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Structural response of concrete-filled elliptical steel hollow sections under eccentric compression

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ABSTRACT

The purpose of this research is to examine the behaviour of elliptical concrete-filled steel tubular stub columns under a combination of axial force and bending moment. Most of the research carried out to date involving concrete-filled steel sections has focussed on circular and rectangular tubes, with each shape exhibiting distinct behaviour. The degree of concrete confinement provided by the hollow section wall has been studied under pure compression but remains ambiguous for combined compressive and bending loads, with no current design provision for this loading combination. To explore the structural behaviour, laboratory tests were carried out using eight stub columns of two different tube wall thicknesses and applying axial compression under various eccentricities. Moment-rotation relationships were produced for each specimen to establish the influence of cross-section dimension and axis of bending on overall response. Full 3D finite element models were developed, comparing the effect of different material constitutive models, until good agreement was found. Finally, analytical interaction curves were generated assuming plastic behaviour and compared with the experimental and finite element results. Ground work provided from these tests paves the way for the development of future design guidelines on the member level.

1. Introduction

Concrete-filled tubes are highly suitable for use as column members in structures, owing to their superior strength, constructability and appearance in comparison with numerous other types of cross-section. In this efficient arrangement, the outer steel tube prevents or delays lateral expansion and failure of the concrete core, which in turn mitigates inward buckling of the steel hollow section. This behaviour is influenced by the tube shape, as discussed by Susantha et al. [1], with the optimum strength achieved by circular sections. The non-uniformity of the perimeter in square and rectangular tubes both increases the susceptibility to local buckling and leads to a variation in confining pressure to the concrete core, resulting in inferior resistance to that of a circular section. To date, a considerable degree of research has been executed on square, rectangular and circular sections, leading to design guidelines such as EN1994-1-1 [2].

The use of elliptical tubes is increasingly popular, owing to the presence of both major and minor axes, which potentially improve the efficiency and aesthetics of the member in certain applications. Hollow elliptical sections have been tested under compression by Chan and Gardner [3], bending by Chan and Gardner [4], and combined compression and bending by Gardner et al. [5], leading to a number of design recommendations. The cross-sectional buckling behaviour of hollow elliptical sections has been found to lie between that of a circular tube and a flat plate, as demonstrated by Chan and Gardner [3], Ruiz-Teran and Gardner [6]. Tests have also been conducted applying pure compression to concrete-filled elliptical stub columns, such as Yang et al. [7] and Zhao and Packer [8]. The strength of these sections was found to be inferior to equivalent circular sections, owing to the varying curvature of the steel perimeter and non-uniform confining pressure to the concrete core. Further to these tests, a considerable degree of finite element modelling has been carried out for concrete-filled tubes, owing to the speed and economy offered in comparison with conducting laboratory experiments. Full 3D finite element models were created by Dai and Lam [9,10], for elliptical concrete-filled tubes under pure compression. Here, an existing constitutive model for concrete confined by circular tubes by Hu and Schnobrich [11] and Hu et al. [12] was modified for application to elliptical sections and satisfactory agreement was achieved with experimental results.

Following from the research of [7–10] there is now scope to assess the performance of concrete-filled elliptical stub columns under eccentric compression. Interaction curves have already been developed for circular and rectangular sections under combined bending and compression in EN1994-1-1 [2] and CIDECT [13] but

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Nomenclature

a	major (maximum) radius of ellipse
A_c	area of concrete in cross-section
A_{cc}	area of concrete in compression
a_m	major (maximum) radius (from centre of ellipse to mid-thickness of tube)
A_s	area of steel section
A_{sc}	area of steel in compression
A_{st}	area of steel in tension
b	minor (minimum) radius of ellipse
b_m	minor (minimum) radius (from centre of ellipse to mid-thickness of tube)
D_e	equivalent circular diameter for ellipse
$D_{e,c}$	equivalent diameter for section in compression
$D_{e,b}$	equivalent diameter for section in bending
e	loading eccentricity
e'	loading eccentricity normalised with respect to cross-section depth
E_{cc}	static elastic modulus of confined concrete
f	function for determining D_e (Eq. (4))
f	concrete stress in constitutive relationship (Eq. (11), [17])
f_{cc}	compressive strength of confined concrete
f_{ck}	compressive strength of unconfined concrete
f_e	confined concrete stress at point of transition between softening regions
f_l	concrete strength enhancement value (Eq. (10))
f_u	ultimate stress of confined concrete
f_y	yield stress of steel
k_1	coefficient for determining f_{cc}
k_2	coefficient for determining ε_{cc}
k_3	coefficient for ultimate concrete stress
M	bending moment
M_{FE}	moment corresponding to maximum load (FE)
M_{hollow}	bending moment corresponding to maximum load for hollow specimens [5]
M_{test}	moment corresponding to maximum load (experiment)
N	axial force
N_{hollow}	maximum axial load for hollow specimens [5]
$N_{max,FE}$	maximum axial load from finite element analysis
$N_{max,test}$	maximum axial load from experiments
R_c	distance between centre of ellipse and steel–concrete interface
R_E, R_σ, R_ε	parameters for stress–strain relationship of confined concrete [17]
t	tube wall thickness
W_{pl}	plastic modulus of steel section
$W_{pl,cc}$	plastic modulus of concrete in compression
$W_{pl,sc}$	plastic modulus of steel in compression
$W_{pl,st}$	plastic modulus of steel in tension
x	normalised concrete strain
y	normalised concrete stress
α, β	angles defining position of point on ellipse perimeter
β_0, η	parameter for stress–strain relationship of confined concrete [18]
ε	coefficient depending on f_y [15]
ε	concrete strain in constitutive relationship (Eq. (11), [17])
ε_{cc}	strain corresponding to maximum compressive stress of confined concrete
ε_{ck}	strain corresponding to maximum compressive stress of unconfined concrete
ε_e	confined concrete strain at point of transition between softening regions
ε_u	ultimate strain of confined concrete
ξ	ratio of steel to concrete in cross-section axial resistance
σ_0	compressive strength of concrete
ψ	ratio of cross-sectional stresses at extreme fibres

there is no equivalent guidance for elliptical cross-sections. The difference between the maximum and minimum curvatures provides varying confinement to different regions of the concrete and possibly differing behaviour between each axis of bending. Hence a series of experiments was conducted, applying combined compression and bending to elliptical cross-sections, comparing different tube wall thicknesses for both major and minor axis bending. Following this, finite element models were developed to assess the suitability of previously developed confined concrete models for this loading application, to enable further parametric studies.

2. Experimental program

A series of tensile steel material tests, compressive concrete material tests and stub column tests under eccentric compression were carried out to investigate the structural response of concrete-filled elliptical steel hollow sections under eccentric compression. All tests were performed in the Structures Laboratory of the School of Engineering, University of Warwick.

2.1. Specimen geometry

Eccentric compression was applied to eight concrete-filled elliptical stub columns. All specimens were 300 mm long, with cross-section dimensions of 150 × 75 mm ($2a \times 2b$ as shown in Fig. 1). This gave an aspect ratio of 2 for the cross-section, to facilitate comparisons with results from previous researchers, such as Yang et al. [7].

Prior to conducting the experiments, the actual tube wall thickness was measured at a number of locations around the perimeter of each section and local imperfections were also measured by recording the surface profile at 20 mm intervals along each of the specimen faces. The specimen identifications, average measured wall thickness, applied loading and maximum measured

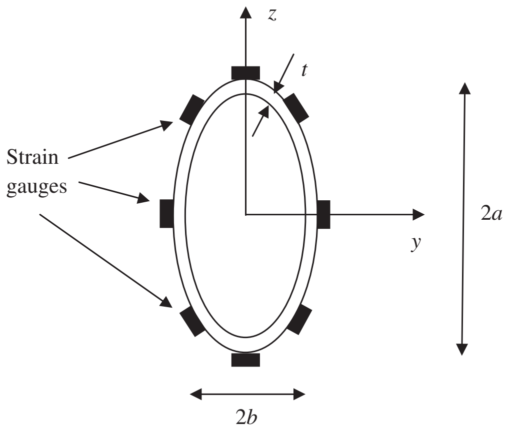

Fig. 1. Specimen dimensions and strain gauge locations.