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Local buckling and ultimate strength of slender elliptical hollow sections in compression

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ABSTRACT

The local buckling behaviour and ultimate cross-sectional strength of tubular elliptical profiles in compression is examined in this study through numerical modelling. The numerical models were first validated against previous experimental data with good agreement observed, enabling an extensive parametric study to be performed. A total of 270 elliptical sections were simulated in order to examine the influence of cross-section aspect ratio, geometric imperfections and local slendernesses. The obtained ultimate capacities, load–deformation responses and failure modes are discussed. It was found that for lower cross-section aspect ratios the behaviour of the elliptical hollow sections (EHS) was similar to that of cylindrical shells across a number of metrics; however, as the aspect ratio increased, more plate-like stable postbuckling behaviour was observed. Imperfection sensitivity was found to decrease with increasing slenderness and aspect ratio. The influence of the shape of the initial imperfection on the strengths of the EHS columns was also assessed and was found to be generally limited. Finally, a design method has been proposed for Class 4 EHS members that reflects the reduction in capacity due to local buckling with increasing slenderness, but also recognises the improved postbuckling stability with increasing aspect ratio; the proposals were shown to provide safe and accurate predictions for the strengths of the EHS columns with nondimensional local slendernesses up to 2.5 and aspect ratios from 1.1 to 5.0.

1. Introduction

In recent years, structural steel elliptical hollow section (EHS) members have attracted increased research focus. This can be attributed to their introduction and availability as hot-finished products [1], their aesthetic properties, which have led to their use in high-profile projects such as Heathrow Terminal 5, and their enhanced flexural properties about the major principal axis compared to CHS tubes [2]. Research into the structural response of EHS tubes has included testing, numerical modelling and the development of design rules for cross-sections in compression and bending [3–5], analysis of the buckling response of EHS columns [6], stainless steel EHS columns [7], EHS columns in fire [8], concrete-filled columns [9–12], beams [13] and beam-columns [14], and the behaviour of members in shear [15].

The focus of the present investigation is on the behaviour and strength of slender EHS tubes under compression. Potential applications of such members include aesthetic lightweight cladding rails, mullion posts and concrete-filled steel tubes in composite construction. A number of the current range of hot-finished elliptical hollow sections [16], which have been used in a range of structural applications, as outlined in [17], are Class 4 in compression. Cold-formed elliptical sections are also produced from both structural carbon steel [18] and stainless steel [7,19], and are often of slender proportions. Although cold-formed profiles are not specifically addressed in the present study, it is envisaged that the findings and proposed design approach also apply to these sections since the level of local geometric imperfections in cold-formed and hot-finished tubular sections are generally similar [20] and the dominant through-thickness residual stresses in cold-formed tubular sections have been shown to not have a strong influence on their local stability [21]. The above assertions should however be verified in future research, and if necessary, lower strength curves can be assigned to cold-formed sections through the use of a higher imperfection factor (see Section 4).

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Early studies of elastic local buckling and postbuckling of elliptical hollow sections were reported by [22–24], while more recent work has been reported by [2,25,26]. A key finding of these investigations is that, in contrast to CHS tubes, EHS tubes in compression can have stable postbuckling responses and may therefore be able to resist further load beyond the elastic buckling load. Previous numerical studies [25] into the elastic local postbuckling behaviour of EHS columns led to the following conclusions: (i) the maximum stress that a fully-elastic EHS tube with a moderate to high aspect ratio ($a/b \geqslant 2.0$) could carry is higher than its critical buckling stress f_{cr} due to the stable postbuckling response, where $2a$ and $2b$ are the larger and smaller outer diameters of the EHS, respectively, as shown in Fig. 1. The slope of the ascending post-peak equilibrium path increased with increasing aspect ratio a/b and could reach up to 40% of the initial slope of the linear primary path; (ii) concentrated zones of compressive stress in an EHS column were located near the point of minimum radius of curvature (akin to the edges of simply-supported plates), while the zones of maximum radius of curvature experienced an approximately uniform and relatively low compressive stress level; (iii) the imperfection sensitivity significantly decreased with increasing aspect ratio a/b, representing a transition from shell-type behaviour (imperfection sensitive) for EHS columns with low a/b ratios to plate-type behaviour (imperfection insensitive) with increasing a/b ratios. These observations suggest that strength curves for elliptical sections may need to be both a function of local slenderness to allow for the increased susceptibility to local buckling and cross-sectional aspect ratio a/b to reflect the differing postbuckling stability. The present study explores the buckling, postbuckling and collapse responses of slender elliptical cross-sections in compression with elastic–plastic material behaviour.

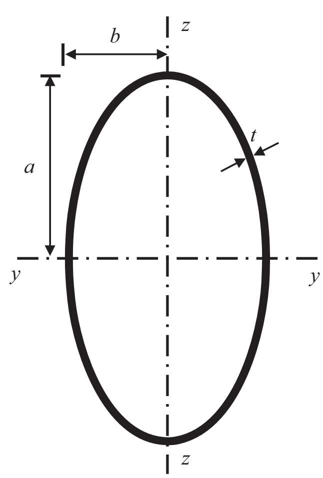

Fig. 1. Cross-sectional geometry of an EHS.

Firstly, the development and validation of a numerical model to simulate the response of EHS in compression is described. After achieving satisfactory agreement between the numerical results generated herein and previous experimental results, the axial compressive response of EHS stub columns with aspect ratios ranging from 1.1 to 5.0 is examined. Other parameters varied in the study include local buckling slenderness, imperfection amplitude and imperfection shape. The results of the parametric study are used as a basis for the formulation of new strength and effective area reduction curves for the design of Class 4 EHS compression members. Comparisons are made with existing provisions from Eurocode 3 for the design of CHS tubes. Thus, the objectives of the present study can be summarised: (i) to establish a database of resistances of slender elliptical cross-sections in compression; (ii) to assess the influences of various design parameters on these resistances; (iii) to assess the suitability of current design provisions for Class 4 CHS for the design of EHS; (iv) propose new design rules for the design of Class 4 EHS in compression.

2. Development and validation of numerical model

In this section, the modelling strategy used to simulate the EHS stub columns in compression is described, followed by the validation of the model against previous experiments.

2.1. Description of finite element model

2.1.1. Geometry

A numerical model was developed using the finite element analysis software ABAQUS [27]. Five different aspect ratios were considered, namely, $a/b = 1.1$, 1.5, 2.0, 3.0 and 5.0. The reference geometry is based on the commercially-available 300 × 150 series of elliptical sections with $a/b = 2.0$. The cross-sectional geometry for the other four aspect ratios was based on maintaining a constant perimeter P of 726.3 mm. It was found previously that length effects are reduced in EHS with higher aspect ratios [2]; a length effect coefficient proposed by [2] was used in the present study to define suitable lengths for the EHS models so that length effects were minimised, while also ensuring that global buckling was precluded.

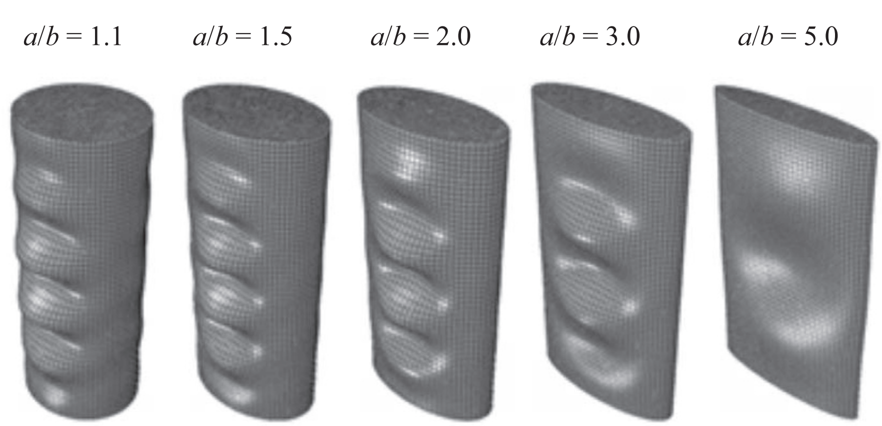

Fig. 2. Examples of elastic buckling mode shapes for EHS tubes with different aspect ratios.