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Numerical analysis and design of slender concrete-filled elliptical hollow section columns and beam-columns

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ABSTRACT

A numerical model simulating the behaviour of elliptical concrete-filled columns under either concentric or eccentric compressive load has been developed in ABAQUS. The numerical results have been compared against a range of experimental results for ultimate load, load–deflection behaviour and failure modes, with good agreement observed. An extensive parametric study has been undertaken whereby the slenderness, load eccentricity, cross-sectional geometry and reinforcement ratio of the concrete-filled columns were varied, creating a data set upon which to formulate design guidance since currently there are no specific provisions in the European Standard EN 1994-1-1 [1] for the design of concrete-filled steel elliptical section columns or beam-columns. It is shown that the current provisions of EN 1994-1-1 [1] for the design of concrete-filled steel columns of circular or rectangular cross-section are also appropriate for the design of members of elliptical cross-section, employing either buckling curve b or c, depending on the level of steel reinforcement. Finally, an assessment is made of the reliability of the design proposals for concrete-filled elliptical hollow section columns and beam-columns.

1. Introduction

In recent years, concrete-filled steel tubular (CFST) columns have gained increasing usage and popularity owing 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 footprint, greater stability of slender cross-sections, enhanced fire resistance, no requirement for temporary formwork and greater resistance to seismic loads [2,3]. 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 members globally in the past two decades, particularly in China [4]. Previous investigations into the structural performance of CFST elements have been varied, and have included studies into the material behaviour of the composite sections [5–7], the testing of stub columns [8–11], concrete-filled stainless steel columns [12–14] and the testing of slender columns [15–17]. A comprehensive review of practical applications of CFST columns is provided in [18].

Existing studies [5–17] into the structural behaviour of CFST sections have generally focussed on circular, square and rectangular hollow sections (CHS, SHS and RHS, respectively). In the past fifteen years, steel elliptical hollow sections (EHS) have gained increased practical interest due to their introduction and availability as hot-finished products [19], their aesthetic properties and their enhanced flexural properties compared to CHS tubes [20]. Studies investigating the behaviour of steel EHS members include testing under concentric and eccentric compression [21,22] and bending [23], the buckling of steel EHS columns [24] and beams [20,25], and the local buckling, postbuckling [26] and ultimate strength [27] of slender elliptical hollow sections. These studies provided a basis upon which design rules for steel EHS members have been formulated [28], including rules for compressive resistance [21], bending [23], flexural buckling [24] and shear [29]. In the context of concrete-filled elliptical hollow section (CFEHS) members, previous experimental studies include compression testing of stub columns [4,30,31], members in bending [32], concentrically-loaded slender columns [33] and eccentrically-loaded columns [34–37]. The behaviour of CFEHS columns in fire conditions was also examined by [35].

Numerical studies of the behaviour of concrete-filled structural members include the modelling of the material behaviour of confined concrete [5–7], simulations of the behaviour of CFST stub columns [10] and complementary analytical modelling of the behaviour of CFST members [38]. Numerical analysis of concrete-

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Nomenclature

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_f	flow potential eccentricity for concrete damage plasticity model
e_y	load eccentricity in the y direction
e_z	load eccentricity in the z direction
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_{b0}	compressive strength of concrete under biaxial loading
f_c	compressive strength of unconfined concrete
f_{cc}	compressive strength of confined 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
K_c	second stress invariants on the tensile and compressive meridians
L	length of specimen
M_{Ed}	design moment
$M_{u,exp}$	second-order inelastic ultimate moment
N_{cr}	elastic critical buckling load
$N_{cr,eff}$	effective elastic critical buckling load for calculating second-order moments
N_{Ed}	design axial load
N_u	ultimate load
$N_{u,exp}$	experimental ultimate load
$N_{u,EC4}$	design ultimate capacity of columns according to EN 1994-1-1 [1]
$N_{u,FEA}$	ultimate load predicted by finite element analysis
$N_{pl,Rd}$	plastic resistance of cross-section in compression according to EN 1994-1-1 [1]
t	steel tube wall thickness

Greek script symbols

ε_c	strain at f_c
χ	buckling reduction factor
Δ	axial displacement
$\bar{\lambda}$	nondimensional global slenderness
μ	viscosity parameter for concrete damage plasticity model
ρ	reinforcement ratio
ψ	dilation angle for concrete damage plasticity material model
ω_g	initial global imperfection amplitude
ω_u	mid-height lateral deflection at ultimate load

filled CHS, SHS and RHS stub columns has been conducted by [39]. Previous numerical studies of CFEHS tubes have included the examination of short columns in axial compression [40], slender columns under axial compression [41] and columns in fire conditions under axial and eccentric compression [42].

In Section 2 of this paper, a summary of previous experiments on CFEHS columns is presented, along with key results from those experiments. The development of a finite element model of CFEHS members under either concentric or eccentric compressive load is then described, followed by a presentation of the validation of the numerical model against the experimental results. The details and results of an extensive parametric study are described, followed by comparisons with existing guidance from the European Standard EN 1994-1-1 [1] for the design of concrete-filled columns of circular or rectangular section. Finally, a reliability assessment, based on the results of the previous experiments, the parametric study and the predictions of the current design method of EN 1994-1-1 [1], is presented.

2. Review of experimental studies on CFEHS members

In this section, a summary of previous experimental studies of CFEHS columns is provided, along with the test results and a brief description of the test methodologies. While testing was conducted by [4,30,31] on CFEHS stub columns, the present study focuses on more slender columns. The three main experimental studies used for validation of the numerical model and the assessment of design proposals in the present study are [34–36]. The geometric and material properties, reinforcement ratios ρ, nondimensional slenderness $\bar{\lambda}$ (defined in Section 4.1) and ultimate loads recorded by [34–36] are summarised in Table 1. The cross-sectional geometry of the tested specimens is shown in Fig. 1. A total of 48 tests from [34–36] were used for validation of the numerical model presented in Section 3.

In the experimental study described in [34], a total of 24 concrete-filled slender columns of $150 \times 75 \times 6.3$ EHS cross-section and various lengths, either with or without steel reinforcement and loaded in compression either concentrically or eccentrically, were tested. The ends of the columns were fitted with knife-edges, resulting in the boundary conditions in the intended axis of bending and buckling being pinned-pinned while in the orthogonal direction, no end rotations were permitted.

An investigation into the fire resistance of CFEHS columns of $220 \times 110 \times 12$ EHS cross-section carried out by [35] also included 6 tests at room temperature, 3 of which also possessed steel reinforcement. The specimens were loaded either concentrically or eccentrically, with knife-edges attached to the ends of the columns, which were orientated such that buckling occurred about the minor axis in all tests. When testing specimen RE-00, a 2 mm load eccentricity was included to encourage buckling to initiate in a single particular direction.

The investigation of [36] into the behaviour of CFEHS beams and columns included 6 tests on concentrically-loaded concrete-filled columns and 8 tests on eccentrically-loaded concrete-filled columns of $192 \times 124 \times 3.82$ EHS cross-section. None of the specimens contained steel reinforcement. The specimens were orientated with respect to knife-edge fittings at the ends of the columns so that buckling about the major axis was enforced in all tests.

3. Numerical analysis

In this section, a numerical model developed to simulate the behaviour of CFEHS columns and beam-columns is described. The model was validated against the experimental results of [34–36] by comparing ultimate loads, load–deflection behaviour and failure modes. Once satisfactory agreement between the experimental and numerical results was achieved, an extensive

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