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Finite element modelling and design of welded stainless steel I-section columns

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ABSTRACT

Stainless steel is widely used in construction due to its combination of excellent mechanical properties, durability and aesthetics. Towards more sustainable infrastructure, stainless steel is expected be more commonly specified and to feature in more substantial structural applications in the future; this will require larger and typically welded cross-sections. While the structural response of cold-formed stainless steel sections has been extensively studied in the literature, welded sections have received less attention to date. The stability and design of conventionally welded and laser-welded austenitic stainless steel compression members are therefore the focus of the present research. Finite element (FE) models were developed and validated against a total of 59 experiments, covering both conventionally welded and laser-welded columns, for which different residual stress patterns were applied. A subsequent parametric study was carried out, considering a range of cross-section and member geometries. The existing experimental results, together with the numerical data generated herein, were then used to assess the buckling curves given in European, North American and Chinese design standards. Following examination of the data and reliability analysis, new buckling curves were proposed, providing, for the first time, design guidance for laser-welded stainless steel members.

1. Introduction

Stainless steel is used in a wide range of applications within the construction industry. To date, the predominant product types have been cold-formed sections, whose structural behaviour have been the most extensively explored in research and whose design have the broadest coverage in international structural design standards. In recent years, however, welded stainless steel sections, offering larger cross-section sizes and higher load-bearing capacities, have become more widely studied and employed in practice.

In conventional welding processes, two pieces of material are joined together by melting the base metal and an additional filler material. Some of the most commonly used welding methods include shielded metal arc welding (SMAW), gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW). An innovative alternative fabrication process is laser-welding, which uses laser beams to locally melt and join two pieces of metal with minimum heat input, producing smaller heat affected zones, lower thermal distortions and lower residual stresses than would typically arise from traditional welding processes. Laser-welded I-section columns may, due to the lower residual stress magnitudes, show superior structural performance over their conventionally welded counterparts, and exploration of this point is a key aspect of the paper.

The structural behaviour of welded stainless steel compression members has been studied for I-sections [1–5] and box sections [6,7], while the response of welded stainless steel I-section beams and plate girders has been examined in [8–11]. The key experimental results from these studies are employed herein for the validation of finite element models for both conventionally welded [1,2] and laser-welded [3] stainless steel I-section columns. The validated numerical models are used to generate a series of parametric data and the combined set of experimental and numerical results are employed to assess the design provisions in EN 1993–1-4 [12], Design Guide 27 [13], and CECS-410 [14] for stainless steel compression members.

2. Finite element modelling

2.1. Introduction

A numerical investigation into the behaviour of welded stainless steel I-section columns is presented in this section. The study was carried out using the general-propose finite element (FE) package ABAQUS. The models were validated against the experimental results from previous studies on the flexural buckling of welded stainless steel I-section columns [1–3]. For conventionally welded members, Burgan et al. [1] carried out 15 tests on I-section columns of austenitic grade EN 1.4301 and duplex grade EN 1.4462 stainless steel, with 6 buckling about the minor axis and 9 buckling about the major axis,

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while Yang et al. [2] performed 22 tests on I-section columns of austenitic grade EN 1.4301 and duplex grade EN 1.4462 stainless steel, with 12 buckling about the minor axis and 10 buckling about the major axis. For laser-welded members, Gardner et al. [3] conducted 22 tests on I-section columns of austenitic grades EN 1.4307, 1.4571 and 1.4404 stainless steel, with 14 buckling about the minor axis and 8 buckling about the major axis. The section sizes, stainless steel grades, axis of buckling and method of fabrication of these test specimens are summarised in Table 1, where L is the buckling length of the columns. The cross-sections (e.g. I-160 × 80 × 6 × 10) are designated as follows: I-section height (h) × section width (b_f) × web thickness (t_w) × flange thickness (t_f). The sum of the measured global geometric imperfection magnitude plus any additional applied load eccentricity, termed the total measured eccentricity w_m, is also tabulated; such measurements were not reported in [1]. The experimental results described in [1–3], including the full load-displacement histories, ultimate loads and failure modes, were used for the validation of the numerical models developed in this paper. Upon validation of the models, a series of parametric studies was carried out to assess the structural behaviour of both conventionally welded and laser-welded I-section columns.

Table 1
Summary of geometric dimensions, material and fabrication method of the column specimens.

Welding type and references	Cross-section	Specimen ID	Grade	Axis of buckling	L (mm)	h (mm)	b_f (mm)	t_w (mm)	t_f (mm)	w_m (mm)
Conventional welding	I-160 × 80 × 6 × 10	I160 × 80-C1	1.4301	Minor	650.0	158.00	79.50	6.00	9.80	–
Burgan et al. [1]	I-160 × 80 × 6 × 10	I160 × 80-C2			1248.0	161.70	80.80	6.00	9.80	–
	I-160 × 80 × 6 × 10	I160 × 80-C3			2046.0	161.40	79.80	6.00	9.80	–
	I-160 × 160 × 6 × 10	I160 × 160-C1			1248.0	158.30	159.20	6.00	9.80	–
	I-160 × 160 × 6 × 10	I160 × 160-C2			2049.0	157.70	159.90	6.00	9.90	–
	I-160 × 160 × 6 × 10	I160 × 160-C3			3347.0	158.00	160.10	6.00	9.80	–
	I-160 × 80 × 6 × 10	I160 × 80-C1	1.4301	Major	2048.0	157.00	79.40	6.00	9.80	–
	I-160 × 80 × 6 × 10	I160 × 80-C2			3343.0	157.60	78.90	6.00	9.80	–
	I-160 × 80 × 6 × 10	I160 × 80-C3			5031.0	158.50	80.10	6.00	9.80	–
	I-160 × 160 × 6 × 10	I160 × 160-C1			2025.0	158.30	160.00	6.00	9.90	–
	I-160 × 160 × 6 × 10	I160 × 160-C2			3348.0	158.40	159.80	6.00	9.90	–
	I-160 × 160 × 6 × 10	I160 × 160-C3			5145.0	158.00	159.20	6.00	9.90	–
	I-160 × 160 × 6 × 10	I160 × 160-C1	1.4462		2050.0	162.70	159.80	6.80	10.60	–
	I-160 × 160 × 6 × 10	I160 × 160-C2			3348.0	161.40	159.50	6.80	10.60	–
	I-160 × 160 × 6 × 10	I160 × 160-C3			5046.0	160.40	161.00	6.80	10.60	–
Conventional welding	I-150 × 150 × 6 × 10	H304–1500	1.4301	Minor	1875.7	150.20	149.10	6.00	10.00	2.42
Yang et al. [2]	I-150 × 150 × 6 × 10	H304–2000			2377.4	150.10	149.10	6.00	10.00	17.35
	I-150 × 150 × 6 × 10	H304–3000			3383.7	150.00	149.60	6.00	10.00	4.10
	I-150 × 150 × 6 × 10	H304–3500			3877.3	149.60	149.60	6.00	10.00	32.86
	I-150 × 150 × 6 × 10	H304–4000			4376.8	150.00	149.40	6.00	10.00	26.85
	I-150 × 120 × 6 × 10	H304–4000-B			4369.1	149.70	119.10	6.00	10.00	12.66
	I-150 × 150 × 6 × 10	H2205–1500	1.4462		1879.3	150.80	149.90	6.00	10.20	10.38
	I-150 × 150 × 6 × 10	H2205–2000			2378.9	150.40	150.00	6.00	10.20	5.02
	I-150 × 150 × 6 × 10	H2205–3000			3381.4	150.30	149.70	6.00	10.20	44.49
	I-150 × 150 × 6 × 10	H2205–3500			3880.8	150.10	151.20	6.00	10.20	43.12
	I-150 × 150 × 6 × 10	H2205–4000			4375.5	150.10	149.90	6.00	10.20	3.90
	I-150 × 120 × 6 × 10	H2205–4000-B			4378.2	150.30	120.10	6.00	10.20	13.77
	I-150 × 150 × 6 × 10	I304–2000	1.4301	Major	2377.1	149.80	149.20	6.00	10.00	8.17
	I-150 × 150 × 6 × 10	I304–3000			3373.5	150.30	149.30	6.00	10.00	3.64
	I-150 × 150 × 6 × 10	I304–3500			3874.8	110.40	149.50	6.00	10.00	5.00
	I-150 × 150 × 6 × 10	I304–4000			4374.4	150.20	150.00	6.00	10.00	4.02
	I-100 × 120 × 6 × 10	I304–4500			4872.9	100.00	120.10	6.00	10.00	0.93
	I-150 × 150 × 6 × 10	I2205–2000	1.4462		2380.2	150.30	150.70	6.00	10.20	10.17
	I-150 × 150 × 6 × 10	I2205–3000			3377.2	150.00	149.90	6.00	10.20	3.68
	I-150 × 150 × 6 × 10	I2205–3500			3883.7	150.40	150.90	6.00	10.20	1.36
	I-150 × 150 × 6 × 10	I2205–4000			4378.7	150.10	148.50	6.00	10.20	0.53
	I-110 × 150 × 6 × 10	I2205–4500			4876.0	110.80	150.40	6.00	10.20	0.93
Laser-welding	I-140 × 140 × 10 × 12	1A1	1.4307	Minor	1030.1	139.73	140.64	9.73	11.88	0.35
Gardner et al. [3]	I-140 × 140 × 10 × 12	1A2			2032.1	140.12	140.62	9.86	11.91	1.42
	I-50 × 50 × 4 × 4	2A1			1631.1	50.43	50.53	4.03	4.05	0.53
	I-50 × 50 × 4 × 4	2A2			1931.1	50.68	50.54	4.00	4.02	1.52
	I-160 × 82 × 10 × 12	3A1			1730.1	160.86	83.23	9.88	11.84	1.22
	I-160 × 82 × 10 × 12	3A2			2323.1	160.49	82.80	9.88	11.85	1.67
	I-102 × 68 × 5 × 5	4A1	1.4571		931.1	101.56	67.96	5.03	5.00	0.80
	I-102 × 68 × 5 × 5	4A2			1330.1	101.51	67.96	5.02	5.04	0.65
	I-102 × 68 × 5 × 5	4A3			1730.1	101.80	67.99	5.03	5.02	1.05
	I-102 × 68 × 5 × 5	4A4			2030.1	101.76	67.88	4.99	4.98	1.85
	I-102 × 68 × 5 × 5	4A5			2430.1	101.77	67.83	5.01	4.99	1.60
	I-150 × 75 × 7 × 10	5A1	1.4404		634.1	150.18	75.87	6.91	9.81	0.55
	I-150 × 75 × 7 × 10	5A2			1181.1	150.22	75.91	6.91	9.85	1.35
	I-150 × 75 × 7 × 10	5A3			2331.1	151.19	75.90	6.87	9.86	1.44
	I-50 × 50 × 4 × 4	2B1	1.4307	Major	680.1	51.00	50.56	3.99	3.93	1.05
	I-50 × 50 × 4 × 4	2B2			1130.1	50.59	50.60	4.04	3.86	1.90
	I-50 × 50 × 4 × 4	2B3			1580.1	50.28	50.32	3.99	3.98	2.15
	I-50 × 50 × 4 × 4	2B4			2530.1	50.90	50.55	4.01	3.94	3.00
	I-50 × 50 × 4 × 4	2B5			3030.1	50.21	50.55	4.00	3.91	3.40
	I-102 × 68 × 5 × 5	4B1	1.4571		1330.1	101.91	67.51	4.99	4.94	1.05
	I-102 × 68 × 5 × 5	4B2			2330.1	102.37	67.94	5.21	5.01	3.15
	I-102 × 68 × 5 × 5	4B3			3080.1	102.11	67.93	5.04	5.01	3.90

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