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Experimental study on ferritic stainless steel simply supported and continuous beams

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ABSTRACT

Development of efficient design guidance for stainless steel structures is key for the increased use of this corrosion-resistant material by considering both nonlinear behaviour and strain hardening into resistance prediction expressions, together with the moment redistribution in indeterminate structures. With the aim of analysing the bending moment redistribution capacity of ferritic stainless steel beams, a comprehensive experimental programme on continuous beams is presented. These tests contribute to the assessment of EN1993-1-4 specifications, where no plastic design is allowed, and the classical and new plastic design methods available in the literature for indeterminate stainless steel structures. Four three-point and eight four-point bending tests are also reported for the assessment of current codified and revised cross-sectional classification limits, analysing the different methods for the prediction of the ultimate bending capacities of ferritic hollow sections. Additional test results reported by other authors in different stainless steel grades and carbon steel are also studied and presented. The analysis indicates that Class 1 cross-sectional classification limits are too optimistic for ferritic stainless steels and further research is needed for the extension of plastic design to these grades, although promising predictions of ultimate loads are obtained for austenitic and lean duplex stainless steels.

1. Introduction

The increased use of stainless steel elements in construction is the result of its excellent corrosion resistance, good mechanical properties, reduced maintenance requirements and aesthetic appearance. Unfortunately, these appealing characteristics are usually overlooked by the high initial investment requirement if the full life-cycle costs are not considered. Ferritics are therefore important in the spread of stainless steels, as they have a lower associated material cost due to their lower nickel content but yet maintain the rest of desirable stainless steel properties. Therefore, they are cheaper and more price-stable than typical austenitic stainless steel grades, but still present significant corrosion resistance, good ductility, formability and impact resistance as reported by Baddoo and Cashell [1].

Various metallic alloys such as stainless steel have a nonlinear stress–strain relationship, even for low strain values, together with strain hardening and this material response needs to be considered when proposing specific design expressions. European design guidance for stainless steel EN1993-1-4 [2], based on EN1993-1-1 [3] for carbon steel, considers four cross-sectional classes depending on their local buckling susceptibility, and a different resistance is assigned to each class. Nevertheless, no plastic design is allowed for stainless steel elements in EN1993-1-4 [2] despite their high ductility, which, with the fact that strain hardening effects are not considered when stainless steel structures are designed, leads to overconservative load carrying capacity predictions.

Although tests on continuous stainless steel beams have already been conducted for austenitic and lean duplex grades with the aim of assessing the moment redistribution capacity of stainless steel beams and the possibility of incorporating plastic design, no experimental results on ferritic stainless steels are available as far as the authors know. Hence, the objective of the continuous beam tests on hollow elements presented in this work is to understand the behaviour of indeterminate ferritic stainless steel structures and the redistribution capacity of these beams. Additionally, a new design method based on the Continuous Strength Method (CSM) for indeterminate structures developed by Gardner et al. [4] and Theofanous et al. [5] is assessed with the conducted tests. Furthermore, three-point and four-point bending tests are also presented for the same cross-sections in order to utilize the experimental results in the analysis of indeterminate structures, and the assessment of the cross-sectional classification limits and design expression is described.

2. Experimental tests

2.1. Introduction

This paper presents a comprehensive experimental investigation on ferritic stainless steel hollow section beams. Simply supported tests

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were conducted for the determination of the ultimate cross-sectional bending capacity and these results were then utilized in the study of two span continuous beams, where the redistribution capacity of the different beams was investigated. Five different cross-sections were analysed, comprising three Rectangular Hollow Sections (RHS) and two Square Hollow Sections (SHS). The cross-sections were named as follows: S1—80 × 80 × 4, S2—60 × 60 × 3, S3—80 × 40 × 4, S4—120 × 80 × 3 and S5—70 × 50 × 2, which will be used throughout this paper. All the tests were conducted in the Laboratori de Tecnologia d'Estructures Luis Agulló, in the Department of Construction Engineering at Universitat Politècnica de Catalunya. This experimental programme was developed together with additional compression tests and simply supported bending tests on slender ferritic stainless steel RHS and SHS, reported in Bock et al. [6] and complements this study on the flexural behaviour of ferritic elements with stockier cross-sections. The specimens were made from grade EN1.4003 ferritic stainless steel and were cold-rolled and seam welded. The chemical composition and tensile properties of the original coil material provided by the manufacturer in the mill certificates have already been reported in [6].

2.2. Material and initial imperfection characterization

Cold-forming processes affect cross-sectional behaviour, particularly in the corner regions, with increasing plastic deformations resulting in significant material property enhancement. Hence, the material behaviour of the different cross-sections was characterized by conducting tensile tests on coupons extracted both from the flat (F) and corner (C) regions of the cross-sections, as shown in Fig. 1.

Two flat specimens and two corner coupons were tested for each cross-section, resulting in a total of 20 tensile tests. The machining and testing of the coupons were conducted in the technical laboratories of Acerinox, in accordance with ISO6892-1 [7]. Coupons were tested under an initial strain rate of 0.00025 s^{-1} for the determination of the Young's modulus and the yield stress and then increased to 0.008 s^{-1}. Coupons extracted from the corner parts were strips with constant cross-sectional area along their entire length, and were extended two times the thickness of the cross-sections into the adjacent flat faces according to [8], since corner properties affect regions beyond the curved portions. The area was calculated by considering the mass of each coupon and the density of the grade EN1.4003 ferritic stainless steel from EN10088 [9]. The flat coupons were machined to the usual dogbone shape, with a nominal width of 15 mm over the reduced area length, and strains at fracture were measured over the standard gauge length of $5.65\sqrt{A_c}$ where A_c is the cross-sectional area of the coupon.

Averaged key material properties of the flat and corner regions of each cross-section are presented in Table 1, where E is the Young's modulus, $\sigma_{0.05}$ and $\sigma_{0.2}$ are the proof stresses corresponding to 0.05% and 0.2% plastic strains respectively, σ_u is the ultimate tensile strength, ε_u is the corresponding ultimate strain and ε_f is the strain at fracture. Strain hardening exponents *n* and *m* corresponding to the material model proposed by Mirambell and Real [10] are also reported. The material properties have been obtained using a software developed by the authors and described in Real et al. [11] and Arrayago et al. [12].

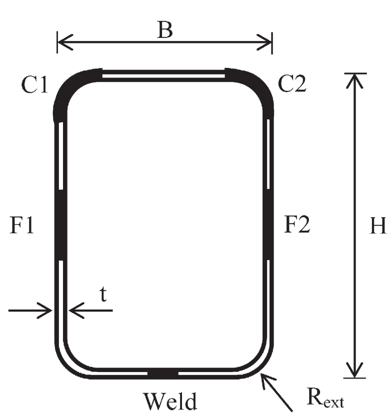

Fig. 1. Location of the flat and corner coupons and definition of cross-section symbols.

Table 1
Average tensile test results for the different cross-sections.

	E [MPa]	$\sigma_{0.05}$ [MPa]	$\sigma_{0.2}$ [MPa]	σ_u [MPa]	ε_u [%]	ε_f [%]	n	m
S1 – F	173,992	465	521	559	8.2	21.7	12.4	2.3
S1 – C	170,049	441	577	645	1.1	7.9	5.0	5.4
S2 – F	186,896	433	485	505	6.8	20.9	12.2	2.6
S2 – C	178,049	459	555	587	1.0	10.1	7.9	5.2
S3– F	181,632	467	507	520	3.6	21.0	16.4	2.5
S3 – C	183,684	434	558	601	1.0	7.0	5.9	4.5
S4 – F	176,704	391	430	490	12.6	27.1	14.6	2.3
S4 – C	194,611	457	540	583	1.0	10.1	7.6	4.8
S5 – F	179,568	381	418	480	13.8	26.8	15.3	2.4
S5 – C	186,026	466	552	575	1.1	6.5	8.0	4.6

The different behaviour of flat and corner regions of cross-sections can be considered in the analysis of the experimental results by determining the weighted average material properties as established by Hradil and Talja [13]. The parameters are weighted according to the area of the considered flat or corner region compared to the total area of the cross-section, assigning the value of the corresponding material parameter to each region. The key weighted average material properties of the different cross-sections presented in this paper are summarized in Table 2.

Initial imperfections were determined by placing each specimen on a milling machine and measuring the deviations with a LVDT and recorded using a data acquisition system (see Fig. 2). Imperfections of the faces at 90° and 180° angles from the weld were measured and amplitudes reported in Table 1 are the average value of the measured maximum values.

2.3. Simply supported tests: three-point and four-point bending tests

Twelve ferritic stainless steel RHS and SHS simply supported beams were tested under three-point and four-point bending loading conditions in order to determine their bending moment resistance and rotation capacity and thereby, assess the existing cross-sectional classification limits and design expressions. Eight four-point (labelled as 4P) bending tests were conducted, covering the five studied cross-sections, and considering both major (denoted as Mj) and minor (Mi) bending axes for RHS. Four three-point (3P) bending tests were also carried out in this experimental programme, not for all cross-sections and bending axis: the S1, S2, S3-Mj and S4-Mj cross-sections were tested under three-point bending loading conditions. The comparison between different loading conditions will highlight the effect of the bending moment gradient and shear upon the cross-sectional resistance capacity. Although web crippling was not prevented at the loading and support sections in three-point bending tests, these sections were stiffened in four-point bending tests by inserting wooden blocks in

Table 2
Weighted tensile material properties.

	E [MPa]	$\sigma_{0.05}$ [MPa]	$\sigma_{0.2}$ [MPa]	σ_u [MPa]	ε_u [%]	n	m
S1	172,615	456	539	587	5.8	8.8	2.6
S2	183,667	442	509	533	4.8	11.0	3.2
S3	182,637	451	529	554	2.5	12.9	2.7
S4	188,482	406	453	509	10.0	13.8	2.6
S5	181,030	400	449	502	10.8	14.7	2.4