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Flexural behaviour of hot-finished high strength steel square and rectangular hollow sections

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ABSTRACT

High strength steels, considered in the context of the structural Eurocodes, as steels with a yield strength over 460 MPa, are gaining increasing attention from structural engineers and researchers owing to their potential to enable lighter and more economic structures. This paper focuses on the bending strength of hot-finished high strength steel (HSS) square and rectangular hollow sections; the results of detailed experimental and numerical studies are presented and structural design rules for HSS cross-sections are proposed. A total of 22 in-plane bending tests, in three-point bending and four-point bending configurations, on HSS sections in grades S460 and S690 were conducted. The experimental results were replicated by means of non-linear finite element modelling. Upon validation of the finite element models, parametric studies were performed to assess the structural response of HSS sections over a wider range of cross-section slenderness, cross-section aspect ratio and moment gradient. The experimental results combined with the obtained numerical results were used to assess the suitability of the current European (EN 1993-1-1 and EN 1993-1-12) cross-section classification limits for HSS structural components. The reliability of the proposed cross-section classification limits was verified by means of the EN 1990 — Annex D method.

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1. Introduction

High strength steels (HSS), with yield strengths in excess of 460 MPa, are being increasingly utilised in construction, and in particular in structural applications where long and column-free spans are an important design requirement [1]. The use of high strength steels, in place of ordinary carbon steels, can enable the selection of structural elements with smaller cross-section sizes, resulting in significant material savings. This, combined with lower transportation and construction costs, bring clear advantages for high strength steel as a sustainable and economical construction material. Recent examples of structures that have made substantial use of HSS are the National Stadium in China [2] and the roof trusses in the Sony Centre in Germany [3].

Previous research into the behaviour and design of HSS structures has included studies of the material characteristics described in references [4–13], residual stress measurements set-out in references [5–7,10,11,14–19], global buckling behaviour of long columns explained in references [5,8,16,17,20,21], local buckling response of stub columns and beams described in references [6,7,15,22–26] and [7,10,15,27,28], respectively, as well as the behaviour of HSS members under cyclic loading [12]. It is worth noting that previous experimental studies of HSS structures were conducted on either welded or cold-formed sections, leaving the structural behaviour of hot-finished HSS sections unexplored. Therefore, as part of a wider study of the structural behaviour of hot-finished HSS square and rectangular hollow sections (SHS and RHS, respectively) the main focus of this paper is to report on an investigation of the flexural behaviour of these components. The local buckling behaviour of HSS plate elements in welded sections and cold-formed sections has been studied in references [6,7,15,24,25] and [22,23,26], respectively. Based mainly on the results of stub column tests, it was found that HSS outstand elements (i.e. plate elements with one longitudinal edge simply supported and the other free, e.g. the flanges of I-sections) exhibit superior local buckling performance to those of ordinary carbon steels, whilst for internal elements (i.e. plates simply supported along both longitudinal edges, e.g. the flanges of SHS/RHS), HSS and ordinary steels were found to exhibit comparable local buckling resistance [6]. In addition, the flexural behaviour of HSS cross-sections has been studied in references [7,10,15,27,28], showing that HSS beams possess lower rotation capacity compared to their ordinary steel counterparts, which can be detrimental for plastic and seismic design.

EN 1993-1-12 [29] provides additional rules that can be used in conjunction with the other parts of EN 1993 to design structures using steel grades S460 up to S700. In common with equivalent design standards for high strength steel structures [30–33], EN 1993-1-12 makes extensive reference to the design rules for ordinary carbon steel in EN

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1993-1-1 [34]. In fact, while the material ductility requirements and the design of connections specific to high strength steels are set out in EN 1993-1-12 [29], the design of structural components at both cross-section level and member level is carried out in the same manner as for ordinary carbon steels. Hence, for the treatment of local buckling in HSS sections, EN 1993-1-12 [29] refers to EN 1993-1-1 [34], where cross-sections are classified into the four conventional classes based on the slenderness of the cross-section. Owing partly to the limited existing test data during the development of EN 1993-1-12 [29], the same cross-section classification limits used for ordinary carbon steel [34] are also adopted for HSS sections. The intent of this paper, therefore, is to investigate whether the current Eurocode slenderness limits are applicable to HSS hot-finished square and rectangular hollow sections in light of a larger pool of test and numerical structural performance data.

A comprehensive experimental programme on grades S460 and S690 HSS square and rectangular hollow sections was carried out at Imperial College London. The programme consisted of material tests, stub column tests, combined axial load and bending tests and in-plane bending tests on a total of eleven SHS/RHS section sizes. While this paper reports on the results of the in-plane bending tests and the associated analysis of the results, a full description of the other tests is reported in [35]. Accurate finite element models of the beam tests were also developed and, once validated, were used to perform parametric studies, where the effect of variations of cross-section slenderness, cross-section aspect ratio, moment gradient and material grade on the structural performance of HSS hot-finished hollow SHS/RHS was investigated. Based on the combination of the obtained experimental and numerical results, the suitability of existing cross-section classification limits for HSS internal elements in compression is assessed.

2. Experimental study

2.1. Introduction and material testing

A total of 22 in-plane bending tests, in three-point bending and four-point bending configurations, were carried out to investigate the flexural response of SHS and RHS high strength steel beams. The tested specimens were of grades S460 and S690. Both materials consisted of hot-rolled base materials and were hollowed out in a piercing mill to the final shape, after which the S460 sections were normalised, whereas the S690 were quenched and tempered. The chemical compositions and the tensile material properties of the tested specimens, as provided by the mill certificates, are presented in Tables 1 and 2, respectively. Material tensile and compressive coupon tests were also performed to determine the engineering stress–strain response of the flat and corner material for each of the tested section sizes. The resulting material properties were used in the subsequent analysis of the bending test results and also in the development of the numerical models of the tested specimens. Full details of the material tests are reported in [35], while a summary of the test results is given herein in Table 3, showing tensile flat (TF), tensile corner (TC) and compressive flat (CF) coupon results. The material parameters reported in Table 3 are the Young's modulus E, the upper yield strength f_y, the ultimate tensile strength f_u, the tensile-to-yield stress ratio f_u/f_y, the strain at the ultimate tensile stress ε_u, and the plastic strain at fracture ε_f, based on elongation over the standard gauge length equal to $5.65\sqrt{A_c}$, where A_c is the cross-sectional area of the coupon. It should be noted that for each section, either two or four tensile flat coupons were tested, and the TF results displayed in Table 3 are the averaged values of the TF coupons from each section. Fig. 1a and b show typical measured stress–strain curves for tensile flat, compressive flat and tensile corner coupons extracted from the S460 RHS 100 × 50 × 6.3 and S690 RHS 50 × 50 × 5 sections, respectively. From Table 3 and Fig. 1a and b, it can be seen that both grades of material display a sharply-defined yield point, while the S690 materials generally exhibit less strain hardening and lower ductility in comparison with the S460 coupons, as measured by the tensile-to-yield ratio and the ultimate and fracture strains.

Table 2
Mechanical properties as stated in the mill certificates.

Cross-section	$f_{y,\mathrm{mill}}$ (MPa)	$f_{u,\mathrm{mill}}$ (MPa)	ε_f (%)
S460 SHS 50 × 50 × 5	473	615	26.5
S460 SHS 50 × 50 × 4	524	639	33.0
S460 SHS 100 × 100 × 5	492	619	29.0
S460 SHS 90 × 90 × 3.6	463	656	25.5
S460 RHS 100 × 50 × 6.3	495	668	23.5
S460 RHS 100 × 50 × 4.5	505	642	27.5
S690 SHS 50 × 50 × 5	797	838	22.4
S690 SHS 100 × 100 × 5.6	821	829	20.1
S690 SHS 90 × 90 × 5.6	789	825	16.6
S690 RHS 100 × 50 × 6.3	792	834	20.9
S690 RHS 100 × 50 × 5.6	778	822	19.7

2.2. Geometric imperfection measurements

Measurements of initial geometric imperfections is important for enabling accurate modelling of the structural response of tested specimens in finite element simulations. Since lateral torsional buckling was precluded, due to the closed nature of the tested cross-sections and short length (i.e. low $\bar{\lambda}_{LT}$) of the beam specimens, only local geometric imperfections needed to be considered herein. Hence, measurements of the initial local geometric imperfection amplitudes were conducted prior to testing, following the procedures outlined in [36]. A displacement transducer mounted on the head of a milling machine was moved along the central 900 mm length of each of the 1700 mm beam specimens. A total of three runs, one in the middle and two close to the edges of each of the faces of the sections, were recorded. The obtained results were used to determine the maximum deviations from a flat datum for each of the four faces of each section, and the maximum of those values are reported in Table 4 and denoted ω_0. The average measured geometric dimensions of the beam specimen are also provided in Table 4, where L is the beam length, h is the section depth, b is the section width, t is the thickness and r_i is the average internal corner radius.

Table 1
Chemical composition of tested specimens.

Grade	C (%)	Si (%)	Mn (%)	P (‰)	S (‰)	Cu (%)	Cr (%)	Ni (%)	Mo (%)	V (%)	Ti (‰)	Nb (‰)	B (‰)	Al (‰)
S460 SHS 50 × 50 × 5	0.15	0.37	1.53	0.17	0.01	0.02	0.07	0.06	0.03	0.10	0.03	0.01	–	–
S460 SHS 50 × 50 × 4	0.15	0.37	1.53	0.17	0.01	0.02	0.07	0.06	0.03	0.10	0.03	0.01	–	–
S460 SHS 100 × 100 × 5	0.15	0.37	1.53	0.17	0.01	0.02	0.07	0.06	0.03	0.10	0.03	0.01	–	–
S460 SHS 90 × 90 × 3.6	0.15	0.37	1.53	0.17	0.01	0.02	0.07	0.06	0.03	0.10	0.03	0.01	–	–
S460 RHS 100 × 50 × 6.3	0.21	0.31	1.56	0.16	0.01	0.03	0.09	0.05	0.03	0.11	0.06	0.01	–	0.35
S460 RHS 100 × 50 × 4.5	0.15	0.37	1.53	0.17	0.01	0.02	0.07	0.06	0.03	0.10	0.03	0.01	–	–
S690 SHS 50 × 50 × 5	0.15	0.28	1.50	0.10	0.02	0.02	0.67	0.12	0.21	0.07	0.04	0.31	0.003	0.30
S690 SHS 100 × 100 × 5.6	0.14	0.28	1.50	0.11	0.02	0.03	0.68	0.10	0.21	0.06	0.04	0.29	0.003	0.22
S690 SHS 90 × 90 × 5.6	0.15	0.29	1.53	0.10	0.01	0.04	0.69	0.10	0.21	0.06	0.04	0.27	0.003	0.21
S690 RHS 100 × 50 × 6.3	0.15	0.28	1.50	0.10	0.02	0.02	0.67	0.12	0.21	0.07	0.04	0.31	0.003	0.30
S690 RHS 100 × 50 × 5.6	0.14	0.28	1.50	0.11	0.02	0.03	0.68	0.10	0.21	0.06	0.04	0.29	0.003	0.22

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