TESTS OF COLD-FORMED STAINLESS STEEL TUBULAR COLUMNS

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Abstract

The paper summarises a series of tests on cold-formed stainless steel tubular structures recently conducted in Singapore and Hong Kong. The tubular structures consist of circular, square and rectangular hollow sections subjected to compressive axial force. The experimental investigation focused on the strength and behaviour of stainless steel columns. The test strengths were compared with design strengths calculated using the American, Australian/New Zealand and European specifications for cold-formed stainless steel structures. In addition, current and future research on cold-formed stainless steel tubular structures (which is ongoing and to be carried out by the author and his co-workers), will also be described in this paper. The research focuses on high strength material that includes the experimental investigation of material properties, columns, beams, beam-columns, web crippling and welded connections.

1 INTRODUCTION

Cold-formed stainless steel tubular structures are being increasingly used for structural applications. This is due to the aesthetic appearance, high corrosion resistance, ease of maintenance and ease of construction. There are several specifications available for the design of cold-formed stainless steel structural members. These include the American Society of Civil Engineers (ASCE) Specification for the design of cold-formed stainless steel structural members published in 1991 [1] and 2003 [2], the Australian/New Zealand Standard (Aust/NZS) for cold-formed stainless steel structures [3], and the European Code 3 (EC3) design of steel structures, part 1.4: supplementary rules for stainless steels [4]. In addition, design rules for stainless steel columns are also proposed by other researchers, such as Rasmussen and Hancock [5], Rasmussen and Rondal [6, 7], Gardner and Nethercot [8], and Nethercot and Gardner [9]. The column design rules in the specifications as well as the design rules proposed by the aforementioned researchers are mainly based on the investigations of *pin-ended* columns cold-rolled from annealed flat strips of austenitic stainless steel types 304 and 304L.

In practice, normally there is certain degree of rotational restraint at the end supports, and the column is somewhere between fixed and pinned. However, limited test data is available on *fixed-ended* cold-formed stainless steel tubular columns. Hence, it is also important to investigate the other limiting case of fixed supports. In addition, the proportional limit for carbon and low-alloy steels is assumed to be at least 70% of the yield point, but for stainless steel the proportional limit ranges from approximately 36 to 60% of the yield strength [10]. Therefore, the lower proportional limits affect the buckling behaviour of stainless steel structural members. The author and his co-workers performed a series of tests to examine the strength and behaviour of fixed-ended cold-formed stainless steel tubular columns, which are summarised in this paper. The findings of the research have been published in international journals, and reference is made to these publications for further details.

The current design rules in the American, Australian/New Zealand and European specifications for cold-formed stainless steel structures were developed mainly based on investigations of structural members that were cold-formed from normal strength austenitic stainless steel of types 201, 301, 304 and 316. There are not many test data being reported on high strength stainless steel structural members such as duplex (austenitic-ferritic) and high strength austenitic stainless steel. The current design rules may not be applicable to high strength structural members. Therefore, there is a need to investigate the appropriateness of the current design rules for high strength stainless steel structural members. The current and future research on cold-formed high strength stainless steel tubular structures being and to be conducted by the author and his co-workers is described in this paper.

2 RECENT RESEARCH

2.1 Column tests of square and rectangular hollow sections

Test specimens and material properties

An experimental investigation into the strength and behaviour of cold-formed stainless steel square hollow section (SHS) and rectangular hollow section (RHS) columns are detailed in Liu and Young [11], and Young and Liu [12], respectively. A total of 36 columns were compressed between fixed ends. The specimens were tested over a range of column lengths from 360 to 3600 mm in order to obtain a column curve for each series of test. The test specimens were cold-rolled from annealed flat strips of austenitic stainless steel type 304. The failure modes of the columns involved local buckling, overall flexural buckling and interaction of local and overall buckling.

Two series of SHS having nominal dimensions of 70 by 70 mm with thickness of either 2 or 5 mm were tested. The two test series were S1 and S2 of section sizes 70×70×2 and 70×70×5 mm, respectively. The measured 0.2% proof stress obtained from tensile coupon tests of the finished specimens are 337 and 444 MPa for Series S1 and S2, respectively, and the measured 0.2% proof stress obtained from stub column tests are 381 and 497 MPa for Series S1 and S2, respectively. The longest specimen lengths produced l_e/r_y ratios of 65 and 69 for Series S1 and S2, respectively, where l_e is the column effective length and r_y is the radius of gyration about the y-axis.

Four series of RHS having a nominal depth of 120 mm and the nominal width of either 40 or 80 mm were tested. The nominal thickness ranged from 2 to 6 mm. The four test series were R1, R2, R3 and R4 of section sizes 120×40×2.0, 120×40×5.3, 120×80×2.8 and 120×80×6.0 mm, respectively. The measured 0.2% proof stress for the four test series obtained from tensile coupon and stub column tests were in the range of [350 – 443] MPa and [295 – 498] MPa, respectively. The longest specimen lengths produced l_e/r_y ratios of 104, 113, 55 and 57 for Series R1, R2, R3 and R4, respectively.

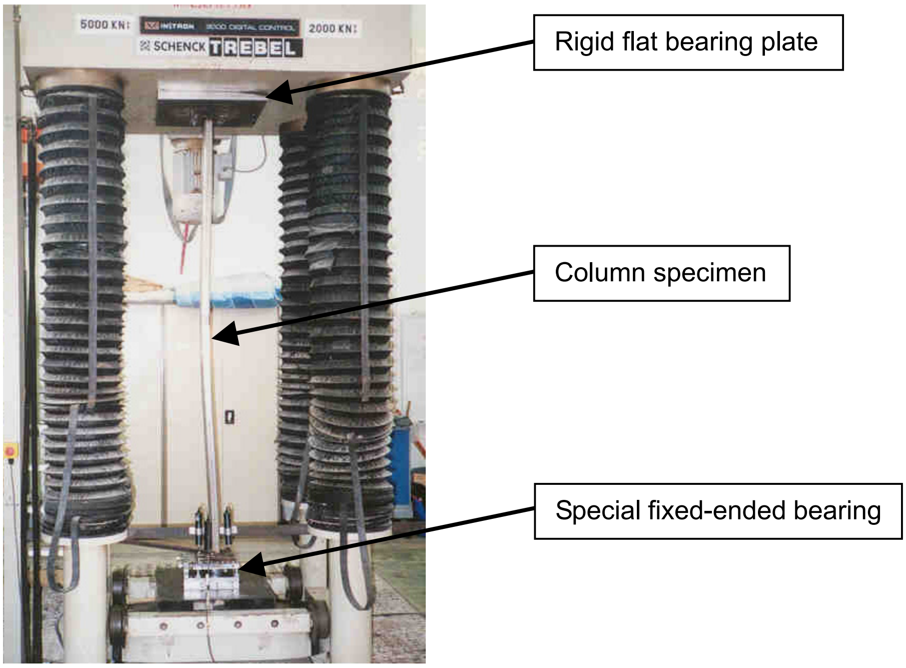

Figure 1 Test set-up

Test set-up

Fig.1 shows a typical test set-up for the columns. A servo-controlled hydraulic testing machine was used to apply compressive axial force to the specimen. A rigid flat bearing plate was connected to the upper end support, and the top end plate of the specimen was bolted to the rigid flat bearing plate, which was restrained against the minor and major axis rotations as well as twist rotations and warping. Hence, the top end of the column was fixed in position. The load was then applied at the lower end through a special fixed-ended bearing. Initially, the special fixed-ended bearing was free to rotate in any direction. The ram of the actuator was moved slowly toward the specimen until the bearing was in full contact with the bottom end plate of the specimen having a small initial load of approximately 2 kN. This procedure eliminated any possible gaps between the special fixed-ended bearing and the bottom end plate of the specimen. The bottom end plate of the specimen was bolted to the special fixed-ended bearing, and the bearing was then restrained against rotations and twisting by using vertical and horizontal bolts, respectively. The vertical and horizontal bolts of the special fixed-ended bearing were used to lock the bearing in position after full contact was achieved. The special fixed-ended bearing was considered to restrain both minor and major axis rotations as well as twist rotations and warping. Three displacement transducers were positioned on the fixed-ended bearing to measure the axial shortening of the specimen. Displacement control was used to drive the hydraulic actuator at a constant speed of 0.7 mm/min. The static load was recorded by pausing the applied straining for 1.5 minutes near the ultimate load. This allowed the stress relaxation associated with plastic straining to take place.

Measured geometric imperfections

Initial overall geometric imperfections of the specimens were measured prior to testing. Geometric imperfections were measured for both *x* and *y* axes of the specimens for SHS, and minor axis for RHS. The maximum overall flexural imperfections at mid-length were 1/950, 1/950, 1/1840, 1/1830, 1/1200 and 1/790 of the specimen length for Series S1, S2, R1, R2, R3 and R4, respectively. The initial local geometric imperfections of the specimens were not measured.

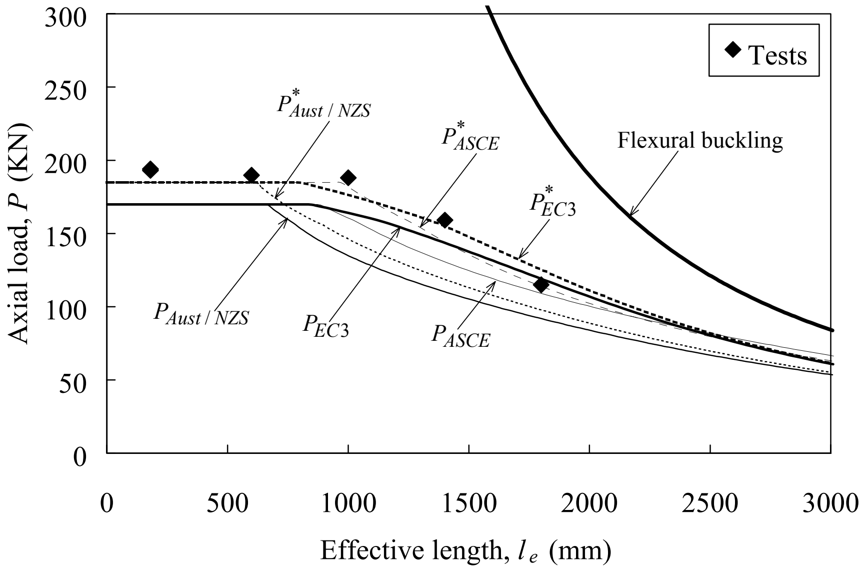

Figure 2 Fixed-ended column curves for SHS Series S1

Comparison of test strengths with design strengths

The test strengths are compared with the *unfactored* design strengths (nominal strengths) predicted using the American [1], Australian/New Zealand [3] and European [4] specifications for cold-formed stainless steel structures. The design strengths were calculated using the material properties obtained from the finished specimens, which takes into account of the enhancement of the material properties due to cold--working. Tensile coupon tests and stub column tests were conducted to determine the material properties, in which the 0.2% proof stresses were used as the corresponding yield stresses. The design strengths were calculated based on an effective length of one-half of the column length.

For SHS Series S1 (70×70×2), the comparison of the test strengths with the design strengths is shown in Fig. 2, where P_{ASCE}, $P_{Aust/NZS}$ and P_{EC3} are the design strengths calculated using the material properties obtained from tensile coupon tests for American, Australian/New Zealand and European specifications, respectively. The P^*_{ASCE}, $P^*_{Aust/NZS}$ and P^*_{EC3} are the design strengths calculated using the material properties obtained from stub column tests. For RHS Series R3 (120×80×2.8), the comparison of the test strengths with the design strengths is shown in Fig. 3. The theoretical elastic flexural buckling loads of the fixed-ended columns are also shown in Figs 2 and 3. It is shown that the design strengths predicted by the three specifications are generally conservative for the tested fixed-ended cold-formed stainless steel SHS and RHS columns. The reliability of the design rules has been evaluated using reliability analysis. The reliability analysis shown that the design rules in the Australian/New Zealand Standard are generally more reliable than the design rules in the American and European specifications. Further details of the investigation of cold-formed stainless steel SHS and RHS columns are described by Liu and Young [11], and Young and Liu [12], respectively.

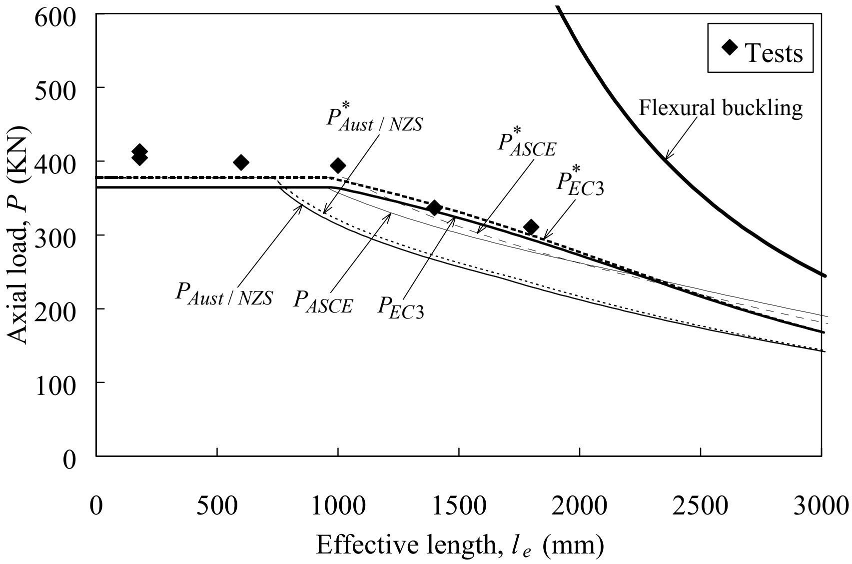

Figure 3 Fixed-ended column curves for RHS Series R3

2.2 Column tests of circular hollow section

Test specimens and material properties

A test program on cold-formed stainless steel circular hollow section (CHS) columns is described in Young and Hartono [13]. A total of 16 fixed-ended columns were tested. Three series of CHS were tested over a range of column lengths, which involved local buckling and overall flexural buckling. The test specimens had an average measured thickness of 2.78, 3.34 and 4.32 mm, and the average outer diameter of 89.0, 168.7 and 322.8 mm with a maximum value of COV of 0.027 for test Series C1, C2 and C3, respectively. The average measured outer diameter to thickness (D/t) ratios are 32.0, 50.5 and 74.7 for Series C1, C2 and C3, respectively. Each specimen was cut to a specified length ranging from 550 to 3000 mm. The specimens were labelled such that the test series and specimen length could be identified from the label. For example, the label "C1L2500" defines the specimen belonged to test Series C1 having a column length of 2500 mm. The test specimens were cold-rolled from annealed flat strips of type 304 stainless steel. The measured 0.2% proof stress obtained from tensile coupon tests of the finished specimens are 270, 288 and 261 MPa for Series C1, C2 and C3, respectively.

Test set-up and measured geometric imperfections

The test rig used for CHS columns is identical to those used for the SHS and RHS column tests. A typical CHS column test is shown in Fig. 4. Initial overall geometric imperfections of the specimens were measured. The geometric imperfections were measured along the weld of the specimens. The maximum overall flexural imperfections at mid-length were 1/630, 1/2200 and 1/2000 of the specimen length for Series C1, C2 and C3, respectively. Flexural buckling and local buckling failure modes of CHS columns are shown in Fig. 5.

Comparison of test strengths with design strengths

The test strengths are compared with the unfactored design strengths predicted using the American [1] and Australian/New Zealand [3] specifications for cold-formed stainless steel structures, and the European (Euro Inox) design manual [14] for structural stainless steel. Furthermore, the test strengths are also compared with the column strengths obtained from the design rules proposed by Rasmussen and Hancock [5], and Rasmussen and Rondal [6]. Table 1 shows the comparison of the test strengths with design strengths for Series C1. The ratios of the test strength to design strength for the American Specification (P_{EXP}/P_{ASCE}), Australian/New Zealand Standard ($P_{EXP}/P_{Aust/NZS}$), European design manual (P_{EXP}/P_{Euro}), Rasmussen and Hancock ($P_{EXP}/P_{R\&H}$) and Rasmussen and Rondal ($P_{EXP}/P_{R\&R}$) are shown in Table 1. It is shown that the design strengths predicted by the three specifications are generally unconservative for the tested fixed-ended cold-formed stainless steel CHS columns. However, the design strengths predicted by Rasmussen and Rondal [6] are generally conservative. The reliability of the design rules has been evaluated using reliability analysis. The details of the test program and the comparison of test strengths with design strengths are described by Young and Hartono [13].

Figure 4 Typical CHS column test

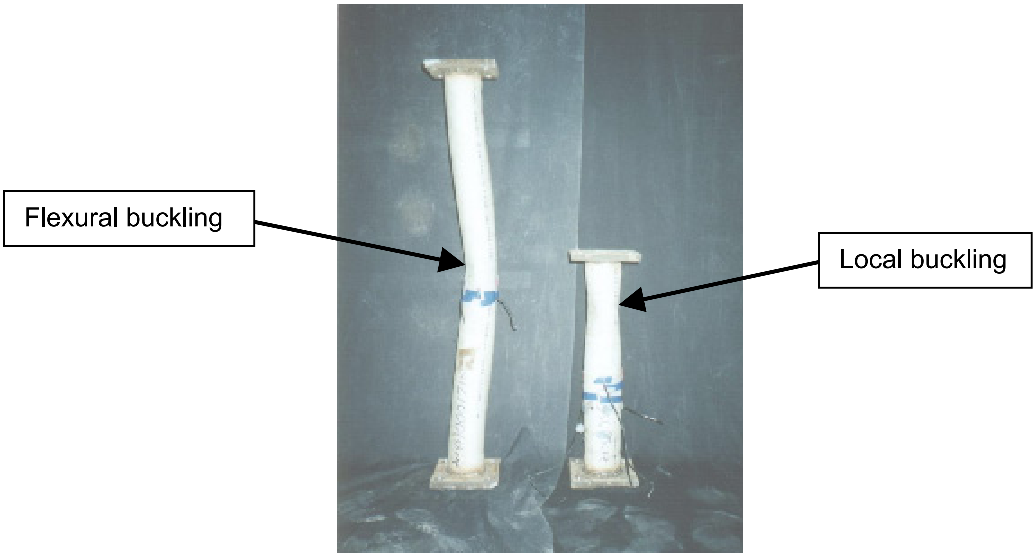

Figure 5 Flexural buckling and local buckling of CHS columns

Table 1 Comparison of test strengths with design strengths for CHS Series C1

Specimen	Test	Comparison				
	P_{Exp}	$\frac{P_{Exp}}{P_{ASCE}}$	$\frac{P_{Exp}}{P_{Aust/NZS}}$	$\frac{P_{Exp}}{P_{Euro}}$	$\frac{P_{Exp}}{P_{R\&H}}$	$\frac{P_{Exp}}{P_{R\&R}}$
	(kN)					
C1L0550	235.2	1.16	1.16	1.16	1.29	1.29
C1L1000	198.4	0.98	0.98	0.98	1.09	1.09
C1L1500	177.4	0.87	0.87	0.87	0.99	1.02
C1L2000	165.1	0.82	0.93	0.81	0.99	1.05
C1L2500	151.6	0.85	0.98	0.79	0.96	1.03
C1L3000	133.4	0.84	0.96	0.74	0.89	0.95
Mean	---	0.92	0.98	0.89	1.04	1.07
COV	---	0.140	0.098	0.171	0.135	0.109
Safety Index, β_o	---	2.19	2.47	1.41	2.63	2.93
Note: 1 kip = 4.45 kN. COV = coefficient of variation.						

3 CURRENT AND FUTURE RESEARCH

The current and future research on stainless steel structures (ongoing and to be carried out by the author and his co-workers), focuses on cold-formed high strength tubular structures. The high strength material includes duplex and high strength austenitic stainless steel. As mentioned in the introduction, the current design rules in the American [1, 2], Australian/New Zealand [3] and European [4] specifications were developed mainly based on normal strength austenitic stainless steel of types 201, 301, 304 and 316. Therefore, there is a need to investigate the cold-formed high strength stainless steel structures. The current and future research is mainly on the experimental investigation of cold-formed high strength stainless steel tubular structures, which includes the following:

- *Material properties:* Compression coupon tests; tensile coupon tests of complete cross-section; tensile coupon tests at elevated temperatures; stub column tests; and residual stress measurements.
- *Geometric imperfections:* Measurements of initial local and overall geometric imperfections.
- *Columns:* Fixed-ended column tests; and finite element analysis.
- *Beams:* Pure bending tests; web crippling tests; and combined bending and web crippling tests.
- *Beam-columns:* SHS beam-column tests.
- *Welded connections:* Tests of T- and X-joints in SHS and RHS; and finite element analysis.

4 CONCLUSIONS

The experimental investigation of cold-formed stainless steel tubular structures performed in Singapore and Hong Kong has been summarised in this paper. A series of fixed-ended column tests on square, rectangular and circular hollow sections has been conducted. The test strengths were compared with the design strengths predicted using the American, Australian/New Zealand and European specifications for cold-formed stainless steel structures. The test strengths were also compared with the design strengths calculated from the design rules proposed by other researchers. It is shown that the design strengths predicted by the three specifications are generally conservative for the tested fixed-ended cold-formed stainless steel SHS and RHS columns. However, this is not the case for CHS columns, where the design strengths predicted by the three specifications are generally unconservative. The design strengths predicted by Rasmussen and Rondal are generally conservative for CHS columns. Furthermore, the current and future research on cold-formed high strength stainless steel tubular structures (ongoing and to be carried out by the author and his co-workers), has been listed in this paper.

5 ACKNOWLEDGMENT

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