experimental investigations on circular and square CFST columns at elevated temperatures can be cited, as the research projects from CIDECT [1–3] and National Research Council of Canada [4–6], or the investigations carried out by Han et al. [7], Kim et al. [8] and the authors of this paper [9,10]. However, new hollow sections such as rectangular or elliptical shapes have been introduced in the catalogues of the steel producers, which need further investigation in order to be accessible to practitioners.

At the same time, despite a large amount of fire tests can be found in the literature on CFST columns subjected to concentric axial load or moderated eccentricities, test results which account for large eccentricities cannot easily be found [11]. Thus, it is needed to extend the experimental database to include the effect of large eccentricities in slender CFST columns. In this paper, rectangular and elliptical concrete-filled tubular columns subjected to both concentric and eccentric loads will be investigated, in order to fill the current void.

Traditionally, circular and square hollow sections have been used in combination with concrete to form composite structural elements – i.e. concrete-filled tubes – being the major compressive components in buildings or bridges [12]. However, it is less frequent to find in practice elliptical or rectangular hollow sections filled with concrete.

Although the use of elliptical hollow sections (EHS) in construction is growing and these new sections are becoming more popular amongst designers [13–15], very few applications can be found where EHS have been filled with concrete, since the design codes for composite members do not cover this new shape. Only the example of the bracing members used in the NEO Bankside residential development in London (UK) can be cited [16]. Therefore, further research is needed in order to establish the structural behaviour of concrete-filled elliptical and rectangular hollow sections and to subsequently develop new design guidance which can be incorporated to the current building codes.

Regarding the fire behaviour of CFST columns, rectangular sections have seldom been studied, being very limited the number of experimental investigations which can be found in the literature, some of which are summarized next.

Han et al. [17] tested a total of eight concrete-filled rectangular hollow section (RHS) columns, varying the steel tube depth-to-width ratio, column slenderness and load eccentricity. It was proved that the fire resistance of the columns can be enhanced through the use of fire-protection coat. This group also tested the residual strength of six rectangular columns after exposure to ISO-834 standard fire [18]. It

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Notation

A_i	cross-sectional area of the of the part i of the composite section
B	smaller outer dimension of an elliptical or rectangular section
B.C.	boundary conditions
CFST	concrete-filled steel 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	larger outer dimension of an elliptical or rectangular 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
L	column length
N	test load
$N_{fi,cr}$	elastic critical load in the fire situation
$N_{fi,pl,Rd}$	design value of the plastic resistance of the cross-section to axial compression in the fire situation
$N_{fi,Rd}$	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
P–P	pinned–pinned boundary conditions
RHS	rectangular hollow section
t	steel tube wall thickness
$\gamma_{M,fi,i}$	partial factors for the materials in the fire situation
ϕ	diameter of a reinforcing bar
θ	temperature
$\bar{\lambda}_y$	relative slenderness at room temperature, for major axis buckling
$\bar{\lambda}_z$	relative slenderness at room temperature, for minor axis buckling
$\bar{\lambda}_\theta$	relative slenderness in the fire situation
ρ	percentage of reinforcement
$\varphi_{i,\theta}$	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
χ	reduction coefficient for the corresponding buckling curve

was found that the loss of strength of the specimens without protection was significantly greater than that of columns with fire protection. It was also observed that the slenderness ratio, sectional dimensions and fire exposure time have a significant influence on the residual strength of such columns.

Jiang et al. [19] also studied the residual behaviour of rectangular concrete-filled steel tubular columns. Fourteen specimens which had been exposed to constant high temperatures were subsequently subjected to bi-axial force and bending. This investigation showed that rectangular concrete-filled steel tubular columns still have relatively high carrying capacity and ductility after being exposed to high temperature.

More recently, Yang et al. [20] studied the performance of concrete-filled RHS columns exposed to fire on three sides. Three rectangular columns were tested to failure, two of which were exposed on three sides and the other on four sides. It was found that the shift of the centre of stiffness and the thermal bowing, associated to the asymmetric fire conditions, promote the buckling of the columns.

The available investigations on concrete-filled EHS columns at elevated temperatures are even more limited. Some experimental programmes at room temperature have been carried out in recent years, such as those from Yang et al. [21], Zhao and Packer [22], Sheehan et al. [23] and Jamaluddin et al. [24], which have helped to establish the compressive behaviour of such columns at ambient conditions. In turn, the fire behaviour of these columns has been numerically examined by the own authors [25] and by Dai and Lam [26], comparing their fire performance with other section shapes. Some work on unfilled EHS columns subjected to hydrocarbon fire carried out by Scullion et al. [27] can be also cited. However, very limited experimental results are available on concrete-filled EHS columns exposed to fire, from previous tests performed by the authors of this paper [28]. Therefore, the need of carrying out more fire tests is plenty justified.

The experiments presented in this paper form part of the fire testing program carried out in the framework of the European Project FRISCC (fire resistance of innovative and slender concrete filled tubular composite columns), which aims at providing a full range of experimental evidence on the fire behaviour of CFST columns as a basis for the development of numerical models and simple calculation rules. Four different section shapes are studied in the mentioned project: circular, elliptical, square and rectangular hollow section columns filled with concrete. The results of the circular and square columns were presented in a previous paper by the authors [29], while the present paper contains the results of the rectangular and elliptical column tests.

The present paper investigates the fire behaviour of slender CFST columns with rectangular and elliptical cross-section, subjected to both concentric and eccentric load, reaching large eccentricities. The effect of the load eccentricity and percentage of reinforcement is studied, considering both major and minor axis eccentricity.

The results from this experimental investigation are also used for evaluating the current simple calculation method in Eurocode 4 Part 1.2 [30]. Previous investigations for concrete-filled CHS and SHS columns by the authors [31,32] and other groups [33] have revealed that this method produces unsafe results for a certain range of slenderness under concentric loads. In this work, the current method will be applied to rectangular and elliptical columns, in order to investigate if these findings hold true also for these shapes, and to evaluate the influence of the effect of the load eccentricity.

2. Experimental investigation

2.1. General

This paper presents the results of part of the experimental program carried out in the framework of the European project