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Buckling of elliptical hollow section members under combined compression and uniaxial bending

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ABSTRACT

Experimental and numerical investigations into the behaviour of elliptical hollow section beam-columns under axial compression and uniaxial bending have been performed and described in this paper. A large-scale experimental programme, comprising a total of 10 tensile coupon tests and 24 beam-column tests, was carried out. The beam-column tests included 6 pure compression tests, 3 buckling about the major axis and 3 about the minor axis, and 18 eccentric compression tests, 9 inducing compression plus bending about the major axis and 9 inducing compression plus bending about the minor axis. All tested elliptical hollow sections were EHS 150 × 75 × 5, and three member lengths of 1 m, 2 m and 3 m were considered. The test results have been supplemented by numerically generated results based on validated FE models to assess the influence of member slenderness and cross-sectional aspect ratio. On the basis of the experimental and numerical findings, design rules covering instabilities in hot-finished EHS beam-columns have been assessed and verified by statistical analysis. The limiting length concept has also been extended to EHS beam-columns.

1. Introduction

The addition of hot-finished elliptical hollow sections (EHS) to the tubular product standard EN 10210 [1] and to industry design guidance [2] has increased awareness among engineers and architects of their availability and led to more practical applications. Recent research into the cross-sectional response of EHS has included studies under isolated compression and bending [3–6] and combined compression plus uniaxial bending [7]. On the basis of experimental and numerical findings, proposals for the cross-section classification of EHS were made and, under combined loading, it was found that a fully plastic interaction formula [8] for Class 1 and 2 cross-sections and an elastic interaction formula for Class 3 and 4 cross-sections give safe predictions of capacity and are suitable for design purposes. Classification of EHS based on the determination of an equivalent circular section was proposed in [3–5] and adopted in [2], while an alternative approach whereby an equivalent rectangular hollow section is defined was proposed in [6,9].

More recently, research focus has shifted to member instabilities. Column buckling was examined by Chan and Gardner [10], while lateral instability of EHS beams was investigated by Law and Gardner [11], and the applicability of the existing buckling curves adopted in EN 1993-1-1 (2005) [12] was assessed. Member instability of EHS beam-columns remains unexplored; hence, an experimental and numerical study of EHS members under combined compression plus uniaxial bending is the subject of the present paper.

The beam-column problem is complex since it involves the features of column buckling, uniaxial or biaxial beam bending and beam buckling (Fig. 1). Since the late nineteenth century, substantial research on beam-column behaviour has been carried out; the development of the theory of beam-columns has been summarised by Massonnet [13] and Chen and Atsuta [14,15]. Initial analysis of beam-column behaviour was confined to the elastic range, but with the development of powerful computational tools, inelastic behaviour of beam-columns has also been examined. The behaviour of beam-columns can be categorised into three types: in-plane behaviour, lateral torsional buckling and biaxial bending. In-plane behaviour refers to a beam-column which is bent about its major principal axis while restrained from deflecting laterally or is bent about its minor principal axis. When a beam-column which is bent about its stronger axis is not restrained laterally, it may buckle prematurely out of the plane by deflecting laterally and twisting and this action is regarded as lateral torsional buckling. Biaxial bending occurs when a beam-column is bent about both principal axes; this biaxial bending involves interactions of beam bending with beam and column buckling. The present paper focuses on the structural response of EHS beam-columns which are loaded eccentrically about one axis.

2. Experimental studies

A full-scale experimental programme on EHS member instability under combined compression and bending has been carried out in

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Symbols

A	Cross-sectional area
a	Half of the larger outer diameter of an EHS
b	Half of the smaller outer diameter of an EHS; average ratio of experimental to model resistance based on a least squares fit
b_{tc}	Necked width of tensile coupon
e_y	Eccentricity to the major (y–y) axis
e_z	Eccentricity to the minor (z-z) axis
E	Young's modulus
EHS	Elliptical hollow section
f_u	Ultimate tensile stress
f_y	Yield stress
G	Shear modulus
i	Radius of gyration
I	Second moment of area
I_t	Torsion constant
I_w	Warping constant
$k_{d,n}$	Design fractile factor
k_{ij}	Interaction factors
L	Length
$L_{c,N}$	Limiting length in the presence of axial load
M_{1st}	First-order elastic moment
$M_{2nd,el.}$	Second-order elastic moment
$M_{2nd,inel.}$	Second-order inelastic moment
$M_{b,Rd}$	Design lateral torsional buckling resistance
M_{cr}	Elastic buckling moment
$M_{cr,0}$	Elastic critical moment for pure bending
$M_{cr,N}$	Elastic buckling moment for pure bending in presence of axial load
$M_{el,Rd}$	Design elastic moment resistance
$M_{pl,Rd}$	Design plastic moment resistance
$M_{y,Ed}$	Design value of major axis moment
$M_{y,Rk}$	Characteristic value of major axis moment resistance
$M_{y,Rd}$	Design value of major axis moment resistance
$M_{z,Ed}$	Design value of minor axis moment
$M_{z,Rk}$	Characteristic value of minor axis moment resistance
$M_{z,Rd}$	Design value of minor axis moment resistance
n	Number of tests; axial load level $= N_{Ed}/N_y$
$N_{b,Rd}$	Design flexural buckling resistance
N_{cr}	Elastic buckling load
$N_{cr,T}$	Elastic torsional buckling load
N_{Ed}	Design value of compression force
N_{Rd}	Design value of compression resistance
N_{Rk}	Characteristic value of compression resistance
N_u	Ultimate applied load
N_y	Yield load
R_m	Mean value of the utilisation ratio
t	Thickness
U	Utilisation
V_r	Combined coefficient of variation incorporating both model and basic variable uncertainties
V_R	Coefficient of variation of resistance predictions
V_δ	Coefficient of variation of the tests relative to the resistance model
W_y	Major axis section modulus
γ	cross-sectional aspect ratio $= a/b$
γ_{M1}	Partial factor for member instability
ΔM_{Ed}	Moments due to the shift of the centroidal axis for Class 4 sections
ε_{f1}	Plastic strain at fracture based on elongation over the standard gauge length
ε_{f2}	Plastic strain at fracture based on reduction of cross-sectional area
$\bar{\lambda}$	Non-dimensional flexural buckling slenderness
$\bar{\lambda}_{LT}$	Non-dimensional lateral torsional buckling slenderness
$\bar{\lambda}_{LT,0}$	Plateau length for lateral torsional buckling curves
$\bar{\lambda}_y$	Major axis non-dimensional flexural buckling slenderness
$\bar{\lambda}_z$	Minor axis non-dimensional flexural buckling slenderness
$\bar{\lambda}_{z,\,lim}$	Limiting non-dimensional slenderness
ω_g	Maximum global geometric imperfection
ω_u	Mid-span lateral deflection at ultimate load
χ_{LT}	Reduction factor for lateral torsional buckling
χ_y	Reduction factor for major axis flexural buckling
χ_z	Reduction factor for minor axis flexural buckling

the Structures Laboratory at Imperial College London. The tested sections were all hot-finished from grade S355 steel and produced by Tata Steel Tubes. The test programme comprised 10 material tensile coupon tests and 24 beam-column tests — 6 pure compression tests; 3 buckling about the major axis and 3 about the minor axis and 18 eccentric compression tests, 9 inducing bending about the major axis and 9 about the minor axis. The tested EHS had an aspect ratio of two, overall outer cross-section dimensions of 150 × 75 mm and a thickness of 5 mm, which is the thinnest non-slender section of the range (based on a yield strength of 355 N/mm^2). The primary aim of the member tests was to investigate the beam-column behaviour of EHS members with pinned end conditions and under eccentric compression (generating uniform moment along the member length).

2.1. Tensile coupon tests

Material tensile coupon tests were conducted in accordance with EN 10002-1 [16] to determine the basic engineering stress–strain response of the material of the tested sections. The specimens originated from 10 lengths of material, and one coupon was taken from each length for material testing. Full details of the tensile coupon tests have been described in Law and Gardner [11], while mean measured dimensions and the key results from the tensile coupon tests are reported in Table 1.

The reported material parameters are the necked width b_{tc} and thickness t of the coupons, Young's Modulus E, static yield stress f_y, static ultimate tensile stress f_u and the plastic strain at fracture based on elongation over the standard gauge length ε_{f1} and the reduction of cross-sectional area ε_{f2} of the coupons. A typical stress–strain curve is shown in Fig. 2. The obtained material properties were subsequently employed to facilitate the analysis of the beam-column test results and were incorporated into the numerical models to replicate the structural response of the tested specimens.

2.2. Pure compression and uniaxial eccentric compression tests

Six pure compression tests and 18 eccentric compression tests were performed. Three different nominal column lengths of 1 m, 2 m and 3 m (see Fig. 3), to which the dimensions of the end conditions were added, were tested to provide a range of member slendernesses $\bar{\lambda}$ ranging from 0.36 to 0.85 for the pin-ended beam-columns eccentrically loaded about the major axis and 0.63 to 1.51 about the minor axis. For the pure compression test specimens (BC-1-$e_y = 0$ and BC-1-$e_z = 0$), where the measured global imperfection was less than L/1000, an eccentricity of loading was applied such that the combined imperfection plus eccentricity was equal to L/1000. For other columns, the load was applied concentrically since the measured imperfections were greater than L/1000. For the eccentric compression tests, the load eccentricity was varied so that a range of proportions of axial load to bending could be achieved.