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Structural performance of stainless steel circular hollow sections under combined axial load and bending – Part 1: Experiments and numerical modelling

Ou Zhao [a,*], Leroy Gardner [a], Ben Young [b]

[a] Department. of Civil and Environmental Engineering, Imperial College London, London, UK
[b] Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China

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A B S T R A C T

A comprehensive experimental and numerical investigation into the structural performance of stainless steel circular hollow sections (CHS) under combined compression and bending moment has been performed and is fully reported in the present paper and its companion paper. The experimental programme employed four CHS sizes made of austenitic stainless steel, and included material tensile coupon tests, four stub column tests and twenty combined loading tests. The initial loading eccentricities for the combined loading tests were varied to provide a wide range of bending moment-to-axial load ratios. In conjunction with the testing programme, a numerical modelling programme was performed to simulate the experiments. The developed FE models were shown to be capable of replicating the key test results, full experimental curves including the post-ultimate range and deformed failure modes. Upon validation of the FE models, a series of parametric studies were conducted in the companion paper, aiming at extending the current test data pool over a range of cross-section sizes and combinations of loading. The experimental data, together with the generated parametric study results, were analysed and employed to evaluate the applicability of the codified provisions given in the European code, American specification and Australia/New Zealand standard for design of CHS under combined loading. Improved design rules were also sought through extension of the deformation-based continuous strength method (CSM) to the case of stainless steel CHS under combined loading.

1. Introduction

In recent years, increasing emphasis is being placed on the whole-life performance of structures, rather than simply the initial material cost. Stainless steel, although being initially more expensive than structural carbon steel, has excellent corrosion resistance, and reduced inspection and maintenance requirements, and thus can become more competitive in terms of material selection when considered on a life-cycle basis [1]. In addition to the excellent durability, the attractive aesthetic appearance, favourable mechanical properties and good ductility have also led to the increased use of stainless steels in structural applications. The behaviour and design of stainless steel circular hollow sections (CHS) under combined loading, which has been largely unexplored to date, is the focus of the present study. A brief review of the previous relevant studies is described below. Stub column [2–12] and four-point bending [4,13,14] tests have been conducted on stainless steel CHS of varying cross-section classes to investigate their cross-sectional load-carrying and deformation capacities under pure compression and bending. New slenderness limits for the classification of CHS were proposed by Gardner et al. [15], which lead to more accurate section capacity predictions than with current codified limits. Considering that the general approach in structural stainless steel codes is to limit the design stress to the 0.2% proof stress and ignore the pronounced strain hardening in the determination of cross-section resistances, a deformation-based design approach called the continuous strength method (CSM) [16–21] was developed to allow a rational exploitation of strain hardening; the CSM has been shown to offer substantially improved predictions of cross-section compression and bending resistances for CHS over current codified design methods. Rasmussen and Hancock [2], Talja [3] and Burgan et al. [4] carried out a series of tests on stainless steel CHS columns and beam-columns to study their global buckling behaviour, while the structural performance of concrete-filled stainless steel CHS stub columns and long columns was studied by Lam and Gardner [11] and Uy et al. [12]. However, to date, there have been no investigations into the cross-sectional behaviour of stainless steel circular hollow

* Corresponding author.
E-mail address: ou.zhao11@imperial.ac.uk (O. Zhao).

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sections subjected to combined axial load and bending moment, and this is therefore the topic of the present study.

This paper and its companion paper [22] describe a comprehensive experimental and numerical study of stainless steel circular hollow sections under combined loading. The present paper includes a testing programme on material tensile coupons, and concentrically and eccentrically loaded stub columns, followed by a numerical study, where the models are firstly validated against the performed experiments. Upon validation of the finite element models, a series of parametric studies is carried out and reported in the companion paper [22]. The experimentally and numerically derived data are initially utilised to evaluate the accuracy of the current codified design provisions in the European code EN 1993-1-4 [23], American specification SEI/ASCE-8 [24] and Australia/New Zealand standard AS/NZS 4673 [25], and then used to develop improved design rules through extension of the deformation-based continuous strength method (CSM) to the case of CHS under combined loading.

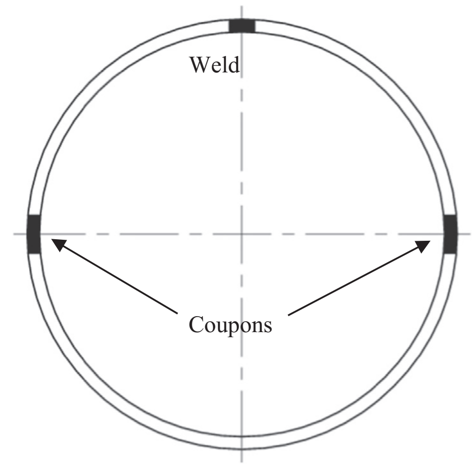

Fig. 1. Locations of tensile coupons in the cross-section.

2. Experimental investigation

2.1. General

An experimental programme was conducted to study the cross-sectional response of cold-formed stainless steel circular hollow sections under combined axial load and bending moment. Four cross-section sizes were employed in the testing: CHS 60.5 × 2.8, CHS 76.3 × 3, CHS 114.3 × 3 and CHS 139.4 × 3, all of grade EN 1.4301 (AISI 304) austenitic stainless steel. The first two cross-sections are defined as Class 1 under pure compression, while the latter two are Class 2 and Class 3, respectively, according to the slenderness limits of EN 1993-1-4 [23]. Overall, the experimental programme comprised material tensile coupon tests, four concentrically loaded stub column tests, and twenty eccentrically loaded stub column tests (combined loading tests). For each type of test, the employed test setup, experimental procedures and the obtained test results are fully described and reported in the following sections.

2.2. Material testing

Prior to structural testing, tensile coupon tests were carried out to determine the material stress–strain response of the tested cross-sections. For each cross-section, two longitudinal coupons, extracted at 90° from the weld (see Fig. 1), were tested. The coupons were dimensioned and machined in accordance with the requirements of the Australian standard AS 1391 [26] and the American standard ASTM E8M [27]. The tensile coupons were 4 mm in width with a 25 mm gauge length. Two holes with a diameter of 8.5 mm were drilled at a distance of 15 mm from both ends of the coupons, and a pair of steel rods was inserted into the holes to apply force to the coupons in the material tensile coupon tests, as shown in Fig. 2. Displacement control was used to drive an MTS testing machine at the loading rates of 0.05 mm/min and 0.2 mm/min up to and beyond the 0.2% proof stress, respectively. The resulting strain rate of the necked part of the coupon conformed to the requirements of AS 1391 [26] and ASTM E8M [27]. The instrumentation consisted of an extensometer mounted onto the specimens by three-point contact knife edges to determine the elongation of the coupon over the 25 mm gauge length, and two strain gauges affixed to the mid-height of the coupons to measure the longitudinal strains. The strain gauge readings were initially employed to determine the Young's modulus and then used to calibrate the strain measurements from the extensometer. Table 1 summarises the average measured material properties, including the Young's modulus E, the 0.2% proof stress $\sigma_{0.2}$, the 1.0% proof stress $\sigma_{1.0}$, the ultimate tensile strength σ_u, the strain at the ultimate tensile stress ε_u, the plastic strain at fracture measured over the standard gauge length (25 mm) ε_f, and the strain hardening exponents n, $n'_{0.2,1.0}$ and $n'_{0.2,u}$, as used in the compound Ramberg–Osgood (R–O) material model [28–32].

2.3. Stub column tests

For each circular hollow cross-section, a concentric stub column test was carried out to determine the cross-section load-carrying and deformation capacities under pure compression. The axial cross-sectional compressive capacity of each concentrically loaded stub column specimen represents the upper limit capacity of the corresponding eccentrically loaded stub column specimens. The nominal length for each specimen complied with the guidelines of Ziemian [33], and is deemed short enough to prevent global buckling, but still long enough to contain a representative pattern of local geometric imperfections and residual stresses. For each stub column specimen, the measured geometric properties, including the member length L, the outer diameter D, the material thickness t and the cross-section area A, are reported in Table 2.

The ends of each stub column were firstly milled flat and square and then clamped by steel loops, as shown in Fig. 3, in order to eliminate any possibility of local failure at the ends due to any out-of-flatness of the end surfaces. An INSTRON 5000 kN hydraulic testing machine with fixed end platens was employed for the stub column testing, which was performed at a constant speed of 0.2 mm/min. Fig. 3 shows the test setup, consisting of three Linear Variable Displacement Transducers (LVDT) to determine the end shortening and three strain gauges, attached to the specimen at mid-height, to measure the axial strains. The strain gauge readings were used to eliminate the elastic deformation of the end platens of the test machine from the end shortening measurements of the LVDTs and determine the true end shortening values, following the procedures recommended in [34]. The modified true load–end shortening curves are shown in Fig. 4, while a summary of the key experimental results, including the ultimate load N_u and the corresponding end shortening δ_u at the ultimate load is reported in Table 3. All the stub columns failed by inelastic local buckling with an elephant foot pattern, a typical example of which is shown in Fig. 5 for specimen CHS 60.5 × 2.8.

2.4. Combined loading tests

For each of the four studied cross-sections, five combined

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