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Compressive resistance of hot-rolled elliptical hollow sections

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Abstract

In recent years, hot-rolled elliptical hollow sections have attracted significant attention from engineers and architects owing to their complementary qualities of aesthetic appearance and structural efficiency. However, there is currently a lack of design guidance for elliptical hollow sections inhibiting more widespread use in construction. The present paper addresses this shortcoming for the fundamental loading condition of axial compression. Laboratory testing, numerical modelling and the development of design rules are described herein. The experimental programme comprised 25 tensile coupon tests and 25 stub column tests. All tested elliptical hollow sections had an aspect ratio of 2 and section sizes ranged from 150 × 75 up to 500 × 250 mm. Results, including geometric imperfection measurements and full load–end shortening curves have been presented. Non-linear finite element models were developed and validated against the generated test data. The validated numerical models were employed to perform parametric studies in order to investigate elliptical hollow sections of varying slenderness and varying aspect ratios. The resulting structural performance data have been used to establish a relationship between cross-section slenderness and cross-section compressive resistance, which demonstrates that the Class 3 slenderness limit of 90 from Eurocode 3 for circular hollow sections can be safely adopted for elliptical hollow sections based upon the proposed cross-section slenderness parameter. The equivalent semi-compact slenderness limit given in BS 5950-1, non-compact limiting slenderness in AISC 360-05 and yield slenderness limit given in AS 4100 are also valid. A modified effective area formula from BS 5950-1 can also be safely adopted. Further investigation into effective area formulations for slender (Class 4) elliptical hollow sections is currently under way.
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Keywords: Compression; Cross-section classification; Elliptical hollow sections; Laboratory testing; Numerical modelling; Oval hollow sections; Slenderness limits; Steel structures

1. Introduction

The introduction of hot-rolled structural steel elliptical hollow sections has drawn considerable attention from engineers and architects in the construction industry. Their aesthetic appearance and structural efficiency have already resulted in a number of applications ranging from sculpture (Honda Central Sculpture) to main structural components (Jarrold Department Store in Norwich) [1]. However, to facilitate their wider application, comprehensive and validated structural design guidance is required. This paper focuses on the compressive resistance of elliptical hollow sections, and provides the results of 25 stub column tests and extensive numerical results, complementing the previous findings of the authors [2–4]. The experimental study included material tensile coupon tests for each of the tested cross-sections together with geometric imperfection measurements. All tested elliptical hollow sections had an aspect ratio of two and section sizes ranged from 150 × 75 up to 500 × 250 mm. The generated structural performance data have been used to establish a relationship between cross-section slenderness and cross-section compressive resistance and to develop cross-section classification limits.

The distinct feature of an elliptical hollow section (EHS) from other tubular sections is its varying radius of curvature around the circumference. This varies from a minimum $r_{\min} = b^2/a$ at the end of the cross-section minor (z–z) axis to a maximum $r_{\max} = a^2/b$ at the end of cross-section major (y–y) axis as shown in Fig. 1. The associated stiffness of each constituent segment depends upon its corresponding radius of curvature. The sum of these segments characterises the overall

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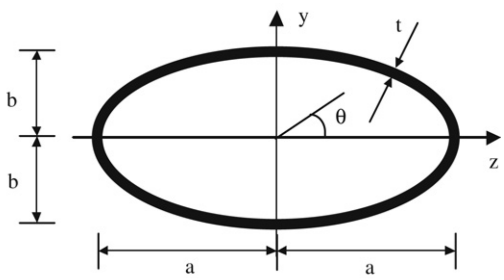

Fig. 1. Geometry of an elliptical hollow section.

compressive response of the cross-section, as given by Eq. (1).

$$N = \int_0^P \sigma_c t \,\mathrm{d}P \tag{1}$$

where N is the axial load, σ_c is the axial compressive stress, and t and P are the thickness and mean perimeter of the cross-section, respectively. Eq. (1) allows for variation of axial compressive stress around the cross-section with the stiffer parts attracting more load. As described in Section 4, the test and numerical results indicate that stocky elliptical hollow sections offer greater load-carrying capacity in comparison to their circular counterparts, due to the achievement of strain hardening in the stiffer regions of the section of low radii of curvature.

2. Experimental study

A series of precise full-scale laboratory tests on EHS (grade S355), manufactured by Corus Tubes [5], was performed at Imperial College London. The test programme comprised a total of 25 material tensile coupon tests and 25 cross-section capacity stub column tests.

2.1. Tensile coupon tests

The primary objective of the tensile coupon tests was to determine the basic engineering stress–strain behaviour of the material for each of the tested section sizes. Results were used to facilitate the numerical study described in Section 3 and the development of cross-section classification limits in Section 4. Tests were carried out in accordance with EN 10002-1 [6].

Parallel coupons, each with the nominal dimensions of 360 × 30 mm or 320 × 20 mm, depending on section size, were machined longitudinally along the centreline of the flattest portions of each of the tested elliptical hollow sections. All tensile tests were performed using an Amsler 350 kN hydraulic testing machine. To ensure no slippage of the coupons in the jaws of the testing machine, pins were inserted into reamed holes located 20 mm from each end of the coupons.

Linear electrical strain gauges were affixed at the mid-point of each side of the tensile coupons and a series of overlapping proportional gauge lengths was marked onto the surface of the coupons to determine the elongation parameters. Load, strain, displacement and input voltage were all recorded using the data acquisition equipment DATASCAN and logged using the DALITE and DSLOG computer packages. Mean measured dimensions and the key results from the 25 tensile coupon tests are reported in Table 1.

2.2. Stub column tests

Stub column tests were conducted to develop a relationship between cross-section slenderness, deformation capacity and load-carrying capacity for elliptical hollow sections under uniform axial compression. A total of 25 stub column tests were performed. Full load–end shortening histories were recorded, including into the post-ultimate range. The nominal length of the stub columns was two times the larger outer diameter ($2 \times 2a = 4a$) of the cross-section. This was deemed sufficiently long to ensure that the stub columns contained a representative distribution of geometric imperfections and residual stresses and to minimise the influence of the end conditions, but suitably short to avoid overall column buckling. The ends of the tubes were milled flat and square. Four LVDTs were located between the parallel end-platens of the testing machine to determine the average end shortening of the stub columns. Four linear electrical resistance strain gauges were affixed to each specimen at mid-height, and at a distance of five times the material thickness from the ends of cross-section minor axis. The strain gauges were initially used for alignment purposes. The testing arrangement is shown in Fig. 2. Load, strain, displacement, and input voltage were all recorded using the data acquisition equipment DATASCAN and logged using the DALITE and DSLOG computer packages. The mean measured dimensions of the stub columns are summarised in Table 2. The cross-sectional area A was calculated from Eq. (2),

$$A = P_m \times t \tag{2}$$

where P_m is the mean perimeter and t is the thickness of the elliptical hollow section. The exact mean perimeter P_m can be obtained by integrating around the circumference of the ellipse to give Eq. (3).

$$P_m = 4a_m \int_0^{\frac{\pi}{2}} \sqrt{\sin^2\theta + \frac{b_m^2}{a_m^2}\cos^2\theta}\,\mathrm{d}\theta \tag{3}$$

in which $a_m = (2a - t)/2$, $b_m = (2b - t)/2$ and θ is the angle for each element measured from the z-axis, as shown in Fig. 1.

Ramanujan [7] proposed the approximate formula of Eq. (4),

$$P_m = \pi(a_m + b_m)\left(1 + \frac{3h_m}{10 + \sqrt{4 - 3h_m}}\right) \tag{4}$$

where a_m and b_m are defined as above and $h_m = (a_m - b_m)^2/(a_m + b_m)^2$. The maximum deviation of the approximate formula of Eq. (4) for determining the perimeter of an ellipse compared to the exact solution of Eq. (3) is only −0.04%. A simpler approximate formula (Eq. (5)) is also provided in EN 10210-2 [8] for the determining the mean perimeter of an ellipse.

$$P_m = \pi(a_m + b_m)(1 + 0.25h_m). \tag{5}$$

For an aspect ratio a/b of 2, the deviation of Eq. (5) from the exact solution of Eq. (3) is −0.02%. However, as the aspect ratio increases, the maximum deviation increases up to −1.8%.

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