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Residual stress distributions in welded stainless steel sections

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ABSTRACT

Residual stress magnitudes and distributions in structural stainless steel built-up sections have been comprehensively investigated in this study. A total of 18 test specimens were fabricated from hot-rolled stainless steel plates by means of shielded metal arc welding (SMAW). Two grades of stainless steel were considered, namely the austenitic grade EN 1.4301 and the duplex grade EN 1.4462. Using the sectioning method, the test specimens were divided into strips. The residual stresses were then computed by multiplying the strains relieved during sectioning by the measured Young's moduli determined from tensile and compressive coupon tests. Residual stress distributions were obtained for 10 I-sections, four square hollow sections (SHS) and four rectangular hollow sections (RHS). Peak tensile residual stresses reached around 80% and 60% of the material 0.2% proof stress for grades EN 1.4301 and EN 1.4462, respectively. Based upon the test data, simplified predictive models for residual stress distributions in stainless steel built-up I-sections and box sections were developed. Following comparisons with other available residual stress test data, the applicability of the proposed models was also extended to other stainless steel alloys. The proposed residual stress patterns are suitable for inclusion in future analytical models and numerical simulations of stainless steel built-up sections.

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1. Introduction

Residual stresses in structural stainless steel sections may differ significantly from those in carbon steel sections, owing to distinct differences in material and thermal properties [1,2]. For cold-formed sections, residual stresses are mainly attributed to the coiling–uncoiling of the sheet material and to the press-braking or cold rolling operations [3,4], whereas in fabricated sections the localised welding heat input and uneven cooling are the key sources of residual stresses [5]. The residual stresses in structural sections can be determined by both destructive and non-destructive methods [6]. However, the non-destructive measuring techniques, such as X-ray diffraction, ultrasonic and magnetic methods, are often not practical for examining structural members. The sectioning method, due to its accuracy and simplicity, has been widely used to evaluate residual stresses in structural steel members. It was successfully used to determine residual stresses patterns in carbon steel sections [7], high strength steel sections [8] and cold-formed stainless steel sections [9]. This sectioning technique is based upon the measurement of residual strains that are relieved when cutting test sections into small strips [10].

Measurements of residual stress in structural stainless steel sections have been reported in a number of previous experimental programmes. Young and Lui [11] presented measurements in two cold-formed RHS by means of the sectioning method, whereas Jandera and Gardner [12] examined residual stresses in cold-rolled stainless steel box sections by X-ray diffraction. A comprehensive experimental programme carried out by Cruise and Gardner [9] involved the measurement of residual stresses in hot-rolled and press braked stainless steel angles, as well as cold-rolled box sections, using the sectioning method. For fabricated structural stainless steel sections, residual stress measurements using the sectioning technique have been made on four I-sections by Bredenkamp et al. [13], two I-sections by Lagerqvist and Olsson [14] and six I-sections by Wang et al. [15]. Overall, with relatively few residual stress measurements on welded stainless steel I-sections and none on welded stainless steel hollow sections, coupled with an increasing use of stainless steel in heavier load-bearing applications, the focus of this study is to carry out comprehensive measurements on fabricated sections and to develop simplified models for predicting the magnitudes and distributions of their residual stresses.

A total of 18 structural stainless steel built-up sections, including 10 I-sections, four SHS and four RHS were examined to acquire the level and distribution of residual stresses present in such sections. The sectioning method, using the wire-cutting technique,

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was adopted in the experimental programme. Relieved strains from a total of 1244 strips were measured using a standard Whittemore gauge. The residual stress magnitudes and patterns were calculated by utilising the material properties obtained from the original plates used to fabricate the sections. Based on the acquired data, together with all previously available results, existing residual stress predictive models [16,17] for carbon steel built-up sections were revised to provide corresponding models for structural stainless steel built-up sections.

2. Test specimens: geometric dimensions, fabrication process and material properties

The basic geometries of the test specimens are shown in Fig. 1. The measured geometric dimensions of the specimens are recorded in Tables 1 and 2. The constitutive plates of all the specimens were cut using a water jet from hot-rolled coil, with the longitudinal direction of the members parallel to the coil rolling direction. The web plates of the SHS and RHS were machined to create beveled edges for butt welds. The specimens were initially assembled by spot welding, prior to the final fillet and butt welding for the I-sections, and hollow sections, respectively. All welds were performed by shielded metal arc welding (SMAW), also known as manual metal arc welding (MMA). The choice of electrodes was dependent on the parent material [18]. Specifically, type E308 electrodes were used for the grade EN 1.4301 specimens (corresponding to type 304 in the ASTM system), while type E2209 electrodes were selected for the grade EN 1.4462 specimens (corresponding to type 2205 in the ASTM system). The size of both the fillet welds and the butt welds was designed to be 5 mm, taking consideration of both strength and construction requirements.

The physical and thermal properties of the investigated stainless steel grades are such that welding distortions can be more significant than in equivalent carbon steel sections. In comparison to carbon steel, larger welding distortions can arise in stainless steel sections due to sharper heat gradients resulting from lower heat conductivity and a higher coefficient of thermal expansion. To alleviate the induced welding distortions, two techniques, namely reverse bending of the I-section flange plates before assembling and symmetric welding sequences, were introduced into the fabrication process. Subsequent to welding, additional straightening of the constitutive plates by means of a hydraulic press and a specially designed clamping apparatus was implemented. The 18 welded test specimens are shown in Fig. 2.

The material properties were tested in a previous study [19], which unveiled both anisotropic and asymmetric features of the alloys. Since the test specimens were built up by plates all cut along the rolling direction, the corresponding tensile and compressive material properties are listed in Table 3, where the following symbols are used: E_0 is Young's modulus, $\sigma_{0.01}$ and $\sigma_{0.2}$ are 0.01% and 0.2% proof stresses, respectively, σ_u is the ultimate tensile stress, ε_f is the plastic strain at fracture, measured from the fractured tensile coupons as elongation over the standard gauge length, and n is the Ramberg–Osgood strain hardening exponent.

3. Measuring technique: the sectioning method

The sectioning method, which is a destructive technique for measuring residual stresses, has been widely used for many years and found to provide accurate and reliable results. This method was employed in the present study. The test specimens were designed to be sufficiently long to enable consistent and uniform welds to be established and to minimise end effects. The total

Table 1
Average measured geometric dimensions for I-section specimens.

Specimen	b_f (mm)	h (mm)	t_w (mm)	t_f (mm)	c_f/t_f	h_w/t_w
I304-150	149.5	149.6	6.00	10.00	7.2	21.6
I304-260	165.7	259.0	6.00	10.00	8.0	39.8
I304-192	126.3	194.2	6.00	6.00	10.0	30.4
I304-252	245.7	253.3	6.00	6.00	20.0	40.2
I304-372	246.1	373.3	6.00	6.00	20.0	60.2
I2205-150	150.0	150.7	6.00	10.20	7.1	21.7
I2205-200	124.9	200.6	6.00	10.20	5.8	30.0
I2205-192	125.8	193.1	6.00	6.00	10.0	30.2
I2205-252	245.3	252.9	6.00	6.00	19.9	40.1
I2205-372	245.0	372.9	6.00	6.00	19.9	60.1

Table 2
Average measured geometric dimensions for RHS and SHS specimens.

Specimen	b_f (mm)	h (mm)	$t_w=t_f=t$ (mm)	c_f/t	h_w/t
R304-200	100.4	199.9	6.00	16.7	33.3
R304-300	200.1	299.7	6.00	33.3	50.0
S304-130	130.3	129.8	6.00	21.7	21.6
S304-300	301.3	300.7	6.00	50.2	50.1
R2205-200	100.4	200.1	6.00	16.7	33.4
R2205-300	200.9	300.6	6.00	33.5	50.1
S2205-130	130.5	130.3	6.00	21.8	21.7
S2205-300	299.9	301.0	6.00	50.0	50.2

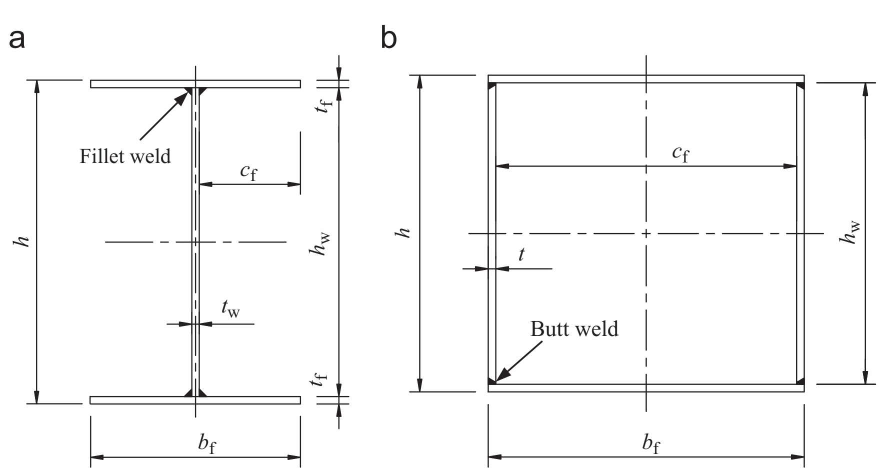

Fig. 1. Definition of symbols and weld locations for the specimens. (a) I-section and (b) SHS or RHS.

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