CSCE Annual Conference
Growing with youth – Croître avec les jeunes

Laval (Greater Montreal)
June 12 - 15, 2019

MECHANICAL PROPERTIES OF HOT-DIP GALVANIZED RECTANGULAR HOLLOW SECTIONS

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Abstract: Hot-dip galvanizing is widely used for corrosion protection of steel structures. However, there has been a plethora of recent reports on premature cracking in galvanized steel structures, which have resulted in some early decommissions or even hazardous collapses. This research focuses on cold-formed Rectangular Hollow Sections (RHS). A total of 108 tensile coupons were tested to investigate the effects of galvanizing as well as different pre-galvanizing treatments on the material properties around the cross sections of the specimens. This paper also reports a comprehensive measurement of residual stresses in different directions at the member ends which are directly relevant to the cracking issue. The results were also compared to the residual stresses far away from the member ends, which are relevant to structural stability research. In all, the research provides a better understanding of the characteristics and structural performance of galvanized RHS to facilitate its application.

1 INTRODUCTION

Among different techniques, hot-dip galvanizing is the most cost-effective measure for corrosion protection of steel structures (AGA 2012). In general, severely cold-formed steels, such as the corner regions of thick-walled rectangular hollow sections (RHS), are prone to liquid metal embrittlement (LME)-induced cracking during galvanizing due to high thermal and residual stresses. Further reduction of ductility due to accelerated strain ageing at elevated temperature during galvanizing may also occur (Packer et al. 2010, Sun and Ma 2019). This paper focuses on cold-formed RHS. On the other hand, the potential benefits of the hot-dip galvanizing process on material properties should not be neglected, other than the improvement on durability of the structures. For example, recent research (Shi et al. 2013) on high-strength HSS for application in transmission towers found that the hot-dipping process can sometimes significantly increase the material strength, lower the residual stress level and in turn improve the column behaviour. Based on an extensive literature review (Sun and Packer 2019), it was concluded that to this day, for HSS material, the relative significances of the steel-related and the galvanizing-related factors on the potential for LME and accelerated strain ageing had not been fully elucidated. Further research on the detrimental/beneficial effects of galvanizing on the mechanical properties of HSS material is needed.

2 Experimental program

2.1 Preparation of specimens

The RHS materials examined in this study are listed in Table 1. Three 12-metre long parent tubes were produced to Grade 350W Class C according to CSA G40.20/G40.21 (CSA 2013). The parent tubes have different width-to-wall thickness ratios corresponding to different overall amounts of cold working. One of the main objectives of this research is to quantify the changes of material properties and residual stresses at different locations of RHS, due to galvanizing and different degrees of pre-galvanizing heat-treatment. A total of 18 short RHS specimens were prepared from the three parent tubes (see Table 1). Each specimen ID includes three components. The first component (i.e. 6, 8 or 13) is the nominal wall thickness (mm). The second component distinguishes the specimens by different pre-galvanizing treatments, where C = cold-formed (Class C) without any treatment; 450 = cold-formed plus subsequently heat-treated to 450ºC to the Canadian standard for a Class H finish (CSA 2013) or to ASTM A1085 by specifying Supplement S1 (ASTM 2015); and 595 = cold-formed plus subsequently heat-treated to an annealing temperature of 595ºC per ASTM A143 (ASTM 2014). The third component of the ID indicates whether the specimen is galvanized, where U = ungalvanized; and G = galvanized. For comparison purposes, half of the specimens were galvanized. All galvanized specimens were dipped into the same chemical solutions for surface preparation and later into the molten zinc bath at the same time. Hence, for all galvanized specimens there is no variation in: (1) chemical compositions of surface preparation solutions or zinc bath mixture; and (2) temperature of the molten zinc bath. The hot-dipping process has a duration of 10 minutes.

Table 1: RHS specimens

Parent RHS	No.	Specimen ID	Parent RHS	No.	Specimen ID	Parent RHS	No.	Specimen ID
102×102×6.4	1	6-C-U	102×102×7.9	7	8-C-U	102×102×13	13	13-C-U
	2	6-450-U		8	8-450-U		14	13-450-U
	3	6-595-U		9	8-595-U		15	13-595-U
	4	6-C-G		10	8-C-G		16	13-C-G
	5	6-450-G		11	8-450-G		17	13-450-G
	6	6-595-G		12	8-595-G		18	13-595-G

2.2 Tensile coupon tests

A total of 108 tensile coupon tests were performed to determine the material properties around the cross-sections of the RHS specimens. For each RHS specimen listed in Table 1, two flat tensile coupons from two flat faces away from the weld seam, and four corner coupons were machined and tested following the procedures in ASTM A370 (ASTM 2017). The locations of coupons on the RHS specimens are shown in Figure 1. The 0.2% strain offset method was applied to determine the yield stress. For testing of corner coupons, a pair of special grips was used to connect the coupon to the universal testing machine (see Figure 2). Typical tensile stress-strain curves are shown in Figure 3(a) and (b). The averages of the key test results for the corner and flat coupons from the all 18 RHS specimens are listed in Tables 2 and 3, respectively. Tables 2 and 3 also include the changes in material properties due to heat-treatment or galvanizing (by comparing to the cold-formed ungalvanized (C-U) base material).

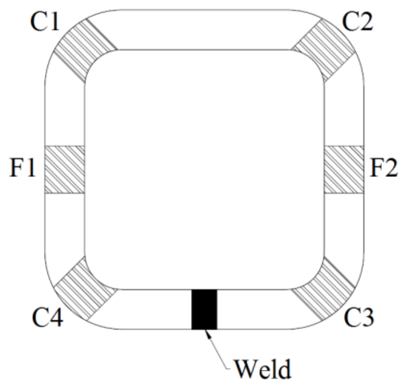
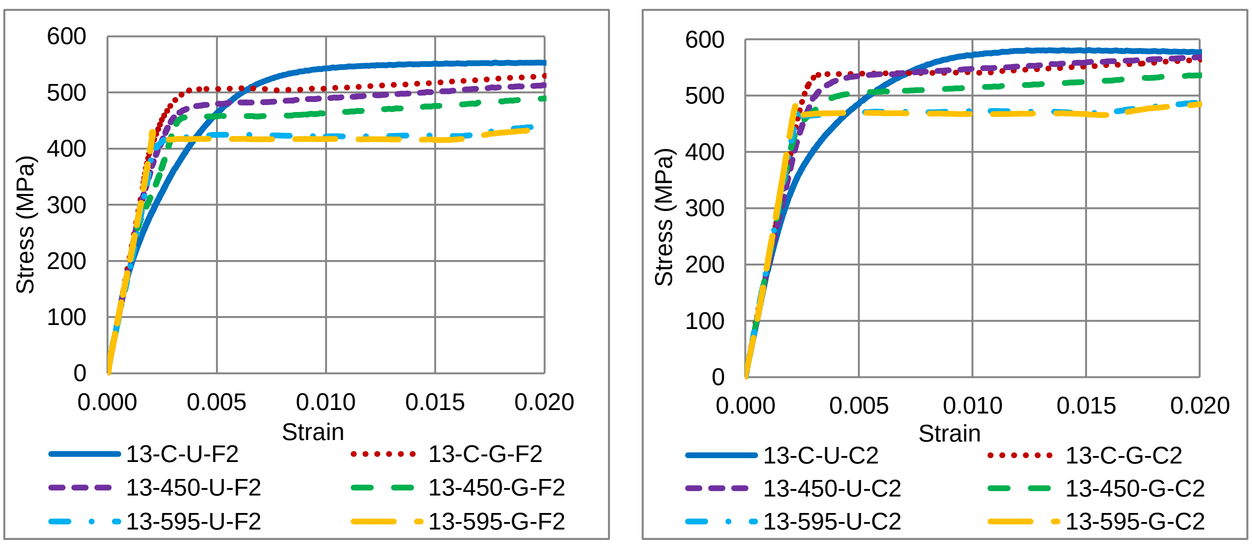


Figure 1: Locations of tensile coupons from RHS specimens

Figure 2: Testing of corner coupons with special grips and pins



(a) Flat coupons from RHS 102×102×13

(b) Corner coupons from RHS 102×102×13

Figure 3: Typical tensile stress-strain curves

By comparing the typical tensile stress-strain curves of the flat coupons from 13-C-U, 13-450-U and 13-595-U in Figure 3, the proportional limit stress increases as the heat treatment temperature increases. It can also been seen from Figure 3(a) that the curves of flat coupons from 13-450-U and 13-C-G are very close to each other. Hence, the decreases in residual stress and the increases in material yield strength as a result of the 30-minute 450ºC Class H heat treatment and the 10-minute hot dipping process can sometimes be comparable. On the other hand, by comparing 13-450-U to 13-450-G and 13-595-U to 13-595-G in Figure 3(a), the hot dipping process resulted in negligible changes in the tensile stress-strain behaviours of pre-galvanizing heat-treated specimens. Similar observations can be made from the corner coupon curves shown in Figure 3(b).

Table 2: Averages of tensile test results of corner coupons

(a) RHS 102×102×6.4

Specimen ID	$f_{yc,avg}$ (MPa)	Change in $f_{yc,avg}$ due to heat treatment or galvanizing	$f_{uc,avg}$ (MPa)	Change in $f_{uc,avg}$ due to heat treatment or galvanizing	$\varepsilon_{rup,avg}$	Change in $\varepsilon_{rup,avg}$ due to heat treatment or galvanizing
6-C-U	496	–	544	–	14%	–
6-450-U	550	+11%	610	+12%	21%	+50%
6-595-U	434	-13%	502	-8%	26%	+86%
6-C-G	508	+2%	554	+2%	16%	+14%
6-450-G	542	+9%	596	+10%	19%	+36%
6-595-G	427	-14%	492	-10%	23%	+64%

(b) RHS 102×102×7.9

Specimen ID	$f_{yc,avg}$ (MPa)	Change in $f_{yc,avg}$ due to heat treatment or galvanizing	$f_{uc,avg}$ (MPa)	Change in $f_{uc,avg}$ due to heat treatment or galvanizing	$\varepsilon_{rup,avg}$	Change in $\varepsilon_{rup,avg}$ due to heat treatment or galvanizing
8-C-U	539	–	577	–	14%	–
8-450-U	566	+5%	629	+9%	21%	+50%
8-595-U	485	-10%	559	-3%	25%	+79%
8-C-G	539	0%	590	+2%	17%	+21%
8-450-G	571	+6%	630	+9%	20%	+43%
8-595-G	464	-14%	533	-8%	24%	+71%

(c) RHS 102×102×13

Specimen ID	$f_{yc,avg}$ (MPa)	Change in $f_{yc,avg}$ due to heat treatment or galvanizing	$f_{uc,avg}$ (MPa)	Change in $f_{uc,avg}$ due to heat treatment or galvanizing	$\varepsilon_{rup,avg}$	Change in $\varepsilon_{rup,avg}$ due to heat treatment or galvanizing
13-C-U	506	–	563	–	14%	–
13-450-U	528	+4%	592	+5%	19%	+36%
13-595-U	459	-9%	546	-3%	26%	+86%
13-C-G	538	+6%	596	+6%	17%	+21%
13-450-G	516	+2%	577	+2%	19%	+36%
13-595-G	465	-8%	549	-2%	25%	+79%

Table 3: Averages of tensile test results of flat coupons

(a) RHS 102×102×6.4

Specimen ID	$f_{yf,avg}$ (MPa)	Change in $f_{yf,avg}$ due to heat treatment or galvanizing	$f_{uf,avg}$ (MPa)	Change in $f_{uf,avg}$ due to heat treatment or galvanizing	$\varepsilon_{fracture}$	Change in $\varepsilon_{rup,avg}$ due to heat treatment or galvanizing
6-C-U	415	–	482	–	30%	–
6-450-U	427	+3%	505	+5%	31%	+3%
6-595-U	384	-7%	486	+1%	33%	+10%
6-C-G	445	+7%	509	+6%	27%	-10%
6-450-G	430	+4%	502	+4%	31%	+3%
6-595-G	369	-11%	447	-7%	32%	+7%

(b) RHS 102×102×7.9

Specimen ID	$f_{yf,avg}$ (MPa)	Change in $f_{yf,avg}$ due to heat treatment or galvanizing	$f_{uf,avg}$ (MPa)	Change in $f_{uf,avg}$ due to heat treatment or galvanizing	$\varepsilon_{fracture}$	Change in $\varepsilon_{rup,avg}$ due to heat treatment or galvanizing
8-C-U	458	–	509	–	25%	–
8-450-U	468	+2%	539	+6%	26%	+4%
8-595-U	409	-11%	505	-1%	31%	+24%
8-C-G	478	+4%	530	+4%	22%	-12%
8-450-G	469	+2%	538	+6%	24%	-4%
8-595-G	413	-10%	501	-2%	29%	+16%

(c) RHS 102×102×13

Specimen ID	$f_{yf,avg}$ (MPa)	Change in $f_{yf,avg}$ due to heat treatment or galvanizing	$f_{uf,avg}$ (MPa)	Change in $f_{uf,avg}$ due to heat treatment or galvanizing	$\varepsilon_{fracture}$	Change in $\varepsilon_{rup,avg}$ due to heat treatment or galvanizing
13-C-U	483	–	549	–	22%	–
13-450-U	480	-1%	566	+3%	25%	14%
13-595-U	433	-10%	527	-4%	30%	36%
13-C-G	493	+2%	555	+1%	21%	-5%
13-450-G	485	0%	559	+2%	25%	14%
13-595-G	439	-9%	527	-4%	30%	36%

The following observations could be made from the corner coupon test results in Table 2:

(1) The 450ºC heat treatment has increased the yield and ultimate strengths of corner materials of RHS 102×102×6.4 by 11% and 12%, respectively. For the same holding time in the furnace (30 minutes), the strength increase as a result of the 450ºC treatment becomes smaller as wall thickness increases from 6.4 mm to 7.9 mm and becomes negligible when the wall thickness becomes 13 mm.

(2) Different from the 450ºC heat treatment, the 595ºC heat treatment has decreased the yield (up to 13%) and ultimate (up to 8%) strengths of corner materials for all three sizes of parent tubes. Similarly, for the same holding time in the furnace (30 minutes) the change in material strength becomes smaller as the RHS wall thickness increases.

(3) For RHS with a nominal wall thickness of 13 mm, the changes on the yield and ultimate strengths of the corner material due to the hot-dip galvanizing process are comparable to those from the 450ºC heat treatment. However, in general the galvanizing process does not increase significantly the strength of the corner material, regardless of whether the material has been subject to pre-galvanizing heat-treatment (e.g. 6-C-U versus 6-C-G) or not (e.g. 6-450-U versus 6-450-G, and 6-595-U versus 6-595-G).

(4) The 595ºC heat treatment improves significantly the ductility of the corner material. However, there is a trade-off between material strength and ductility. On the other hand, both the 450ºC heat treatment and the galvanizing processes can effectively improve the ductility with no strength reduction.

The following observations could be made from the flat coupon test results in Table 3:

(1) Comparing to the corner material, the galvanizing process and the 450ºC heat treatment led to smaller increases in the yield (up to 7%) and ultimate strengths (up to 6%) of flat face materials for all sizes of cross-sections.

(2) Similar to the corner material, the 595ºC heat treatment lowered the yield strengths (up to 11%) and the ultimate strength (up to 4%) of the flat face material.

(3) For the materials subject to pre-galvanizing heat-treatments, the hot-dipping process has negligible effects on the flat face material properties.

(4) Comparing to the corner coupon test results, the improvement of material ductility at the flat faces due to galvanizing and heat treatment to different degrees are smaller.

2.3 Residual stress measurements

The sectioning method has been used for determination of longitudinal residual stress in hollow sections for structural stability research (e.g., Davison and Birkemoe 1983, Key and Hancock 1993, Gardner at al. 2010), where the measurements were typically taken at a location far away from the member ends. However, galvanizing-induced cracking always initiates at the free end. RHS free ends tend to “open” during galvanizing as a result of high residual and thermal stresses in the transverse direction. Hence, for severely cold-formed steels it is important to measure the residual stresses at the susceptible locations. In this research, the residual stresses were measured using the hole-drilling method and the standard equipment and strain gauge rosettes were in ASTM E837 (ASTM 2013). Typical locations of strain gauge rosettes and the test setup are shown in Figure 4.

To evaluate the effects of different pre-galvanizing heat-treatments per ASTM A143 (ASTM 2014), ASTM A1085 (ASTM 2015) and CSA G40.20/G40.21 (CSA 2013) on the residual stress properties of RHS 102×102×6.4, 12 strain gauge rosettes were installed at all four corners at the free end of Specimens 6-C-U, 6-450-U and 6-595-U. The same method was applied to RHS 102×102×7.9 and RHS 102×102×13. To determine the residual stress properties after galvanizing, four strain gauge rosettes were installed at the same locations on specimens 8-C-G and 13-C-G. The calculations of residual stresses in the longitudinal and transverse directions were performed using the procedures in ASTM E837 (ASTM 2013). The results from the 40 strain gauge rosettes were normalized by the average of yield strengths of the two flat coupons ($f_{yf,avg}$) from the cold-formed and ungalvanized base specimens and plotted in Figures 5(a) and (b) against the normalized inside corner radii. The corner radii of all corners of the three parent tubes were measured to identify the degrees of cold-working. To quantify the difference in residual stresses at the free end and the middle of the specimens, an additional 8 strain gauge rosettes were installed at the middle of Specimens 8-C-U, 8-C-G, 13-C-U and 13-C-G. The comparisons of the measured values are shown in Figures 6(a) and (b).

It can be seen that both heat treatment and galvanizing not only lowered the magnitude but also smoothed the distribution of residual stress at different corners for specimens of different cross-sectional dimensions. In general the longitudinal residual stresses are higher than the transverse ones. For the ungalvanized cold-formed specimens (i.e. 6-C-U, 8-C-U and 13-C-U), the longitudinal residual stresses at the free end range from 33% to 54% of $f_{yf,avg}$, and the transverse residual stresses range from 20% to 39% of $f_{yf,avg}$. One important finding is that the residual stresses in the transverse direction at the free end of the measured specimens are in general within the same order of magnitude of the thermal stress in the same direction during the hot dipping process (Sun and Packer 2017, Sun and Ma 2019).

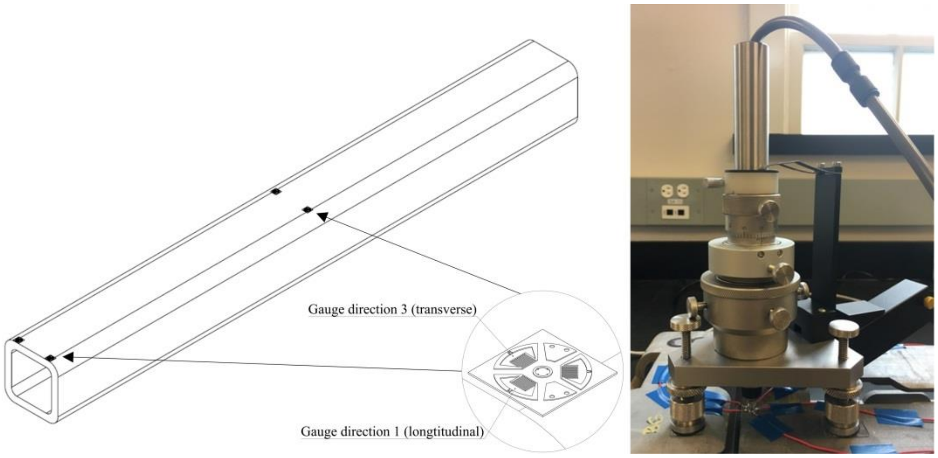
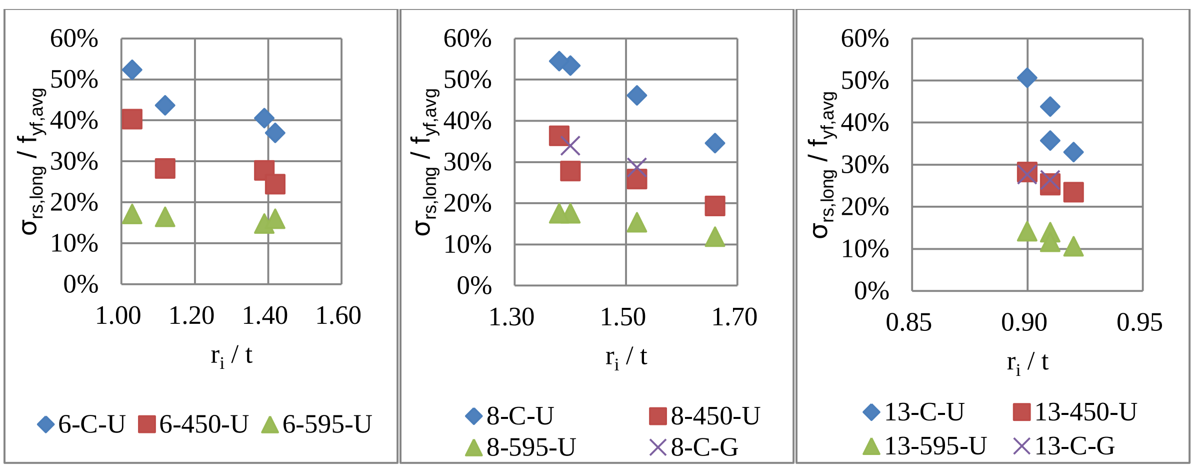
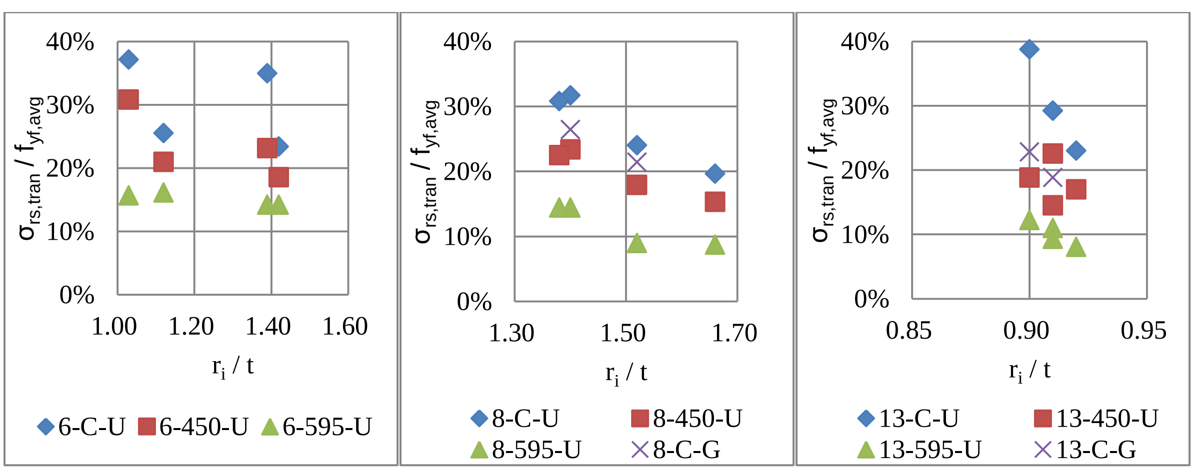


Figure 4: Test setup and typical locations strain gauge rosettes

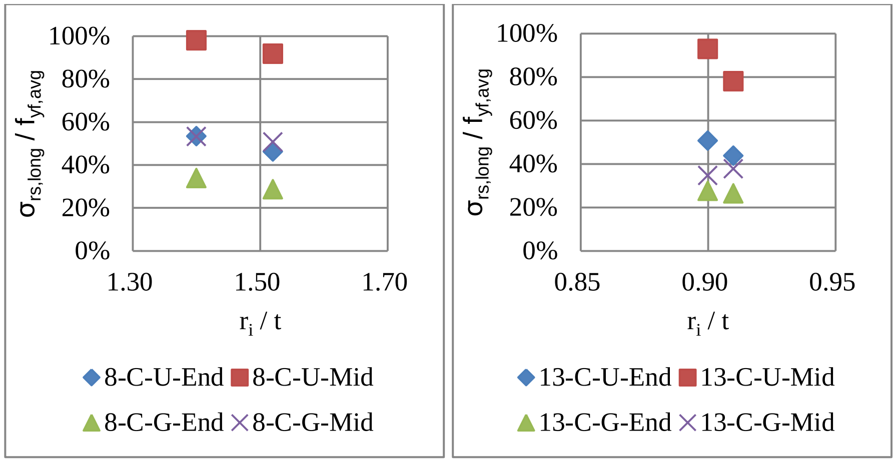


(a) Longitudinal residual stress

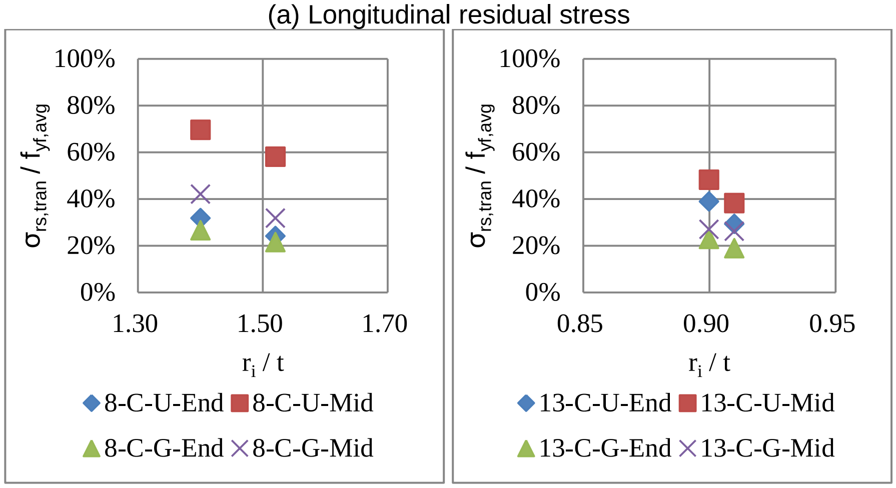


(b) Transverse residual stress

Figure 5: Measured residual stresses at the free end



(a) Longitudinal residual stress



(b) Transverse residual stress

Figure 6: Comparison of measured residual stresses at the middle and free end

The following observations were made by analysing the data in Figures 5 and 6:

(1) By comparing 13-C-U to 13-595-U, the 595ºC heat treatment (ASTM 2014) reduces significantly the residual stresses generated from cold-forming. A 69% decrease in longitudinal residual stress and a 66% decrease in transverse residual stress were observed. Similar observations can be made on the specimens with nominal wall thicknesses of 6.4 mm and 7.9 mm.

(2) By comparing 13-C-U to 13-450-U, a 34% decrease in longitudinal residual stress and a 31% decrease in transverse residual stress were observed. Similar observations can be made on the specimens with nominal wall thicknesses of 6.4 mm and 7.9 mm. It can be seen that the 450 ºC heat treatment (CSA 2013, ASTM 2015) is a lot less effective in relieving the residual stresses comparing to the ASTM A143 heat treatment at 595ºC. Also, the 595ºC is more effective in improving the material ductility. However, it should be noted that, as mentioned in Section 2.2, the 595ºC heat treatment could sometimes significantly decrease the material strength.

(3) By comparing 13-450-U to 13-C-G, it can be seen that hot dipping the RHS material in a molten zinc bath maintained at 450ºC for a much shorter period of time (i.e. 10 minutes) provides a partial residual stress relief comparable to the 450 ºC heat treatment (CSA 2013, ASTM 2015). Similar observations can

be made on the specimens with a nominal wall thickness of 7.9 mm. Hence, the effects of the galvanizing process on the residual stress properties of cold-formed hollow section material should not be neglected. Further research is needed on the optimized duration of heat treatment to different degrees.

(4) By comparing the data in Figure 6, it can be seen that the residual stresses (both longitudinal and transverse) at the free end are a lot lower than those at the middle. The galvanizing process relieves effectively the residual stress at both the free end and the middle of the specimen. However, the correlations between residual stresses at different locations and the cross-sectional dimensions are not clear based on the limited data herein. Hence, further research is needed in this regard.

3 Conclusions

This research represents a first step towards: (1) understanding the corner cracking phenomenon in galvanized rectangular hollow sections (RHS); and (2) quantifying the changes of material properties as a result of the hot-dipping process. Hence, the effects of different fabrication processes on the material and residual stress properties of 18 RHS specimens were investigated via tensile coupon tests and residual stress measurements using the hole-drilling method. In particular, this research for the first time studied comprehensively the residual stresses in the corner regions at the member free ends, since residual stresses at these locations are directly relevant to cracking during galvanizing. Based on the material tested, it was found that:

- Although many of the RHS specimens have very small corner radii, no microcracks were found in the ungalvanized and galvanized specimens. The crack prevention rules in existing standards are in general very brief and qualitative. Further research is needed in this regard.
- The galvanizing process improved the ductility of the tested cold-formed material. It also led to a minor increase in yield strength.
- The effects of the hot-dip galvanizing process on the residual stress properties should not be neglected. Hot dipping the RHS material in a molten zinc bath maintained at 450ºC for 10 minutes provided a partial residual stress relief comparable to a 450ºC heat treatment with a 30-minute holding time. Further research is needed to determine the optimized heat treatment duration for a partial residual stress relief for improvement of column behaviour.
- The 595ºC heat treatment significantly lowered the residual stress and improved the ductility of the corner material. On the other hand, the 450ºC heat treatment is less effective. However, there is a trade-off between material strength and ductility for the 595ºC heat treatment.

Symbols

$\sigma_{rs,long}$	Residual stress in the longitudinal direction
$\sigma_{rs,tran}$	Residual stress in the transverse direction
$\varepsilon_{rup,avg}$	Average of rupture strain (rupture strain is determined by re-joining the fractured coupon and measuring: change in gauge length / initial gauge length)
$f_{yc,avg}$	Average of yield strengths of tensile coupons from corners of RHS
$f_{yf,avg}$	Average of yield strengths of tensile coupons from flat faces of RHS
$f_{uc,avg}$	Average of ultimate strengths of tensile coupons from corners of RHS
$f_{uf,avg}$	Average of ultimate strengths of tensile coupons from flat faces of RHS
r_i	Inside corner radius of RHS

t wall thicknesses of RHS

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