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Experimental study of slender concrete-filled elliptical hollow section beam-columns

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ABSTRACT

Experiments on concrete-filled elliptical hollow section beam-columns have been conducted to examine their fundamental structural behaviour. A total of 27 specimens were tested — 3 stub columns and 24 longer members of varying slenderness. Seven of the tested specimens also contained steel reinforcement. The specimens were loaded in compression, either concentrically or with different major or minor axis eccentricities. Measurements of the applied load, the strains at mid-height, the axial displacement and the lateral deflection at mid-height were recorded. Plots of load against the lateral deflection at mid-height and load against axial displacement are presented for the specimens, along with values of strength index and ductility index. Comparisons have been made between the test results and the provisions of the European Standard EN 1994-1-1:2004 for determining the ultimate load of concrete-filled circular and rectangular hollow section columns. It was found that the predicted resistances are safe for use in the design of concrete-filled elliptical hollow section columns either with or without reinforcement, and loaded either concentrically or eccentrically.

1. Introduction

In recent years, concrete-filled steel tubular (CFST) columns have gained increasing usage and popularity due to a number of benefits that they offer over plain concrete or hollow steel columns. These benefits include greater cross-sectional resistance for the same outer dimensions, greater stability of slender cross-sections, enhanced fire resistances, no requirement for temporary formwork and greater resistance to seismic loads [1,2]. Having originally found use in bridge piers in the UK in the late 1800s [3], research interest increased from the 1960s onwards [1,3–6], but significant uptake of the technology was hampered by construction difficulties at the time [7]. With the advent of high strength concrete and more effective and reliable pouring and pumping techniques, there has been a significant increase in the application of CFST columns globally in the past two decades, particularly in China [7]. Research topics concerning CFST elements are varied and include the material modelling of confined concrete [8], fire resistance [9,10] and testing of stub columns [11–14], slender columns [15–17] and stainless steel CFST members [18–20]. A comprehensive review of practical applications of CFST elements is provided in [21].

Previous studies [8–20] into the structural behaviour of CFST sections have focussed on circular, square and rectangular hollow sections (CHS, SHS and RHS, respectively). In the past fifteen years, more attention has been paid to steel elliptical hollow section (EHS) members, which have become of more practical interest due to their introduction and availability as hot-finished products [22], their aesthetic properties and their enhanced flexural properties compared to CHS tubes [23]. Research on steel tubes of elliptical cross-section has been extensive in recent years, including the testing and complementary numerical analysis of such members under concentric and eccentric compression [24,25] and in bending [26]. The buckling of steel EHS columns and beams was investigated by [27] and [23,28], respectively, while local buckling and postbuckling behaviour was examined by [29]. These studies provided a basis upon which design rules for steel EHS members have been formulated [30], including for compressive resistance [24], bending [26], shear [31] and flexural buckling [27]. Prominent examples [30] of the use of steel EHS members in practice include the Zeeman Building at the University of Warwick, the Society Bridge in Scotland and the main airport terminal buildings in Madrid, Cork and London Heathrow.

In the context of concrete-filled elliptical hollow section (CFEHS) members, while the literature is currently fairly limited, previous experimental studies include compression testing of stub columns [32,33], testing of concentrically-loaded slender columns [34] and eccentrically-loaded columns [35–37]. The behaviour of CFEHS columns in fire conditions was also examined by [37]. In the present study, a total of 27 specimens were tested — 3 stub columns and 24 longer members of varying slenderness. Seven of the columns also contained steel reinforcement. The specimens were loaded in compression, either concentrically or with different major or minor axis eccentricities.

The steel EHS members were filled with self-compacting concrete (SCC), which reflects onsite practice where access for vibrating and compacting equipment is restricted [38]. Developed originally in Japan in the 1980s [39], the high degrees of workability and segregation

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Symbols

Latin script symbols

a	major axis outer radius
A_a	cross-sectional area of steel tube
A_c	cross-sectional area of concrete
A_s	cross-sectional area of steel reinforcement
b	minor axis outer radius
e_y	load eccentricity to the major axis
e_z	load eccentricity to the minor axis
E_a	modulus of elasticity of steel tube
E_{cm}	secant modulus of elasticity of concrete
E_s	modulus of elasticity of steel reinforcement
$(EI)_{eff}$	effective flexural stiffness
$(EI)_{eff,II}$	effective flexural stiffness taking second-order effects into account
f_c	compressive strength of concrete
f_s	yield strength of steel reinforcement
f_y	yield strength of steel tube
I_a	second moment of area of steel tube cross-section
I_c	second moment of area of concrete cross-section
I_s	second moment of area of steel reinforcement
k	design factor to account for second-order effects
L	length of specimen
M_{Ed}	design moment
$M_{u,exp}$	second-order inelastic ultimate moment
N_{cr}	elastic critical buckling load
$N_{cr,eff}$	elastic critical buckling load for calculating second-order moments
N_{Ed}	design axial load
$N_{u,exp}$	experimental ultimate load
$N_{u,EC4}$	design ultimate capacity of columns according to EN 1994-1-1:2004
$N_{pl,Rd}$	plastic resistance of cross-section in compression according to EN 1994-1-1:2004
t	steel tube wall thickness

Greek script symbols

χ	buckling reduction factor
Δ	axial displacement
$\bar{\lambda}$	nondimensional global slenderness
ρ	reinforcement ratio
ω_g	initial global imperfection amplitude
ω_u	mid-height lateral deflection at ultimate load

resistance possessed by SCC were needed in the present study owing to the confined geometry of the steel tubes. While the fresh properties of an SCC mix are quite different to conventional concrete mixes, the hardened strength is very similar [40,41]. Previous investigations of steel specimens filled with SCC include studies on circular and square stub columns [13], CHS tubes in bending [42], CHS columns under eccentric compression [43] and EHS columns under concentric compression [34]. In the present paper, the experimental setups and procedures are first described after which the key test results, including load–lateral deflection curves, load–axial displacement curves, ultimate capacities and strength and ductility indices are presented. Finally, the results are compared with the provisions of the European Standard EN 1994-1-1 [44] for the prediction of the design resistance of the columns.

2. Experiments

In this section, the CFEHS specimens and the procedures employed for conducting the column and beam-column tests are described. Tests on the constituent materials are also outlined. The results of the experiments on the CFEHS members are presented in Section 3.

2.1. Test specimens

All 27 test specimens were of the same cross-section (150 × 75 × 6.3 EHS) but of different lengths in order to assess the effect of varying the nondimensional slenderness $\bar{\lambda}$ which is defined in Section 4.1. The cross-section was chosen to ensure that local buckling did not occur during testing of the slender columns. While the chosen section size is among the smallest commercially-available cross-sections [45], members of similar cross-sectional dimensions have been tested in previous studies [32,34,36,37] that have also examined larger sections, with similar conclusions having been drawn across the range of tested specimens. The cross-sectional geometry is shown in Fig. 1, along with the positions of the steel reinforcing bars and the points of load application. For the eccentrically-loaded specimens, plates offset from the centreline of the tubes were welded onto the ends of the specimens, as shown in Fig. 2. For the concentrically-loaded specimens, where end-plates were not required due to the absence of end moments, the column ends were held in position by means of wooden blocks. The nominal test parameters and associated ranges of variation are presented in Table 1. The full schedule of test specimens is presented in Table 2.

The stub column length L of 300 mm was chosen to be twice the major axis outer diameter $2a$. This ensured that the stub columns were sufficiently short not to fail by overall buckling, yet still long enough to contain representative distributions of residual stresses and geometric imperfections.

Measurements of major and minor outer diameters ($2a$ and $2b$, respectively), buckling length L including the thicknesses of two 77 mm knife-edges, tube wall thickness t and initial global imperfection in the axis of buckling ω_g were taken for each slender column and are presented in Table 2, along with values of the reinforcement ratio ρ, equal to the ratio of the cross-sectional area of the steel reinforcement to that of the concrete core, load eccentricities e_y and e_z to the major and minor axes, respectively, nondimensional slenderness $\bar{\lambda}$ and the compressive strength of concrete f_c on the day of testing. For the concentrically-loaded specimens, which had measured global imperfections close to zero, a load eccentricity of $L/1000$ was applied in the tests. The slender steel tubes were identified using the format of specimen number: nominal length in m – buckling axis – load eccentricity in mm. For example, specimen E7:L3-MA-150 was 3 m in length and loaded with an

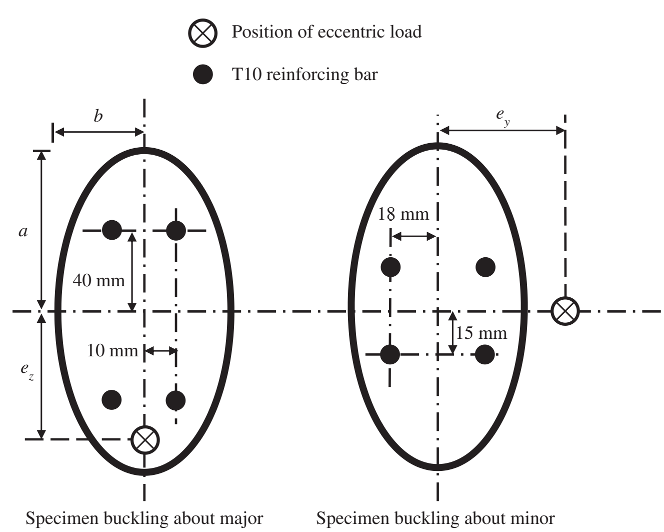

Fig. 1. Cross-sectional geometry of CFEHS specimens with reinforcement and eccentric load positions.