Experiments on Stainless Steel Hollow Sections – Part 2: Member Behaviour of Columns and Beams

L Gardner and D A Nethercot

Abstract

A series of tests were performed on cold-formed austenitic stainless steel square, rectangular and circular hollow section (SHS, RHS and CHS respectively) members. 22 flexural buckling tests and 9 three-point bending tests were carried out. Measurements were taken of cross-section geometry, local and global initial geometric imperfections and material properties in tension and compression. Results from the tests, including full load-deformation histories are presented; these have served as a basis for calibration of numerical models and for the development and verification of a new approach to structural stainless steel design. The test results represent a major contribution to the pool of available test data for stainless steel structures. Combining these data with all previously available test results for stainless steel hollow section columns and beams in a comparison against strengths predicted by Eurocode 3: Part 1.4 shows, on average, the Eurocode method is overly conservative.

Introduction

In the companion paper [1] the authors have explained how a good understanding of basic material stress-strain behaviour plus an appreciation of the response of plate elements in compression is essential to the derivation of appropriate design rules for stainless steel members if such rules are to properly recognise the main physical characteristics of the material. The important role played by test data in calibrating design rules has also been emphasised.

This paper complements the companion paper [1] by reporting on a new series of laboratory tests on stainless steel columns and beams. Results for twenty-two axially loaded column tests plus nine beam tests on square and rectangular hollow section (SHS and RHS, respectively) members are presented. In all cases the main tests have been supported with measurements of basic material properties (including tensile and compressive coupon tests and stub column tests) and geometrical imperfections, reported in [1]. Full load-deformation histories have been recorded for each main test; these have also been used in the validation of the parallel numerical study [2], which, together with all other aspects of the whole programme, is fully reported in [3].

During the past decade several series of tests on stainless steel hollow section members have been conducted, and these are summarised (including the current series) in Table 1. The behaviour of stub columns is not considered herein; results are presented and discussed in [1] and included in Table 1 simply for completeness. This shows how for SHS and RHS members the present study constitutes approximately 50 percent of the available test data.

Column tests

A diagram of the essential features of the column test arrangement is shown as Figure 1. All tests used pinned end conditions and column lengths were between 1 m and 2 m. Although tested under load-control conditions, the use of a stiff rig together with large-bore rigid hydraulic piping ensured that the apparatus was capable of following unloading behaviour. The overall capacity of the rig was 300 T.

Both ends of the specimens were machined flat and square before insertion into the apparatus, where they bore against ground plates fixed to hardened steel knife edges as illustrated in Figure 2. The sliding clamp arrangement of Figure 3 accommodated a range of different section sizes, whilst the spring system of Figure 4 ensured no unwanted end translation whilst permitting free end rotation. The specimens were located such that the geometric centrelines of the column ends were acting on the centreline of the knife edges. Initial global column imperfections were measured using feeler gauges and a straight edge; results are provided in Table 2.

In addition to the displacement transducers illustrated in Figure 1, four strain gauges were affixed to the outside faces of the specimens at mid-height at a distance of four times the plate thickness from each corner. The strain gauges were initially used to assess uniformity of load introduction and as the tests progressed to investigate extreme fibre strains. Material properties for each of the column specimens are available in the companion paper [1].

Column results

Figure 5 presents a full set of 22 load-lateral displacement curves; Figure 5a shows the 7 tests on SHS of nominal length 2 m, Figure 5b shows the 8 tests on RHS of nominal length 2 m, and Figure 5c shows the 6 tests on RHS of nominal length 1 m. A full load history was not recorded for the SHS 80x80x4-LC-1.9m specimen. In every case the curves show the ability of the test rig to cater for controlled post ultimate load behaviour. Figure 5 demonstrates, as expected, that the columns with the more slender cross-sections reach ultimate load at relatively small levels of lateral deflection, whereas the columns with the more stocky cross-sections reach ultimate load at higher lateral deflections.

The predominant mode of failure of the columns was overall flexural buckling, though there was clear evidence of interaction between local and global effects. For the columns with the more slender cross-sections, elastic local buckling was clearly visible at low loads levels. As the loading and lateral deflections increased, the elastic local buckles ran into a single plastic buckle close to the mid-height of the column. This progression can be observed in Figures 6(a), 6(b) and 6(c). For the columns with the more stocky cross-sections, there were no visible elastic local buckles during loading and the lateral deflections were more pronounced. Permanent plastic deformations were observed upon unloading, signifying yielding of the cross-section close to the mid-height of the column.

Beam tests

A diagram of the 3-point bending test arrangement for the beam specimens is given as Figure 7. Spans were either 1000 mm or 1100 mm and testing was again load-controlled. Specimens extended approximately 100 mm beyond the simple supports at each end, and in all cases bending was about the major axis. Steel plates (of width 40 mm and thickness 10 mm) were employed at the points of support and load introduction to prevent local failure. Table 4 gives the average measured dimensions for each specimen. Material properties for each of the beam specimens are available in the companion paper [1].

Beam results

The results of the beam tests are summarised in Table 5. Figure 8 provides a set of 9 bending moment – mid-span deflection curves for the tests. The shape of these broadly accords with the proportions of the individual cross-sections. For example, the three most peaky curves correspond to the three sections having Class 4 properties according to Eurocode 3: Part 1.4 [14], whilst that for the one section having Class 3 properties unloads almost as sharply. In contrast, the 4 sections having Class 1 properties exhibit substantial plateaus, indicating the scope for considerable deformation before any unloading is triggered.

Figure 9 shows the state of one of the beams after testing. This specimen (SHS 100 x 100 x 3) was one of those with properties corresponding to a Eurocode 3 Class 1 cross-section and would, therefore, be expected to behave in a ductile fashion. The mode of failure exhibits buckling of both the compression flange and the upper portion of the web at mid-span.

In Figure 10, the 9 moment-deflection curves of Figure 8 have been normalised by the simple plastic moment resistance, M_{pl} for each cross-section, defined as the product of the 0.2% proof stress and the plastic section modulus. For the 4 Class 1 specimens, the ultimate moment from the tests exceeds M_{pl} by an average of 42%. The Class 3

100x100x4 specimen exceeds M_{pl} by over 10% and exceeds the simple elastic moment resistance, M_{el} by some 30%. Interestingly, even 3 out of the 4 Class 4 cross-sections comfortably exceed M_{pl} , whereas the very slender 100x100x2 specimen falls just below M_{el} .

For the Class 1 cross-sections the primary reason for the underestimate of capacity by the design code is the significant strain hardening, which is of course neglected by the assumed bi-linear material model. For the Class 3 and 4 cross-sections the poor prediction of strength may also be attributed to strain hardening and possibly inappropriate cross-section classification limits.

Comparison with Eurocode 3: Part 1.4

Resistances of all the available tests on stainless steel hollow section columns and beams (including the 22 column specimens and the 9 beam specimens from the current study) have been calculated using the rules of Eurocode 3: Part 1.4. These calculations have employed measured dimensions and measured material properties and all partial factors have been set to unity. Thus the comparisons with the test loads provide a clear illustration of the accuracy with which the design formulae are able to predict resistance. Figures 11 and 12 display the results in form of block diagrams for all specimens for each of the 4 Eurocode 3: Part 1.4 classes. For columns the predictions are quite good for classes 1-3 but somewhat conservative for members containing Class 4 elements. In the case of beams, all classes are under predicted, by as much of 30% in the case of Class 1 cross-sections.

Also shown on these figures are block diagrams using the author's proposed design method [15]. This does not use the concept of classification of the cross-section but employs a continuous approach to the determination of plate strength based on plate slenderness. Figure 11 shows marginal improvement for the Class 1-3 sections but a significant gain for those members containing Class 4 plate elements, for which the author's proposal is very slightly conservative. In the case of the members subjected to bending, significant improvements may be observed for all classes of cross-sections.

Conclusions

The results of 22 column tests and 9 beam tests on stainless steel SHS, RHS and CHS members are reported. Full load-deformation histories and all test variables are provided so as to facilitate future use of the results for validation of numerical studies, calibration of design approaches or for other purposes. Comparison of the maximum test loads against the prediction of Eurocode 3: Part 1.4 shows the design procedure to be overly conservative. An improved procedure is reported in [15].

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Figure 1: Essential features of column test arrangement

(a) Top detail

(b) Base detail

Figure 2: End conditions for pin-ended columns

Figure 3: System of sliding clamps to accommodate different cross-section sizes

Figure 4: Safety features on top knife-edge

Figure 5(a): Load-lateral deflection curves for SHS columns

Figure 5(b): Load-lateral deflection curves for RHS columns (nominal length 2 m)

Figure 5(c): Load-lateral deflection curves for RHS columns (nominal length 1 m)

Figure 6: Local buckling and failure of pin-ended columns

Figure 7: Location of displacement transducers for bending tests

Figure 8: Bending moment-vertical deflection curves for beam tests

Figure 9: Elevation of deformed SHS 100×100×3 simply-supported beam

Figure 10: Bending moment (normalised by the simple plastic moment resistance)-vertical deflection at mid-span curves for the 9 beam tests

Figure 11: Comparison between Eurocode 4 Part 1.4 and proposed design method for prediction of flexural buckling resistance from tests

Figure 12: Comparison between Eurocode 4 Part 1.4 and proposed design method for prediction of bending resistance from tests

Table 1: Tests conducted on stainless steel hollow sections (as part of the present study and by other investigators)

Member type	Structural configuration	No. of SHS tested	No. of RHS tested	No. of CHS tested	References
Columns	Stub columns	20 (17)	18 (16)	10 (4)	[1], [4], [5]
Columns	Flexural buckling – pin ends	16 (8)	20 (14)	10	[3], [4], [5], [6], [7]
Columns	Flexural buckling – fixed ends	8	16	12	[8], [9], [10]
Beams	In-plane bending	11 (5)	12 (4)	8	[3], [5], [7], [11], [12], [13]
Beam-columns	Axial load plus uniaxial bending	4	8	8	[5], [7]
Total:	All	59 (30)	74 (34)	48 (4)	181 (68)

Note: Bracketed values indicate the number of tests (of the total) carried out in the present study

Table 2(a): Measured dimensions and imperfections for pin-ended SHS columns

Column identification	Length, L (mm)	Depth, D (mm)	Breadth, B (mm)	Thickness, t (mm)	Internal corner radius, r_i (mm)	Area, A (mm ²)	Imperfection, v_0 (mm)	Imperfection, v_1 (mm)
SHS 80×80×4-LC-1.9m	1899.8	79.7	79.6	3.78	4.5	1106	0.4	0.4
SHS 80×80×4-LC-2m	2000.7	79.5	79.8	3.74	4.5	1093	0.4	0.1
SHS 100×100×2-LC-2m	2000.3	99.8	99.9	1.86	1.3	723	0.1	0.1
SHS 100×100×3-LC-2m	2000.4	100.1	100.2	2.83	1.5	1089	0.1	1.0
SHS 100×100×4-LC-2m	2000.4	99.8	100.0	3.77	4.5	1410	0.6	0.2
SHS 100×100×6-LC-2m	1999.9	100.1	100.5	5.92	5.8	2145	0.3	0.3
SHS 100×100×8-LC-2m	1999.6	100.1	100.7	7.96	8.0	2778	0.3	0.4
SHS 150×150×4-LC-2m	1999.8	150.4	150.0	3.77	5.8	2159	0.0	0.2

Notes: v_0 is imperfection in buckling direction
 v_1 is imperfection at 90° to buckling direction

Table 2(b): Measured dimensions and imperfections for pin-ended RHS columns

Column identification	Buckling axis	Length, L (mm)	Depth, D (mm)	Breadth, B (mm)	Thickness, t (mm)	Int. corner rad., r_i (mm)	Area, A (mm ²)	Imperfection, v_0 (mm)	Imperfection, v_1 (mm)
RHS 60×40×4-LCJ-2m	major	2000.1	60.0	40.0	3.83	2.9	675	1.0	0.0
RHS 100×50×2-LCJ-2m	major	2000.2	99.8	49.8	1.83	2.3	523	0.6	0.0
RHS 100×50×3-LC-2m	minor	2000.2	100.1	50.1	2.87	3.1	807	1.1	0.3
RHS 100×50×4-LC-2m	minor	2000.2	99.7	49.9	3.70	3.6	1018	0.8	0.1
RHS 100×50×6-LC-2m	minor	2000.2	100.0	50.0	5.96	5.5	1559	0.0	0.8
RHS 120×80×3-LC-2m	minor	1999.0	120.0	80.2	2.91	4.6	1101	1.1	0.5
RHS 120×80×6-LC-2m	minor	2000.4	120.0	80.4	5.87	7.0	2115	0.5	0.4
RHS 150×100×4-LC-2m	minor	1999.5	149.8	99.9	3.79	5.6	1787	0.1	0.2
RHS 60×40×4-LC-1m	minor	1000.2	59.9	39.9	3.82	2.9	673	0.2	0.1
RHS 100×50×2-LC-1m	minor	1000.2	99.8	50.0	1.82	2.3	522	0.1	0.0
RHS 100×50×3-LC-1m	minor	1000.1	100.1	50.0	2.86	3.1	804	1.0	0.1
RHS 100×50×4-LC-1m	minor	999.6	99.7	50.3	3.73	3.6	1028	0.6	0.1
RHS 100×50×6-LC-1m	minor	999.8	100.0	50.1	5.94	5.6	1555	0.1	0.3
RHS 120×80×3-LC-1m	minor	1000.6	120.0	80.2	2.86	4.6	1083	1.0	0.0

Notes: v_0 is imperfection in buckling direction

v_1 is imperfection at 90° to buckling direction

Table 3(a): Results from pin-ended SHS column tests

Column identification	$\sigma_{0.2}$ (N/mm ²)	E_0 (N/mm ²)	$\bar{\lambda}$	$\beta_{\max}$	Cross-section classification ¹	A_{eff}/A_g ¹	Ultimate load, F_u (kN)
SHS 80×80×4-LC-1.9m	416	203200	0.89	0.91	1	1.00	293
SHS 80×80×4-LC-2m	416	203200	0.94	0.92	1	1.00	307
SHS 100×100×2-LC-2m	370	207125	0.67	2.23	4	0.72	176
SHS 100×100×3-LC-2m	379	208800	0.68	1.46	4	0.96	350
SHS 100×100×4-LC-2m	437	203400	0.76	1.18	4	1.00	464
SHS 100×100×6-LC-2m	473	197900	0.82	0.78	1	1.00	842
SHS 100×100×8-LC-2m	330	205200	0.69	0.46	1	1.00	770
SHS 150×150×4-LC-2m	294	195350	0.42	1.51	4	0.95	692

Notes: ¹ According to Eurocode 3 Part 1.4

$\beta_{\max}$ is defined by Equation 6 of the companion paper and represents the slenderness of the most slender element in the cross-section

Table 3(b): Results from pin-ended RHS column tests

Column identification	Buckling axis	$\sigma_{0.2}$ (N/mm ²)	E_0 (N/mm ²)	$\bar{\lambda}$	$\beta_{\max}$	Cross-section classification ¹	A_{eff}/A_g ¹	Ultimate load, F_u (kN)
RHS 60×40×4-LCJ-2m	major	469	193100	1.47	0.72	1	1.00	109
RHS 100×50×2-LCJ-2m	major	370	205900	0.75	2.27	4	0.81	157
RHS 100×50×3-LC-2m	minor	455	200900	1.46	1.61	4	0.94	113
RHS 100×50×4-LC-2m	minor	439	203900	1.45	1.20	4	1.00	165
RHS 100×50×6-LC-2m	minor	494	206267	1.61	0.77	1	1.00	234
RHS 120×80×3-LC-2m	minor	429	197300	0.90	1.88	4	0.90	313
RHS 120×80×6-LC-2m	minor	466	192300	0.99	0.96	1	1.00	677
RHS 150×100×4-LC-2m	minor	319	200260	0.62	1.54	4	0.96	515
RHS 60×40×4-LC-1m	minor	469	193100	1.02	0.72	1	1.00	169
RHS 100×50×2-LC-1m	minor	370	205900	0.64	2.28	4	0.81	163
RHS 100×50×3-LC-1m	minor	455	200900	0.73	1.62	4	0.94	304
RHS 100×50×4-LC-1m	minor	439	203900	0.72	1.19	4	1.00	422
RHS 100×50×6-LC-1m	minor	494	206267	0.80	0.77	1	1.00	624
RHS 120×80×3-LC-1m	minor	429	197300	0.45	1.91	4	0.89	448

Notes: ¹ According to Eurocode 3 Part 1.4

$\beta_{\max}$ is defined by Equation 6 of the companion paper and represents the slenderness of the most slender element in the cross-section

Table 4: Measured dimensions for SHS and RHS simply-supported beams

Specimen identification	Span, Ls (mm)	Depth, D (mm)	Breadth, B (mm)	Thickness, t (mm)	Internal corner radius, r _i (mm)	Area, A (mm ²)
SHS 80×80×4- B1	1100.0	79.6	79.7	3.75	4.4	1099
SHS 100×100×2- B1	1000.0	99.9	99.9	1.84	1.3	715
SHS 100×100×3- B1	1100.0	100.1	100.3	2.84	1.5	1091
SHS 100×100×4- B1	1100.0	99.8	99.8	3.79	4.5	1415
SHS 100×100×8-B1	1100.0	100.7	100.2	7.92	8.0	2768
RHS 60×40×4- B1	1100.0	59.9	39.9	3.79	2.9	669
RHS 100×50×2- B1	1000.0	99.7	49.8	1.79	2.3	514
RHS 100×50×3- B1	1100.0	100.1	50.0	2.88	3.2	810
RHS 100×50×4- B1	1100.0	99.7	49.9	3.68	3.6	1014

Table 5: Summary of results from simply-supported beam tests

Specimen identification	$\sigma_{0.2}$ (N/mm ²)	E_0 (N/mm ²)	$\beta_{\max}$	Cross-section classification ¹	W/W_{pl} ¹	$\sigma_{0.2} W_{el}$	$\sigma_{0.2} W_{pl}$	Ultimate bending moment, M_u (kNm)
SHS 80×80×4- B1	416	203200	0.92	1	1.00	10.8	12.8	17.5
SHS 100×100×2- B1	370	207100	2.25	4	0.72	8.4	9.7	8.0
SHS 100×100×3- B1	379	208800	1.46	4	0.84	13.0	15.0	17.2
SHS 100×100×4- B1	437	203200	1.17	4	0.85	18.8	22.0	24.5
SHS 100×100×8-B1	330	205200	0.47	1	1.00	25.2	31.1	44.2
RHS 60×40×4- B1	469	193100	0.47	1	1.00	4.8	6.0	10.5
RHS 100×50×2- B1	370	205900	1.14	4	0.81	5.0	6.1	7.1
RHS 100×50×3- B1	455	200900	0.78	1	1.00	9.4	11.7	15.4
RHS 100×50×4- B1	439	203900	0.58	1	1.00	11.0	13.9	21.6

Notes: ¹ According to Eurocode 3 Part 1.4 (where $W = W_{pl}$ for Class 1-2 sections, $W = W_{el}$ for Class 3 sections and $W = W_{eff}$ for Class 4 sections)

$\beta_{\max}$ is defined by Equation 6 of the companion paper and represents the slenderness of the most slender element in the cross-section