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Behaviour of structural stainless steel cross-sections under combined loading – Part I: Experimental study

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ABSTRACT

Stainless steel has been gaining increasing use in a variety of engineering applications due to its unique combination of mechanical properties, durability and aesthetics. Significant progress in the development of structural design guidance has been made in recent years, underpinned by sound research. However, an area that has remained relatively unexplored is that of combined loading. Testing and analysis of stainless steel cross-sections under combined axial load and bending is therefore the subject of the present paper and the companion paper (Zhao et al., submitted for publication). The experimental programme covers both austenitic and duplex stainless steels, and five cross-section sizes including three square hollow sections (SHS) and two rectangular hollow sections (RHS). In total, five stub column tests, five four-point bending tests, 20 uniaxial bending plus compression tests and four biaxial bending plus compression tests were carried out to investigate the cross-sectional behaviour of stainless steel tubular sections under combined loading. The initial loading eccentricities for the combined loading tests were varied to provide a wide range of bending moment-to-axial load ratios. For each type of test, the test setup, experimental procedures, full experimental load–deformation histories and key test results are reported in detail. All the experimental results are then employed in the companion paper (Zhao et al., submitted for publication) for the validation of finite element (FE) models, by means of which a series of parametric results is generated, and for the assessment of the design provisions given in EN 1993-1-4 (2006) and SEI/ASCE-8 (2002). Improved design rules for stainless steel cross-sections under combined loading are also sought through extension of the deformation-based Continuous Strength Method (CSM).

1. Introduction

Cold-formed stainless steel hollow sections are becoming an attractive choice in a range of structural applications since they combine the durability advantages of stainless steel with the aesthetic appeal, structural efficiency and potential for concrete infilling [1–5] of tubular profiles. The tested cross-sections were formed from austenitic and duplex stainless steels. Extensive experimental and numerical studies have been previously conducted on tubular sections of these grades under compression and bending, acting in isolation. Stub column tests on different cross-section classes have been carried out to study the compressive response and local buckling behaviour of austenitic [6–11] and duplex [12,13] stainless steel cross-sections. Three-point and four-point bending tests have been performed to investigate the flexural response and rotation capacity of austenitic [14–18] and duplex [19,20] stainless steel beams under a moment gradient and constant moment, respectively. On the basis of the findings, revised slenderness limits for cross-section classification [21] and new effective width formulae for slender sections [12] have been proposed. Theofanous et al. [22] conducted two-span continuous beam tests on austenitic and duplex stainless steel sections to enable the influence of moment redistribution within statically indeterminate beams to be examined. As highlighted by previous researchers, the general codified approach of limiting the design stress to the 0.2% proof stress, and ignoring the pronounced strain hardening exhibited by stainless steels can lead to greatly underestimated cross-sectional resistances. To address this shortcoming, a deformation-based design approach called the Continuous Strength Method (CSM) [23–25] was proposed to allow a rational exploitation of strain hardening. The latest developments to the CSM for stainless steel were presented by Afshan and Gardner [26], where substantially improved predictions of capacity over current design methods

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were demonstrated. However, to date, limited research has been conducted into the cross-sectional behaviour of stainless steel tubular sections under combined axial load and bending moment, and this is therefore the focus of the present investigation.

This paper and its companion paper [27] describe experimental and numerical investigations conducted on SHS and RHS made of austenitic and duplex stainless steels under combined loading. The numerical modelling programme comprises a calibration study and a parametric study carried out to generate further structural performance data. These data are analysed and discussed in combination with the test results, and used to evaluate the accuracy of the existing design provisions in EN 1993-1-4 (2006) [28] and SEI/ASCE-8 (2002) [29] and to develop more efficient design rules for stainless steel cross-sections under combined loading conditions.

2. Experimental investigation

2.1. General

An experimental programme covering austenitic and duplex stainless steels and a range of hollow section sizes including both SHS and RHS was conducted at the University of Liege and Imperial College London, with the aim of investigating the cross-sectional behaviour of tubular sections under combined loading. Overall, the laboratory testing programme comprised material testing, geometric imperfection measurements, five stub column tests, five four-point bending tests, 20 uniaxial bending plus compression tests and four biaxial bending plus compression tests. Five cross-section sizes were employed, which were SHS 100 × 100 × 5, SHS 120 × 120 × 5, RHS 150 × 100 × 6, and RHS 150 × 100 × 8 of austenitic grade (EN 1.4301, 1.4571, 1.4307 and 1.4404, respectively) [30] and SHS 150 × 150 × 8 of duplex grade (EN 1.4162) [30]. Note that the examined duplex grade has low nickel content and is often referred to as a 'lean' duplex grade, but its structural performance is considered to remain reflective of the wider duplex family [12]. The chemical compositions for each section, as provided by the mill certificates, are presented in Table 1. The testing apparatus, experimental procedures and test results for each type of test are reported in detail in the following sections. The adopted specimen ID system comprises a number and a letter (e.g. 1A); the number identifies the section size as follows: (1) SHS 100 × 100 × 5, (2) SHS 120 × 120 × 5, (3) RHS 150 × 100 × 6, (4) RHS 150 × 100 × 8 and (5) SHS 150 × 150 × 8, while the letter indicates the test type/loading, as follows: A identifies a stub column under pure compression, B is a beam, C–F are stub columns under uniaxial bending plus compression and G–J are stub columns under biaxial bending plus compression.

2.2. Material testing

A comprehensive description of the tensile tests carried out on coupons cut out of the sections studied herein was given by Afshan et al. [31], while only a brief summary is provided in the present paper. All the tensile coupon tests were conducted using a Zwick/Roell Z100 kN electromechanical testing machine, in which a set of end-clamps (flat surface clamps used for the flat coupons and V-shaped clamps employed for the corner coupons) were utilized to allow appropriate gripping of the coupons in the machine jaws. For each section size, two flat coupons and two corner coupons were tested. Two flat coupons were cut from the centrelines of the faces adjacent to the welded face whilst two corner coupons were taken from the curved corner regions opposite to the weld, as shown in Fig. 1. All the coupon tests were performed under strain-control according to the requirements of EN ISO 6892-1 [32]. For each cross-section studied herein, the average measured flat and corner material properties are reported in Tables 2 and 3, respectively, while the tensile properties of the coil material from the mill certificates are listed in Table 4, where E is the Young's modulus, $\sigma_{0.2}$ is the 0.2% proof stress, $\sigma_{1.0}$ is the 1.0% proof stress, σ_u is the ultimate tensile strength, ε_u is the strain at the ultimate tensile strength, ε_f is the plastic strain at fracture measured over the standard gauge length, and n and $n'_{0.2,1.0}$ are the strain hardening exponents used in the compound Ramberg–Osgood (R–O) material model [33–36].

2.3. Geometric imperfection measurements

Geometric imperfections are an inevitable and important characteristic of thin-walled structures, which influence the structural performance. Owing to the absence of global buckling phenomena in the present study, only local imperfections were measured. The procedures and test setup for imperfection measurements are similar to those suggested by Schafer and Peköz [37] in which a Linear Variable Displacement Transducer (LVDT) was affixed to the head of the milling machine with specimens lying on the moving machine base, as shown in Fig. 2. For each specimen, imperfection measurements were conducted along the centrelines of all the four faces. To eliminate the effect of end flaring [38] due to the release of residual stress and the influence of the welds, all the imperfection measurements were taken over the central 50% of the member length, at 2 mm intervals. The

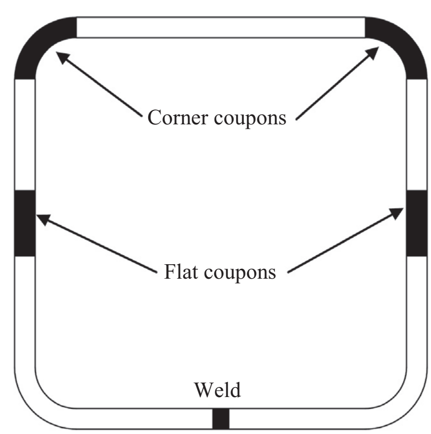

Fig. 1. Locations of coupons in the cross-section.

Table 1
Chemical compositions stated in the mill certificates.

Cross-section	Grade	C (%)	Si (%)	Mn (%)	P (%)	S (%)	Cr (%)	Ni (%)	N (%)	Mo (%)	Cu (%)	Nb (%)
SHS 100 × 100 × 5	1.4301	0.044	0.35	1.34	0.029	0.001	18.24	8.12	0.058	0.21	–	–
SHS 120 × 120 × 5	1.4571	0.040	0.39	1.22	0.027	0.001	16.70	10.70	0.010	2.06	–	–
RHS 150 × 100 × 6	1.4307	0.023	0.39	1.76	0.029	0.001	18.20	8.10	0.043	–	–	–
RHS 150 × 100 × 8	1.4404	0.022	0.49	1.74	0.032	0.002	17.00	10.00	0.042	2.04	–	–
SHS 150 × 150 × 8	1.4162	0.029	0.74	4.97	0.020	0.001	21.68	1.59	0.215	0.32	0.34	–

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