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Testing, simulation and design of cold-formed stainless steel CHS columns

Craig Buchanan[a,*], Esther Real[b], Leroy Gardner[a]

[a] Department of Civil and Environmental Engineering, Imperial College London, London, UK
[b] Department of Construction Engineering, Universitat Politècnica de Catalunya, Barcelona, Spain

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ABSTRACT

Stainless steel tubular members are employed in a range of load-bearing applications due to their strength, durability and aesthetic appeal. From the limited existing test data on stainless steel circular hollow sections (CHS) columns it has been observed that the current Eurocode 3 provisions can be unconservative in their capacity predictions. A comprehensive experimental programme has therefore been undertaken to provide benchmark data to validate numerical models and underpin the development of revised buckling curves; in total 17 austenitic, 9 duplex and 11 ferritic stainless steel CHS column buckling tests and 10 stub column tests have been carried out. Five different cross-section sizes (covering class 1 to class 4 sections) and a wide range of member slendernesses have been examined. The experiments were initially replicated using finite element (FE) simulations; the validated FE models were then used to generate 450 additional column buckling data points. On the basis of the experimental and numerical results, new design recommendations have been made for cold-formed stainless steel CHS columns and statistically validated according to EN 1990 [1].

1. Introduction

Circular hollow sections (CHS) are a common form of structural element that have been used for almost 200 years [2]. They are popular with architects and structural engineers due to their aesthetics and numerous benefits over other open and closed cross-sections, such as a high torsional resistance, the ability to be filled with concrete to act as a composite member, reduced drag loading in a fluid, good bi-axial bending resistance and reduced maintenance requirements with a smaller exposed external area. CHS are commonly used as compression members, with iconic examples including the main cantilever compression members of the Forth Bridge in Scotland, constructed in 1890, and many of the components of the London Eye, opened in 2000. Stainless steel has been available as a material since 1912–13, having been developed separately in the UK and Germany, with the name applied to iron alloys with corrosion resisting properties and containing a minimum of 10.5% chromium [3]. A thin chromium-rich oxide film forms on the surface in the presence of oxygen which provides the corrosion resistance [3]. Austenitic, duplex and ferritic are the most frequently used grades of stainless steel in construction, and their design is included in EN 1993-1-4 [4]. Austenitic grades are the most prevalent and have a typical chromium content of 17–18% and a nickel content of 8–11%. Duplex grades offer generally higher corrosion resistance, good wear resistance and higher strength, but also have a greater initial cost with a typical chromium content of 22–23% and a nickel content of 4–5%. Ferritic grades have a lower initial cost due to their reduced chromium and nickel content, typically 11–17% and 0–2.5% respectively, albeit at the expense of corrosion resistance [5].

EN 1993-1-4 [4] provides design guidance for the flexural buckling capacity of stainless steel CHS members through a harmonised approach that is consistent with the design of carbon steel elements in EN 1993-1-1 [6]. Prior to the experiments reported in this paper, existing test results on stainless steel CHS elements in compression have been rather limited. Previous test data have comprised predominantly austenitic stainless steel stub column results from Rasmussen and Hancock [7], Talja [8], Burgan et al. [9], Rasmussen [10], Young and Hartono [11], Kuwamura [12], Gardner and Nethercot [13], Lam and Gardner [14], Uy et al. [15] and Zhao et al. [16] and a small number of longer member results from Rasmussen and Hancock [7], Talja [8], Burgan et al. [9], Young and Hartono [11] and Zhao et al. [17]. There have also been a limited number of duplex stainless steel stub column tests by Bardi and Kyriakides [18], Paquette and Kyriakides [19] and Lam and Gardner [14] and ferritic stainless steel stub column tests by Stangenberg [20], but no existing test results on longer columns of either duplex or ferritic grades. It has been previously observed that many of the existing data points lie below the current EN 1993-1-4 [4] flexural buckling curve [11,21–26]. The primary reason for this is that the buckling curve was calibrated using predominantly cold-formed square hollow section (SHS) and rectangular hollow section (RHS) column buckling test results [21], due to a lack of stainless steel CHS

* Corresponding author.
E-mail address: craig.buchanan08@imperial.ac.uk (C. Buchanan).

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experimental data at the time that the standard was produced. Cold-formed SHS and RHS benefit from increased material strength in the heavily work-hardened corner regions [27], and hence a buckling curve calibrated to experimental data on cold-formed SHS and RHS may be inappropriate for CHS.

It is apparent that there is a requirement firstly to expand the existing flexural buckling dataset on stainless steel CHS and to evaluate existing proposals for an updated buckling curve and secondly to put forward revised design recommendations; this is the focus of the work presented in this paper.

2. Experimental testing programme

2.1. General overview

The experimental programme consisted of material property tests, stub column tests and concentrically loaded long column tests. The test specimens covered a wide range of local slenderness values spanning all four classes of cross-section [4], a wide range of global slenderness values, with effective column lengths varying from 300 mm to 3080 mm, and included all three main types of stainless steel used in construction. The experimental programme was split between Imperial College London (ICL) and Universitat Politècnica de Catalunya (UPC). Five cross-section sizes were tested. The column tests for the two austenitic (A) cross-sections, 106 × 3 CHS (class 1/2) and 104 × 2 CHS (class 3/4), and the duplex (D) cross-section, 88.9 × 2.6 CHS (class 3/4), were carried out at ICL, along with the tensile coupon testing. The CHS tested at ICL were all close to the class 2 or class 3 limit, and hence depending upon the measured dimensions could be one of two cross-section classes. The column tests on the two ferritic (F) cross-sections, 80 × 1.5 CHS (class 3) and 101.6 × 1.5 CHS (class 4), were undertaken at UPC. The austenitic and duplex tubes were cut at ICL using a band saw, with wooden cylinders inserted to reduce clamping deformations, while the ferritic specimens were laser cut by the supplier. The chemical composition of the specimens, as stated in the mill certificates, are provided in Table 1. The CHS were all produced by cold-forming and longitudinal welding. Prior to cutting it was noted that the 104 × 2 tubes came from two different sources, both from the country markings (Sweden and Finland) on the tubes and the external finish around the weld, although there was no distinction on the mill certificate. The specimen notation is illustrated by the following example: 104 × 2-400-F is a 104 × 2 cross-section with a 400 mm nominal length (or effective length) with 'F' indicating fixed end conditions, whereas a specimen with a 'P' indicates pinned end conditions; a specimen ending with 'R' denotes a repeat specimen.

2.2. Material properties

Tensile coupon tests were undertaken to determine the basic material stress-strain properties of the tubes. The tensile coupon tests were undertaken in compliance with EN ISO 6892-1 [28] using an Instron 8802 testing machine, with a data recording frequency of 1 Hz. Two tensile coupons were prepared from each cross-section, with the coupons having the traditional dog-bone shape and cut on opposite sides at 90° to the weld position, and had the standard gauge lengths marked.

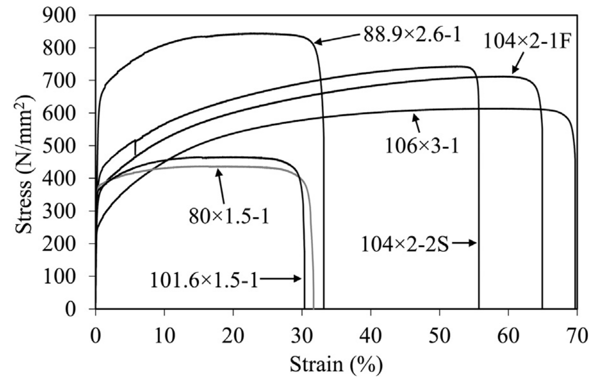

Fig. 1. Typical tensile coupon stress-strain curves.

The instrumentation consisted of two mid-height electrical resistance strain gauges to measure strains up to the material 0.2% proof stress, a video extensometer that measured the strains beyond this point and a load cell to measure the applied tensile load. As recommended in EN ISO 6892-1 [28] two crosshead separation rates were used before and post yield, depending upon the parallel length of the necked region, with a gradual ramp between them. Filler material was applied to the concave face of the coupons to prevent the machine grips from deforming the ends of the coupons and inducing bending within the coupon due to an eccentrically applied tensile force. The cross-sectional area of the necked region of the coupons was determined using AutoCAD from the average measured coupon dimensions. Typical stress-strain curves from the tensile coupons are shown in Fig. 1, while the Young's modulus E, 0.2% proof stress $\sigma_{0.2}$, 1.0% proof stress $\sigma_{1.0}$, ultimate tensile stress σ_u, strain at the ultimate tensile stress ε_u, fracture strain over the marked gauge length ε_f, the Ramberg-Osgood parameter n [29] and the extended parameters $n'_{0.2,1.0}$ and $n'_{0.2,u}$ [30–32] determined from the coupon tests are reported in Table 2. The Ramberg-Osgood and extended parameters were determined using weighted total least squares regression that is independent of the distribution of the data points. As noted previously, the 104 × 2 tubes came from Sweden and Finland and hence the relevant coupons are labelled with an 'S' and 'F' respectively, with the difference apparent from Table 2 with the 'S' coupons having a higher Young's modulus E, 0.2% proof stress $\sigma_{0.2}$ and ultimate tensile stress σ_u than the 'F' coupons.

2.3. Geometric properties

The geometric properties of the CHS specimens were measured before testing. Outer diameter measurements were taken at three equally spaced longitudinal locations for the short stub columns and shorter pin-ended columns (L < 400 mm) and at five equally spaced longitudinal locations for the longer columns. At each location the outer diameter was recorded in four evenly distributed orientations (at 45° intervals) with callipers, allowing the average outer diameter D of the specimen to be calculated along with its 'out-of-roundness' as defined in EN 10219-2 [33]. Prior to cutting the individual austenitic and duplex specimens from the delivered tubes, the lengths of CHS tube with the least 'out-of-roundness' were identified and the required specimens

Table 1
Chemical composition of the test specimens, as stated in the mill certificates.

Section	Grade	Type	C (%)	Si (%)	S (%)	P (%)	Mn (%)	Cr (%)	Ni (%)	Mo (%)	Ti (%)	N (%)	Co (%)
106 × 3	1.4432	A	0.020	0.39	0.003	0.029	1.30	16.70	10.60	2.79	–	0.046	–
104 × 2	1.4307/1.4301	A	0.026	0.39	0.001	0.030	1.48	18.10	8.10	–	–	0.049	–
88.9 × 2.6	1.4462	D	0.015	0.41	0.001	0.018	1.39	22.40	5.75	3.10	–	0.170	–
80 × 1.5	1.4512	F	0.011	0.46	0.010	0.024	0.27	11.68	0.25	0.04	0.22	0.008	0.01
101.6 × 1.5	1.4512	F	0.016	0.44	0.001	0.026	0.28	11.55	–	–	0.24	0.012	–