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Y. Q. Li

D. H. Wen

L. P. Wang

Z. Y. Shen

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Y.Q. Li[1], D.H. Wen[2], L.P. Wang[3] and Z.Y. Shen[1]

Abstract

In this paper, the mechanical properties of the flat and corner parts of cold-formed hollow sections with thickness over 6mm and up to 16mm, which is called 'cold-formed thick-walled steel sections' herein in comparison with that with common thickness less than 6mm, were investigated by tensile coupon tests. Experimental results for coupons from corner and regions adjacent to corner areas of sections were presented. Increasing of strength in both the yield stress and the ultimate stress of the corner coupons as compared with flat coupons in the same section part was observed. Meanwhile, corresponding stub columns of thick-walled hollow section with different geometrical dimensions were tested under axial compression. The yield strengths of whole section obtained from the experiment were compared with the predicted values by the tensile coupon tests of the same section, as well as the AS/NZS, ER3 and Chinese GB 50018-2002 design codes. The difference between the experimental results and the predicted values indicates that the related provisions in the existing codes are not suitable for estimating strength increase on cold-formed thick-walled steel hollow sections considering the effect of cold-forming.

Keywords: cold-formed thick-walled hollow sections; effect of cold-forming; tensile coupon; stub column

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[1]Professor, Department of Building Engineering & State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China
[2]Doctoral candidate, Department of Building Engineering, Tongji University, Shanghai, China
[3]Graduate Student, Department of Building Engineering, Tongji University, Shanghai, China

Introduction

Cold-formed steel as one of main construction materials with cross-section efficiency, good economy and the production of high degree of industrialization, green, etc., is widely used in the low multi-storey and high-rise residential and other construction field. A good understanding and knowledge of the mechanical properties is essential for the development of accurate and cost-effective design methods for cold-formed thick-walled steel structures.

It is well known that the strength of corners was increased significantly than that of the flat portions due to the cold work. Many researchers have investigated the corners properties of cold-formed steel sections (Karren 1967; AbdelRahman and Sivakumaran 1997). However, previous research on the cold-formed steel has been mainly focused on thin-walled steel with wall-thickness less than 6 mm. Recently, with large cross-sections and thick-walled steel can be cold-formed successfully into structural shapes, a few researchers began to investigate the behavior of cold-formed thick-walled steels (Guo, Zhu et al. 2007; Hu, Ye et al. 2011).

The existing research results on material behavior of cold-formed steel sections with thickness less than 6mm, show a significant increase in the yield strength at and around the corner areas. (Karren 1967; AbdelRahman and Sivakumaran 1997). In order to investigate the strength increase of these areas for cold-formed thick-walled steel sections, an experimental investigation was undertaken to determine the mechanical properties of the corner regions and regions adjacent to corners. Then material properties and structural behavior of cold-formed thick-walled hollow sections were also tested. Based on the test results, the stub column test strengths with the design strengths predicted by related standards for cold-formed steel structures were compared.

Experimental investigation

Material property tests

Coupon shape in the corners

In order to investigate the difference of the strength increase between the corner areas and the regions close to corners (Fig. 1), two kinds of coupons were taken from the same corner areas, as shown in Fig. 2.

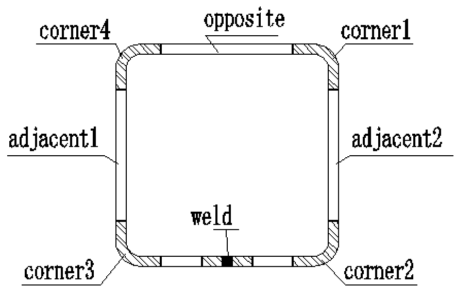
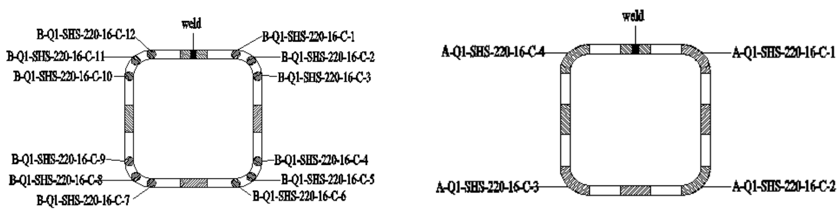


Fig. 1 Positions of corner regions



(a) Rounded specimens (b) Curved specimens

Fig. 2 Two kinds of coupons for corner areas

Test device

The tensile testing machine used for the flat and rounded corner specimens in this study was a Zwick/Roell Z400 Universal testing machine of 400KN capacity. A fully automatic contact extensometer was used to measure the axial deformations of the middle part of the coupon specimens. The test set-up for flat and rounded coupons is shown in Fig. 3.

The corner coupons were tested in a 1000KN capacity Material Test System machine. The coupons were mounted in the testing machine using the gripping devices and were aligned with the vertical axis of the machine. Two strain gauges attached to both inside and outside of curved coupon were used to measure the axial elongation of the coupons during the test, which can eliminate bending strains from the strain readings (Fig. 4). The readings of both the axial load and the strain gauges during the test were recorded using a data acquisition system. A real-time display of the load-strain relationship during the test was monitored by connecting a computer with software to the data acquisition system.

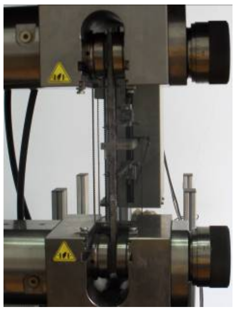


Fig. 3 Test set-up for flat and rounded coupons

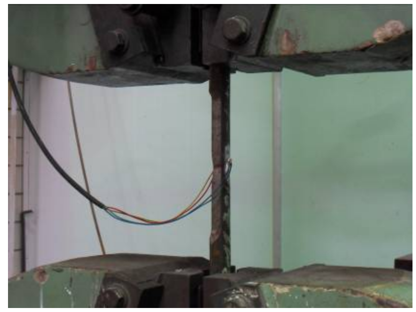


Fig. 4 Location of strain

Labeling of Specimen

Three repeat hollow section tubes were taken for each cross section. Coupons were taken from different locations over the cross-section. Fig.5 shows the positions of the test coupons in the weld, flats and corners of the sections. Three coupons were taken from the flats of each hollow section. One was cut from the face opposite the weld, and others from each side adjacent to the weld. One coupon was taken from the weld area of each hollow section. A coupon was also taken from each of the four corners of all sections.

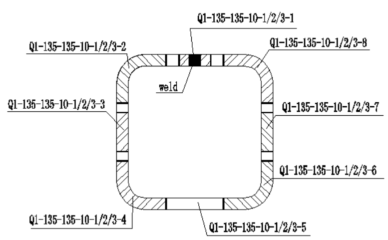


Fig. 5 Numbering of coupons for section 135-135-10

The specimen labeling method is as follows: steel grade-height dimension-width dimension-thickness-repeat label-specimen number. The steel grades of Q1 and Q2 have the nominal yield strength of 235MPa and 345MPa respectively. The repeat label 1, 2 and 3 are used to distinguish the three repeated coupons from the same position of the same cross-section. The specimen number from 1 to 8 represents different locations on sections for the coupons. For instance, the specimen number 1 refer to the weld coupon, and the numbers 2, 4, 6 and 8 refer to the curved corner coupons, and 3, 5 and 7 represent the flat coupons.

Stub column tests

Test setup

Compression tests were carried out using a 10000KN electro-hydraulic servo multi-function testing machine. Axial load was applied through the end plates on the top of the stub columns. The end plates are shown in Fig. 6, which can be used repeatedly. The stub columns located between the two end plates during the tests.

Testing procedure

Four displacement transducers were installed to record the displacements of the stub columns under axial compression. The transducers located in the four corners of each section. At the mid-height of the stub columns, 8 strain gauges were installed at the outer surfaces of the all sections to measure the strains at each loading level. Fig.7 shows locations of the strain gauges.

Fig. 6 The end plates

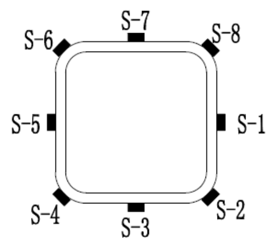


Fig. 7 Locations of strain gauges

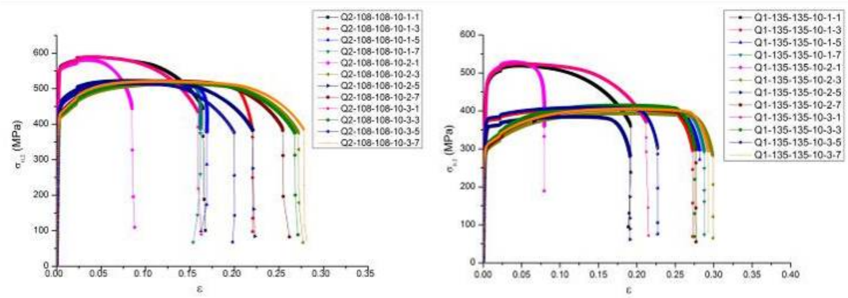
Two steps were used for the alignment of the stub columns. First, geometric center of the stub column was adjusted so that it aligned with the centerline of the top and bottom end plates. Then the preloading method was used for precise geometric alignment. Loading at about 50% of the proportional limit was slowly applied to a stub column and readings were recorded from the strain gauges. If the difference between the various strain measurements was greater than 5%, alignment of the stub column was adjusted. The process of pre-loading continued until the difference was within 5%.

Test results

Material tests

Coupon test results in flat parts

The stress-strain relationship of a flat tensile coupon was derived from the load-elongation relationship using its original cross-sectional area and the gauge length. Three cross-sections perpendicular to the longitudinal axis in the central region of the parallel length of a flat coupon were measured, and the minimum of three cross-sections was used as the cross-sectional area of the flat coupon. The applied loading was divided by the original (measured) cross-sectional area to obtain engineering stress values. Strain values were obtained by dividing the axial deformations by the initial gauge length. Typical stress-strain curves for flat coupons are shown in Fig.8.



(a) Section type: 108-108-10 (b) Section type: 135-135-10

Fig.8 Typical stress-strain curves for flat coupons

As shown in Fig. 8, the yield stress and the ultimate stress of the weld coupons are significantly higher than that of the flat coupons. But ductility of the weld coupons is reduced than that of the flat coupons. In addition, the stresses of the flat coupons in different parts of the section vary slightly.

Coupon test results in the corner parts

Fig.9 shows variation of yield strengths and ultimate stresses for rounded specimens from B-Q1-S-220-16-C-1 to B-Q1-S-220-16-C-12. The specimen B-Q1-S-220-16-C-6 has the minimum yield strength and ultimate stress. The specimen B-Q1-S-220-16-C-2 and B-Q1-S-220-16-C-11 have lower yield stresses and ultimate stresses compared with other specimens, which located on the core region of corner areas. Experimental results showed that the change in mechanical properties due to cold work is not uniformly distributed over the corner regions.

The stress-strain relationship of a corner tensile coupon was derived from the load-strain relationship using its original cross-sectional area. The cross-sectional area of a curved corner coupon was determined by the method outlined as follows: (1) cut the central part of the corner coupon specimen; (2) measure the length (L) and the mass (M) of the part taken from the corner coupon specimen; (3) calculate the original length (L_0) of the part according to the measured length; (4) calculate the cross sectional area of the corner specimen as $A = M / L_0$. The strain used for the curves was the average from the two strain readings. Typical stress-strain curves for corner coupons are shown in Fig. 10 (a) and (b).

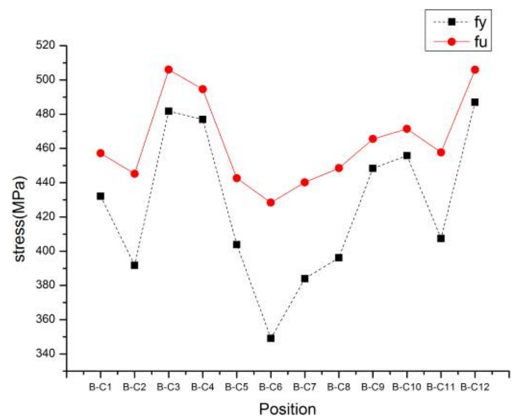
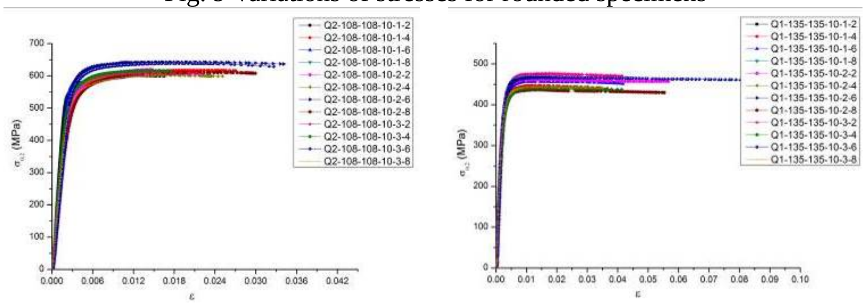


Fig. 9 Variations of stresses for rounded specimens



(a) Section type: 108-108-10

(b) Section type: 135-135-10

Fig. 10 Typical stress-strain curves for corner coupons

The strength of corners from different parts of sections is close to each other. The corners of the cold-formed section have higher stresses than that of the flat coupons due to the extra working at those locations but reduced ductility. The stresses of the corners are higher than that of the weld coupons for some sections, for instance, section 108-108-10; for other sections, the stresses of the corners are lower compared to the data obtained from the weld coupons, for instance, section 135-135-10.

Table 1 Summary of corner specimens for section 220-220-16

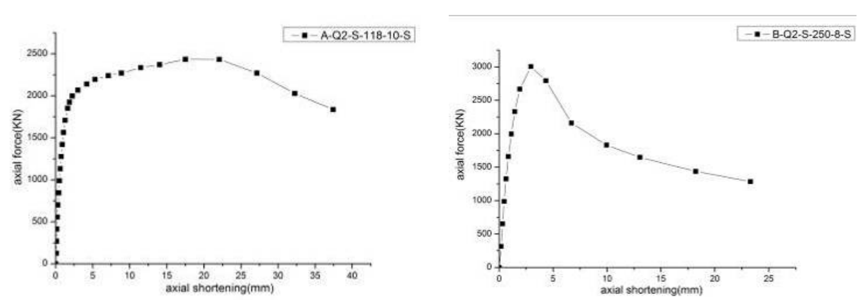
Section D*B*t (Grade)	Specimen type	Specimen No.	f_y (MPa)		f_u (MPa)		d	
			Single result	Average	Single result	Average	Single result	Average
220*220*16 (Q235)	rounded	B-Q1-S-220-16-C-1	432.07	435.18	457.20	469.50	26.34%	25.47%
		B-Q1-S-220-16-C-2	391.76		445.25		33.92%	
		B-Q1-S-220-16-C-3	481.70		506.05		16.14%	
		B-Q1-S-220-16-C-4	477.00	409.98	494.55	455.19	19.02%	28.24%
		B-Q1-S-220-16-C-5	403.82		442.67		30.66%	
		B-Q1-S-220-16-C-6	349.13		428.36		35.04%	
		B-Q1-S-220-16-C-7	383.98	409.51	440.22	451.41	37.84%	32.67%
		B-Q1-S-220-16-C-8	396.20		448.48		33.62%	
		B-Q1-S-220-16-C-9	448.34		465.52		26.54%	
		B-Q1-S-220-16-C-10	455.87	450.09	471.42	478.35	18.60%	23.33%
		B-Q1-S-220-16-C-11	407.47		457.69		35.42%	
		B-Q1-S-220-16-C-12	486.93		505.94		15.96%	
	curved	A-Q1-S-220-16-C-1	422.54	422.54	477.45	477.45	20.65%	20.65%
		A-Q1-S-220-16-C-2	406.79	406.79	457.21	457.21	23.24%	20.65%
		A-Q1-S-220-16-C-3	409.00	409.00	461.26	461.26	22.06%	20.65%
		A-Q1-S-220-16-C-4	425.61	425.61	479.13	479.13	20.53%	20.65%

Table 1 summarizes values of the yield stress, ultimate tensile stress and percentage elongation after failure on a gauge length of 5.65 $\sqrt{S_0}$ from each test. As the yielding was gradual, the yield stress quoted is the 0.2% proof stress.

It can be seen that the yield stress and ultimate stress for corner2 obtained from A-Q1-S-220-16-C-2 and the average of B-Q1-S-220-16-C-4 to B-Q1-S-220-16-C-6 are very close to each other. This is the same for corner3. In addition, the yield stress and ultimate stress for corner1 and corner4 obtained from A-Q1-S-220-16-C-1 and A-Q1-S-220-16-C-4 separately are slightly lower than the average values obtained from rounded coupons of corresponding regions. The percentage elongation after failure of rounded specimens is higher than that of curved specimens. Therefore, the curved specimens are used for the follow-up corner specimens for saving time.

Stub column tests

Fig. 11(a) and Fig. 11(b) show the typical load-axial shortening curves for stub columns numbered A-Q2-S-108-10-S and B-Q2-S-250-8-S. Behavior of the other stub columns is similar. The failure modes of the stub columns are mainly divided into two categories. One category is shown in Fig. 12(a). The stub columns failed by yielding of material. The total cross section of one end of the specimens crushed at the end of the test, and the weld area of some stub columns cracking. The sections with lower width to thickness ratio belong to this type. Another category is shown in Fig. 12(b). The yielding of the stub columns with larger width to thickness ratio often accompanied with local instability.



(a) Section 118-118-10 (b) Section 250-250-8

Fig. 11 Load-axial shortening curves

(a) Yielding of material (b) Local buckling

Fig. 12 Typical failure modes of stub columns

Comparison of results

Increasing of yield strength of flat coupons

Fig.1 shows the positions of flat coupons. The normalized yield stress of every flat was plotted against the width to thickness ratio of its corresponding section (Fig. 13). The yield stress of every flat in the section was normalized according to the minimum yield strength of all flats. As seen in Fig. 13, increasing of strength in the yield stress of the flat coupons located on the opposite of weld side as compared with flat coupons in the adjacent parts was observed. It was concluded from the curves that the yield stress of the flat coupons located on the opposite side decreased with the increment of b/t ratios, while that of the adjacent flat coupons didn't depend on the b/t ratios. The mean yield stresses of all flats, flats from opposite side and flats from adjacent sides are 1.04, 1.10 and 1.01, respectively.

Increasing of strength of corner coupons

Fig. 14 and 15 show the variation of normalized yield stress of corner coupons against the inner radius to thickness ratio and the centerline length of sections to inner radius ratio, respectively.

It is noted that the increase of corner yield strength is between 17% and 67%, and increases with the increase of R/t and L_s/R ratios.

The increase of corner ultimate strength is between 7% and 24%, and the mean increase is 16%. The effect of R/t was found to be insignificant for ultimate strength of corners as shown in Fig. 16.

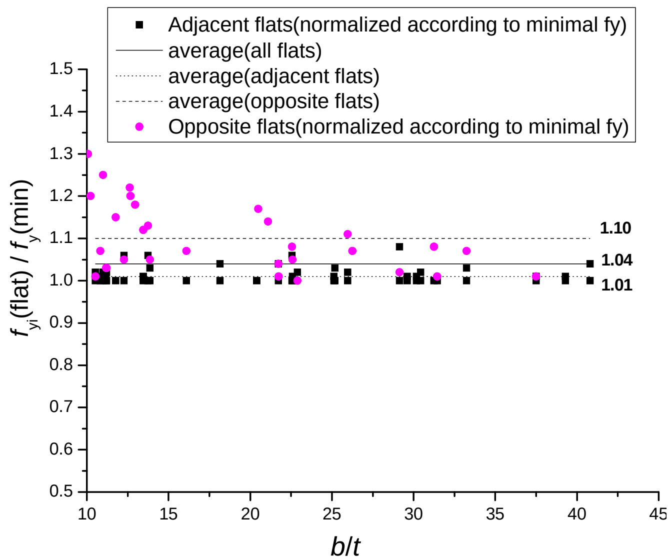


Fig. 13 Effect of b/t ratios for flat coupons

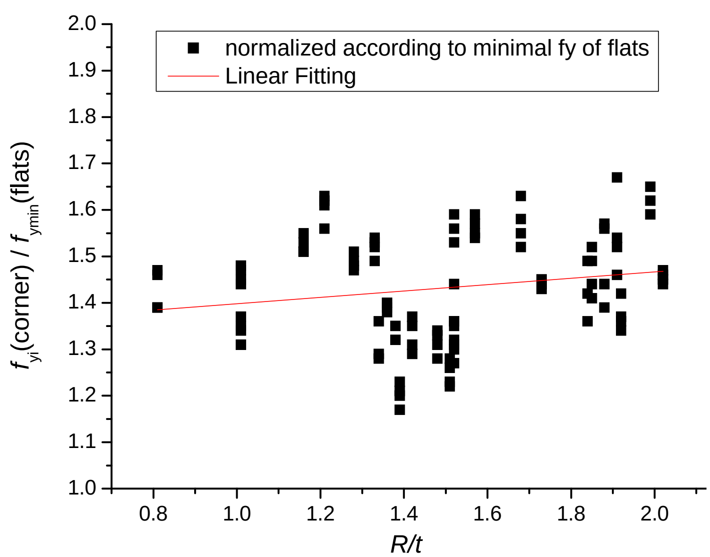


Fig. 14 Increase of yield strength versus R/t ratios for corner coupons

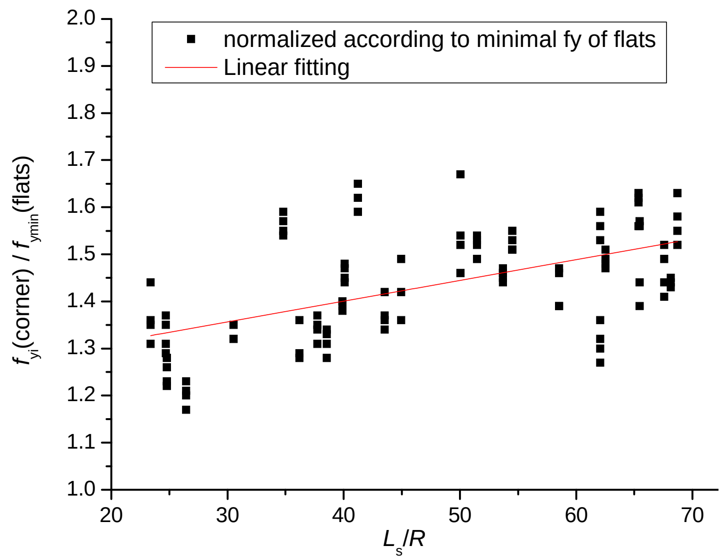


Fig. 15 Increase of yield strength versus L_s / R ratios for corner coupons

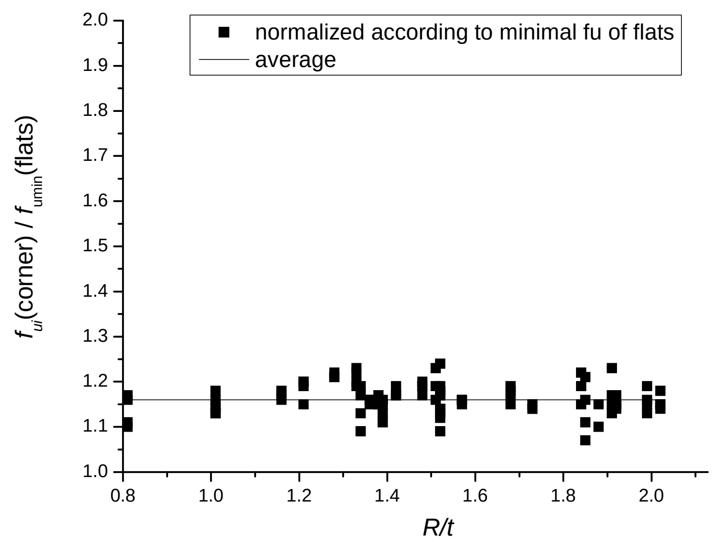


Fig. 16 Increase of ultimate strength versus R / t ratios for corner coupons

Comparison of stub column strengths with design strengths

In Fig. 17, the test yield strengths of stub columns were compared with the those specified in North American, Australian/ New Zealand, Eurocode 3 and Chinese standards for cold-formed steel structures (AmericanStandard 2001; ChineseStandard(GB50018) 2002; AS/NZS4600 2005; EN1993-1-3 2006). All values are normalized according to the corresponding average yield stress of flat coupons. It appears that the values given in those standards are unconservative for specimens with lower R/t ratios and moderate L_s/t ratios. One of the reasons for the low experimental values can be attributed to the residual stresses resulting from the cold-formed process.

Conclusions

An experimental study was carried out on cold-formed thick-walled steel hollow sections. Material properties of different parts of tested sections were obtained. The strengths of corners were found higher than that of flats coupons. But compared with the weld coupons, it was found that the strength of the corners was higher than that of the weld coupon for some sections. On the contrary, the strength of the corners was lower than that of the weld coupon for other sections. A series of stub columns to failure of square and rectangular hollow sections were tested in order to study the failure mode and response of cold-formed axially short columns.

The yield stress of the flat coupons located on the opposite side decreased with the increment of b/t ratios and was increased about 10% compared to coupons from adjacent sides by the cold-forming process. Increasing of strength in both the yield stress and the ultimate stress of the corner coupons as compared with flat coupons in the same section part was observed.

The yield strength considering the cold-formed effect used in the current design standards for cold –formed steel sections are not suitable for cold-formed hollow sections with thickness over 6mm and up to 16mm.

Acknowledgements

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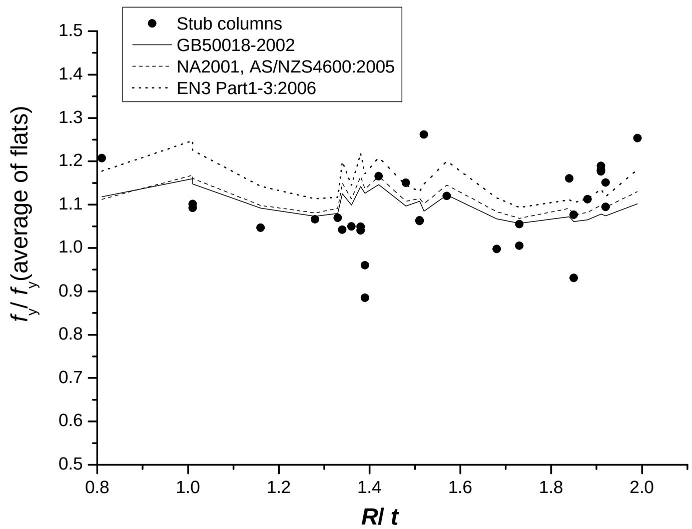
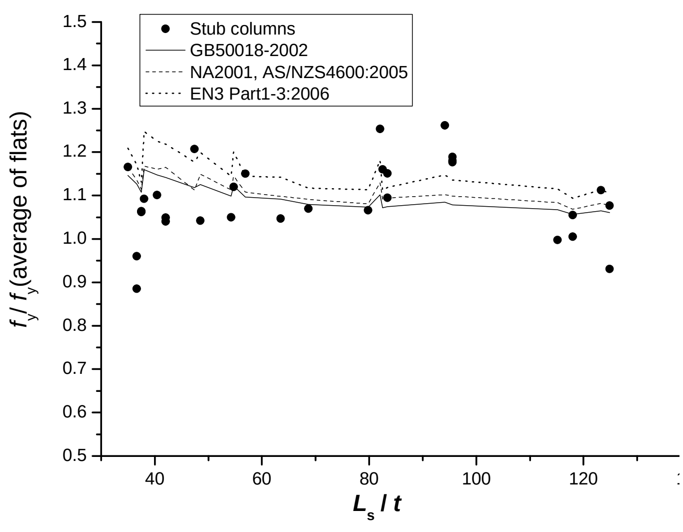


(a) Effect of R/t ratios



(b) Effect of L_s/t ratios

Fig. 17 Comparison of experimental results with current design standards

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Appendix. - Notation

A : Area of the central part of corner coupon that is cut down

b/t : Width to thickness ratio

f_y : The 0.2% proof stress

f_u : The ultimate tensile stress

L : Length of the central part of corner coupon that is cut down

L_0 : Original length of the central part of corner coupon that is cut down

L_s/R : The centerline length of sections to inner radius ratio

L/t : The centerline length of sections to thickness ratio

M : Mass of the central part of corner coupon that is cut down

Q_1 : Steel grade with nominal yield strength of 235 MPa

Q_2 : Steel grade with nominal yield strength of 345 MPa

R/t : Inner radius to thickness ratio

S_0 : The minimal cross-sectional area of the central region of the parallel length of a flat coupon