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Experimental study of stainless steel angles and channels in bending

M. Theofanous [a], A. Liew [b], L. Gardner [c,*]

[a] School of Civil Engineering, University of Birmingham, Birmingham B15 2TT, UK
[b] Institute of Structural Engineering, Swiss Federal Institute of Technology (ETH), Zurich, Switzerland
[c] Department of Civil and Environmental Engineering, Imperial College London SW7 2AZ, UK

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ABSTRACT

Substantial research has been conducted in recent years into the structural response of stainless steel components, with the focus being primarily on doubly symmetric cross-sections. Limited experimental data exist on non-doubly symmetric stainless steel sections in compression, while there is an absence of such data in bending, despite these sections being widely used in the construction industry as wind posts, lintels and so on. To address this limitation, and to bring an improved understanding of the behaviour of these sections, an experimental study into the flexural response of stainless steel channels bent about their minor axis and angles bent about their stronger geometric axis is described herein. In total, 16 bending tests on austenitic stainless steel beams have been conducted and the obtained results, including the full load-deformation history and observed failure modes have been described. Auxiliary tests on tensile coupons extracted from the tested sections and initial geometric imperfection measurements have also been performed and are reported in detail. The influence of the spread of plasticity and strain hardening on the shift of the neutral axis and the ultimate load carrying capacity is also examined. Based on the obtained test results, the current design provisions of EN 1993-1-4 [1] for these types of cross-sections were assessed and found to be unduly conservative. The effect of strain hardening on the structural response of stocky stainless steel sections and the need to account for it in design has been highlighted.

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1. Introduction

Owing to its favourable structural properties, excellent durability and aesthetic appeal, stainless steel is gaining increasing usage in the construction industry and has attracted considerable attention from researchers and practising engineers alike [2–4]. Previous experimental research on stainless steel components has been dominated by tests on cold-formed circular, square and rectangular hollow sections (CHS, SHS and RHS, respectively) and welded I-sections [5], with other cross-section types receiving less attention. Column and beam tests have been performed on stainless steel oval hollow sections (OHS) [6,7], whilst tests on stainless steel non-doubly symmetric sections have been mainly focusing on angle [8], channel [8] and lipped channel sections [9–11] in compression. Recently, tests on stainless steel lipped channel section beams bent about their major axis have been conducted [12] to investigate the interaction between distortional and global buckling. When asymmetric sections are subjected to bending about an axis that is not an axis of symmetry, flexure induces different stresses at the extreme tensile and compressive extreme fibres and leads to a shift in neutral axis with the progression of plasticity. No test data on the cross-sectional response of stainless steel sections subjected to bending not about an axis of symmetry have been reported to date.

Current structural stainless steel design guidance [1] is concerned mainly with doubly symmetric sections, primarily tubular sections and I-sections, which are commonly employed in structural applications. However, mono-symmetric stainless steel sections and in particular angle sections are widely employed in a range of structural applications, to act as wind posts, lintels, truss chords, lattice towers, pipeline frames, retrofitting of current structures [14] and so on, due to their simple geometry and ease of fabrication of connections; hence their design is of considerable practical significance. The European structural design rules for bending rely essentially on the classification of cross-sections into discrete behavioural groups according to their element width-to-thickness ratios, as compared to specified slenderness limits set out in [1]. As reported in [5], these slenderness limits were derived on the basis of experiments on stainless steel stub columns and beams, conducted primarily on SHS, RHS and I-sections. The lack of relevant test data on non-doubly symmetric stainless steel sections means that the current design provisions in EN 1993-1-4 (2006) [1] rely solely on assumed analogies with structural carbon steel and do not account for the special features of stainless steel, namely its rounded stress–strain response and pronounced strain hardening. Neglecting the high degree of strain hardening has been shown to lead to overly conservative ultimate capacity predictions [5,13] particularly for stocky

* Corresponding author.
E-mail addresses: m.theofanous@bham.ac.uk (M. Theofanous), leroy.gardner@imperial.ac.uk (L. Gardner).

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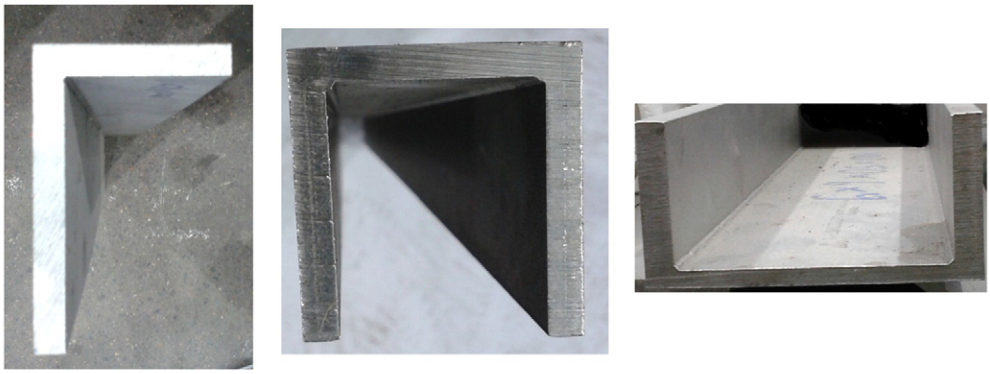

Fig. 1. Laser-welded cross-sections featuring essentially sharp corners.

cross-sections in bending. However, the effect of the nonlinear material behaviour of stainless steel on the structural response of non-doubly symmetric cross-sections in bending has not been studied to date. Given that beyond the elastic limit a shift in neutral axis occurs due to the spread of yielding throughout the cross-section and the high shape factors often associated with non-symmetric sections, it is expected that the effect of the rounded material stress–strain behaviour on the structural response will be even more pronounced for non-doubly symmetric cross-sections in bending.

To address these issues, an experimental study into the structural response of mono-symmetric and asymmetric sections in bending has been carried out. A total of 16 beam tests were conducted in both the 3-point and 4-point bending configurations (8 tests in each). Tensile coupon tests and initial geometric imperfection measurements have also been performed and are reported herein. Based on the obtained results, the current design provisions of EN 1993-1-4 [1] were evaluated and found to be safe, but excessively conservative over the full local slenderness range.

2. Literature review

Although there has only been limited research on stainless steel angles and channels in bending, there has been extensive work conducted on these sections made of structural carbon steel. A brief review of the previous research, with an emphasis on an angle sections, is given in this section.

Trahair studied analytically [15] the behaviour of single angles with different loading and restraint conditions in a series of papers recognizing the complexity that they present due to the lack of double symmetry and the coexistence of flexure, torsion and shear in many cases. Initially, design recommendations were developed for the classification and moment resistance calculation of laterally restrained angle sections subjected to biaxial bending [16], based on modifications to existing rules for I-section flange outstands, and reduction coefficients to account for the combined effect of torsion, shear and bearing were proposed [17]. Subsequently, based on large rotation analysis, design recommendations were proposed for unrestrained angle section beams subjected to major axis bending [18], biaxial bending [19], major axis bending and torsion [20] and biaxial bending and torsion [21]. In all cases the material response was assumed to be elastic-perfectly plastic and slenderness limits were proposed, according to which either the elastic or the plastic moment resistance should be employed in design.

A series of numerical studies have been reported by Earls on slenderness limits and the ultimate moment resistance of single angle members, considering major axis bending [14], geometric axis bending inducing compression in the horizontal leg [22] and geometric axis bending inducing tension in the horizontal leg [23]. Based on the numerical results, design recommendations for slenderness limits and bracing requirements were made [24]. The focus of the research reported in [14,22–24] was on determining local and global slenderness limits to enable the plastic moment resistance of an angle section beam to be achieved, but with no explicit account for strain hardening. The high conservatism embedded in the then applicable design guidance was highlighted and the findings of [24] were taken into account in the development of the latest version of the only structural design code dedicated exclusively to angle members [25].

The above numerical studies [14,22–24] were validated against the tests reported by Madugula et al. [26], who investigated the flexural response of double-angle beams subjected to 3- and 4-point bending, which simulated laterally restrained single angles bent about their geometric axis. Both possible orientations of geometric axis bending (i.e. inducing tension or compression in the horizontal leg) were considered. The experiments revealed a high level of conservatism in structural design codes, as even the most slender cross-sections exceeded their plastic moment resistance. A similar experimental approach to that reported in [26] is followed in the present paper.

3. Experimental investigation

In order to address the lack of experimental data on stainless steel beams with non-doubly symmetric cross-sections, a series of tests has been conducted in the Structures Laboratory of the Department of Civil and Environmental Engineering at Imperial College London. The experiments were performed on austenitic stainless steel angles bent about their geometric axis and channel sections bent about their minor axis. Auxiliary tests on material coupons extracted from the same lengths of section as the test specimens and initial geometric imperfection measurements were also conducted and are reported herein.

Table 1
Geometry of tested angle specimens.

Specimen	Testing configuration	Total length (mm)	Length between supports (mm)	b (mm)	h (mm)	t_f (mm)	t_w (mm)
A50 × 50 × 4-3	3-point bending	849.5	750	50.53	50.45	4.14	4.17
A50 × 50 × 4-4	4-point bending	849.3	750	50.70	50.49	4.16	4.18
A100 × 65 × 11-3	3-point bending	1599.5	1500	65.11	99.46	10.70	10.66
A100 × 65 × 11-4	4-point bending	1599.5	1500	64.95	99.71	10.62	10.63

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