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Corner strength enhancement of high strength cold-formed steel at normal room and elevated temperatures*

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Abstract: In this study, the suitability of current design methods for the 0.2% proof yield strength of the corner regions for high strength cold-formed steel at normal room temperature was investigated. The current standard predictions are generally accurate for outer corner specimen but conservative for inner corner specimen. Based on the experimental results, an analytical model to predict the corner strength of high strength cold-formed steel at normal room temperature was also proposed. The comparison indicated that the proposed model predicted well the corner strength of high strength cold-formed steel not only at normal room temperature but also at elevated temperatures. It is shown that the predictions obtained from the proposed model agree well with the test results. Generally the corner strength enhancement of high strength cold-formed steel decreases when the temperature increases.

Key words: Cold-formed steel, Corner, Elevated temperatures, High strength steel, Yield strength
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INTRODUCTION

Light-gauge structural members (cold-formed steel and stainless steel) are cold-formed by various methods, such as roll-forming and brake-pressing. The mechanical properties of cold-formed sections are sometimes substantially different from those of the steel sheet, strip, plate, or bar before forming, because the cold-forming operation increases the yield point and tensile strength but decreases the ductility. The percentage increase in tensile strength is much smaller than that in yield strength, with a consequent marked reduction in the spread between yield point and tensile strength (Yu, 2000). The changes in the mechanical properties induced by cold work are considered as being caused mainly by three facts: strain hardening, the Bauschinger effect, and strain aging (Chajes *et al*., 1963). Since the material in the corners of a section is cold-worked to a considerably higher degree than that in the flat elements, the mechanical properties are distinct in different parts of the cross section (Yu, 2000).

The current design standards of cold-formed steel structures, such as the Australian/New Zealand Standard (AS/NZS, 2005) and North American Specification (NAS, 2001), explicitly permit the utilization of the changes in the material properties that result from a cold-forming operation. However, the method used in AS/NZS (2005) and NAS (2001) was based on the investigation of normal strength cold-formed steel. Recently, high strength cold-formed steel having yield strength higher than 450 MPa is used widely and many researches towards the utilization of high strength cold-formed steel are carried out (Yang and Hancock, 2004a; 2004b; Yang *et al*., 2004). Therefore, the validation of the method for predicting corner yield strength specified in current standards for high strength cold-formed steel needs assessment.

On the other hand, the current design standards of stainless steel structures, such as the Austra-

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lian/New Zealand Standard (AS/NZS, 2001) and ASCE Standard (ASCE, 2002), also allow the increase in strength obtained from cold-forming process to be taken into consideration in the design. It is stated in the AS/NZS (2001) and ASCE (2002) that "The increase in yield stress due to cold-forming or temper-rolling, or both, may be partly or completely lost by process such as welding, annealing or other heat treatment carried out after forming." This implicitly means that the temperature would affect the strength enhancement of the corner due to cold-forming. However, there is no such information for the cold-formed carbon steel in the Australian/New Zealand Standard (AS/NZS, 2005) and North American Specification (NAS, 2001). Therefore, it is also important to study the effect of temperature on the strength enhancement of the corner region of cold-formed steel. In this study, the effect of temperature on the cold-formed steel corner strength was investigated.

TEST PROGRAM

A series of high strength cold-formed steel flat coupon specimens are tested at normal room and elevated temperatures by Chen and Young (2006; 2007). The tested cold-formed steel coupon specimens include flat coupon specimens of cold-formed steel grade G450 and G550 having nominal yield strength of 450 MPa and 550 MPa, respectively. In addition, two kinds of corner coupon specimens: inner and outer corner coupon specimens of cold-formed steel grad G450, as shown in Fig.1, were also tested at normal room and elevated temperatures. The test specimens were prepared in accordance with the ASTM Standard E21-92 (ASTM, 1997) and Australian Standard AS 2291 (AS, 1979). The tensile testing machine used in this study was an MTS 810 Universal testing machine of 100 kN capacity. The heating device was an MTS Model 653 high temperature furnace with the maximum temperature of 1400 °C, as shown in Fig.2a. The furnace was controlled by an MTS model 409.83 temperature controller. An MTS Model 632.53F-11 of axial extensometer was used to measure the strain of the middle part of the coupon specimens, as shown in Fig.2b. Details of the high temperature tests were presented by Chen and Young (2006; 2007). Measured stress-strain curves of the cold-formed steel G450 for 1.9 mm flat corner specimen, inner corner coupon specimen and outer corner coupon specimen at normal room temperature are shown in Fig.3.

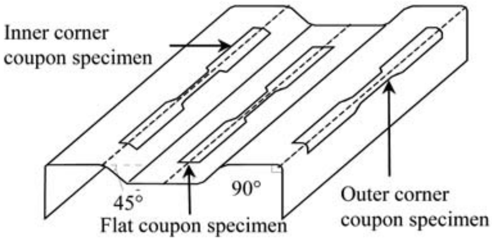
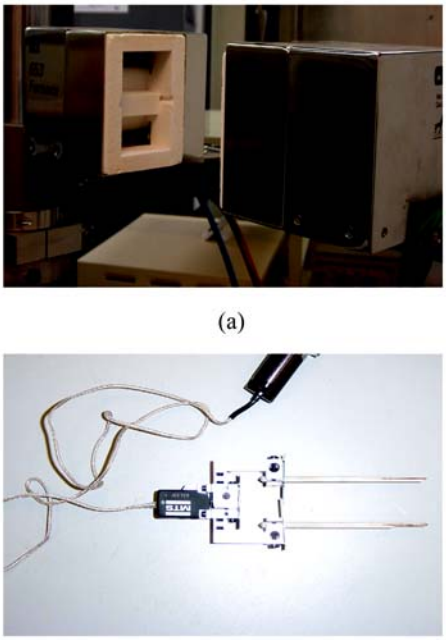


Fig.1 Coupon specimen


(a)

(b)

Fig.2 Test device. (a) Heating device; (b) Extensometer

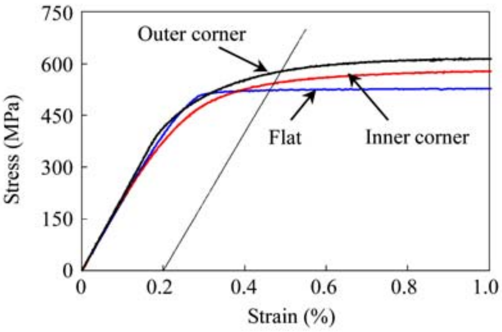


Fig.3 Measured stress-strain curves

CURRENT DESIGN METHOD

The current NAS (2004) and AS/NZS (2005) can be used to calculate the corner yield strength, as shown in Eqs.(1)~(3). As mentioned in the INTRODUCTION, the method was just developed based on normal strength cold-formed steel. Hence, the appropriateness of the method on the high strength cold-formed steel should be further investigated further. In this study, the yield strength is defined as the 0.2% proof yield strength.

$$F_{\mathrm{yc}}=\frac{B_{\mathrm{c}}F_{\mathrm{yv}}}{(R/t)^m}, \tag{1}$$

$$B_{\mathrm{c}}=3.69(F_{\mathrm{uv}}/F_{\mathrm{yv}})-0.819(F_{\mathrm{uv}}/F_{\mathrm{yv}})^2-1.79, \tag{2}$$

$$m=0.192(F_{\mathrm{uv}}/F_{\mathrm{yv}})-0.068, \tag{3}$$

where F_{yc} is the tensile yield point of the corner, F_{yv} is the tensile yield point of the virgin steel, F_{uv} is the tensile strength of virgin steel, R is the inside bend radius and t is the base metal thickness. The predictions for the yield strength enhancement from the current standards are compared with test results in Table 1. It is shown that the predictions are generally accurate for outer corner specimen but very conservative for inner corner specimen.

Table 1 Comparison of standard predicted yield strength with test results

Specimen	$\Delta F_{\mathrm{yc\text{-}test}}$ (MPa)	$\Delta F_{\mathrm{yc\text{-}standard}}$ (MPa)	Comparison $\Delta F_{\mathrm{yc\text{-}test}}/\Delta F_{\mathrm{yc\text{-}standard}}$
Inner corner	21	15	1.40
Outer corner	49	53	0.92

$\Delta F_{\mathrm{yc\text{-}test}}$: corner strength enhancement obtained from test results; $\Delta F_{\mathrm{yc\text{-}standard}}$: corner strength enhancement predicted by the current standards

PROPOSED METHOD

An analytical model was developed by Karren (1967) to predict the yield strength at the corner of cold-formed steel sections at normal room temperature. The strain hardening function was represented in the plastic part of the stress-strain curve by a power function:

$$\bar{\sigma}=k(\bar{\varepsilon})^n, \tag{4}$$

where $\bar{\sigma}=\frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}$ is the generalized stress, equivalent stress or effective stress, $\bar{\varepsilon}=\frac{\sqrt{2}}{3}\sqrt{(\varepsilon_1'-\varepsilon_2')^2+(\varepsilon_2'-\varepsilon_3')^2+(\varepsilon_3'-\varepsilon_1')^2}$ is the generalized strain, equivalent strain or effective strain.

In the case of the purely flexural model which is in a condition of plane strain, the strain function in the corner could be written as

$$\bar{\varepsilon}=\frac{2}{\sqrt{3}}\ln(1+\varepsilon_\theta)=\frac{2}{\sqrt{3}}\ln\left(\frac{r}{r_{\mathrm{o}}}\right), \tag{5}$$

where r is the corner radius, and r_{o} is the corner radius of the middle layer.

Then the average corner yield strength could be obtained by integrating the effective stress from Eq.(4) over the full area of a corner:

$$\sigma_{\mathrm{yc}}=\frac{k}{t}\int_{-t/2}^{t/2}\left|\bar{\varepsilon}\right|^n\frac{r}{r_{\mathrm{o}}}\mathrm{d}r, \tag{6}$$

where t is the plate thickness.

Substituting Eq.(5) into Eq.(6) yields

$$\begin{aligned}\sigma_{\mathrm{yc}}&=\frac{k}{t}\int_a^b\left|\frac{2}{\sqrt{3}}\ln\frac{r}{r_{\mathrm{o}}}\right|^n\frac{r}{r_{\mathrm{o}}}\mathrm{d}r\\&=\frac{r_{\mathrm{o}}}{t}\left[\int_1^{b/r_{\mathrm{o}}}\left(\frac{2}{\sqrt{3}}\ln x\right)^n x\mathrm{d}x+\int_{a/r_{\mathrm{o}}}^1\left|\frac{2}{\sqrt{3}}\ln x\right|^n x\mathrm{d}x\right],\end{aligned} \tag{7}$$

where a is the inside corner radius, and b is the outside corner radius.

It is found that for values of a/t less than 10, Eq.(7) could be approximated by Eq.(8):

$$\sigma_{\mathrm{yc}}=k\frac{(1.0-1.3n)}{(a/t)^{0.855n+0.035}}. \tag{8}$$

For the uniaxial tension, Eq.(4) could be reduced to $\sigma'=k(\varepsilon')^n$. Therefore, the strength coefficient k and the strain-hardening exponent *n* could be determined from the tensile coupon tests. In this study, the two parameters for high strength steel are obtained from the high strength steel experimental results. In total 30 high strength cold-formed steel coupon specimens are tested using the device described above. The nominal and measured material properties of the test coupon specimens are presented in Tables 2~4. Based on the plastic range of the true stress-strain curves obtained from the tensile coupon test results, the strength coefficient *k* and the strain-hardening exponent *n* of the tested high strength cold-formed steel could be obtained, as shown in Fig.4. Equations for the two parameters are also proposed, as shown in Eqs.(9)~(10) and Eqs.(11)~(12) for cold-formed steel G500 and G450, respectively. Thus, new predictions of the corner strength of high strength cold-formed steel are proposed, as shown in Eqs.(13)~(16). The predictions of the corner enhancement of the corner strength obtained from the proposed equation are compared with test results, as shown in Table 5.

For G550:

$$k = 2.8F_u - 1.5F_y, \tag{9}$$

$$n = 0.2F_u / F_y - 0.126; \tag{10}$$

For G450:

$$k = 2.8F_u - 1.6F_y, \tag{11}$$

$$n = 0.2F_u / F_y - 0.134. \tag{12}$$

Table 2 Test results of coupon specimen G550 1.0 mm at normal room temperature

Test series	Nominal	Measured			Calculated	
	F_y (MPa)	F_{yv} (MPa)	F_{uv} (MPa)	F_{yv}/F_{uv}	k	n
G550T10A	550	569	582	0.978	829	0.082
G550T10B	550	577	589	0.980	788	0.078
G550T10C	550	589	599	0.983	788	0.078
G550T10D	550	612	623	0.982	788	0.078
G550T10E	550	575	587	0.980	781	0.077
G550T10F	550	598	615	0.972	788	0.078
G550T10G	550	594	615	0.966	804	0.075
G550T10H	550	573	581	0.986	788	0.079
G550T10I	550	574	583	0.985	804	0.081
G550T10J	550	569	581	0.979	781	0.078
			Mean	0.979	794	0.078
			COV*	0.006	0.019	0.025

* COV: coefficient of variance

Table 3 Test results of coupon specimen G450 1.5 mm at normal room temperature

Test series	Nominal	Measured			Calculated	
	F_y (MPa)	F_{yv} (MPa)	F_{uv} (MPa)	F_{yv}/F_{uv}	k	n
G450T15A	450	532	557	0.955	679	0.075
G450T15B	450	531	557	0.953	659	0.076
G450T15C	450	515	545	0.945	645	0.077
G450T15D	450	525	555	0.946	692	0.078
G450T15E	450	521	549	0.949	665	0.077
G450T15F	450	515	546	0.943	685	0.076
G450T15G	450	534	560	0.954	699	0.074
G450T15H	450	530	555	0.955	672	0.079
G450T15I	450	530	557	0.952	685	0.074
G450T15J	450	530	557	0.952	679	0.075
			Mean	0.950	676	0.076
			COV*	0.005	0.024	0.022

* COV: coefficient of variance

Table 4 Test results of coupon specimen G450 1.9 mm at normal room temperature (Chen and Young, 2007)

Test series	Nominal	Measured			Calculated	
	F_y (MPa)	F_{yv} (MPa)	F_{uv} (MPa)	F_{yv}/F_{uv}	k	n
G450T19A	450	502	528	0.951	685	0.077
G450T19B	450	506	533	0.949	672	0.075
G450T19C	450	496	525	0.945	679	0.073
G450T19D	450	501	529	0.947	679	0.078
G450T19E	450	500	529	0.945	692	0.079
G450T19F	450	511	540	0.946	665	0.078
G450T19G	450	500	527	0.949	665	0.077
G450T19H	450	500	529	0.945	672	0.076
G450T19I	450	503	528	0.953	679	0.078
G450T19J	450	502	529	0.949	665	0.079
			Mean	0.948	675	0.077
			COV*	0.003	0.014	0.024

* COV: coefficient of variance

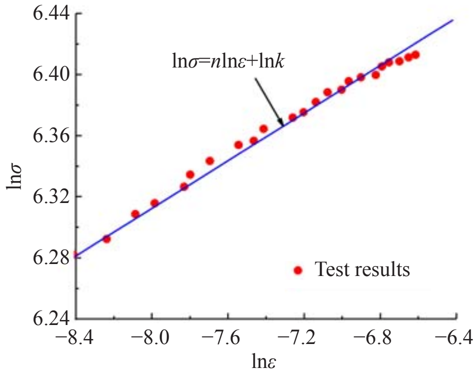


Fig.4 Determination of coefficient in the proposed model

Table 5 Comparison of proposed model predicted yield strength with test results at normal room temperature

Specimen	$\Delta F_{\text{yc-test}}$ (MPa)	$\Delta F_{\text{yc-predicted}}$ (MPa)	Comparison $\Delta F_{\text{yc-test}}/\Delta F_{\text{yc-predicted}}$
Inner corner	21	23	0.91
Outer corner	49	51	0.96

$\Delta F_{\text{yc-test}}$: corner strength enhancement obtained from test results; $\Delta F_{\text{yc- predicted}}$: corner strength enhancement obtained by prediction

For G550:

$$B_c = 3.65(F_{uv}/F_{yv}) - 0.728(F_{uv}/F_{yv})^2 - 1.75, \quad (13)$$

$$m = 0.171(F_{uv}/F_{yv}) - 0.073; \quad (14)$$

For G450:

$$B_c = 3.70(F_{uv}/F_{yv}) - 0.728(F_{uv}/F_{yv})^2 - 1.88, \quad (15)$$

$$m = 0.171(F_{uv}/F_{yv}) - 0.08. \quad (16)$$

where F_u is the tensile strength of the corner, F_y is the tensile yield point of the corner.

EFFECT OF TEMPERATURE

The material properties of cold-formed steel at elevated temperatures are different from those at normal room temperature, as shown in Table 6. Accordingly, the corner strength enhancement could be different from those at normal room temperature. The equations for the corner strength enhancement of cold-formed steel at normal room temperature were also used to predict the corner strength enhancement of cold-formed steel G450 1.9 mm at elevated temperatures by using the yield strength and the ultimate strength of flat coupon specimens. The predicted strength enhancement of inner and outer corner specimens at elevated temperatures are compared with test results in Table 7. It is shown that the predicted values are generally higher than the test results, which means that the proposed equations for the corner strength enhancement at normal room temperature are not suitable for that at elevated temperatures. The reason may be explained as follows: the steel member sections were cold-formed at normal room temperature. With the temperature increasing, the effect of cold-forming was gradually changed, resulting in that the predicted data are not identical with the test results, especially at 320 °C, moreover, it could be concluded that the corner

Table 6 Measured material properties at elevated temperatures

Temperature (°C)	G550 1.0 mm		G450 1.9 mm	
	$F_{yv,T}$ (MPa)	$F_{uv,T}$ (MPa)	$F_{yv,T}$ (MPa)	$F_{uv,T}$ (MPa)
80	589	603	519	545
180	600	623	508	544
320	541	593	508	566
450	122	244	445	509
550	73	119	278	305
660	39	54	58	99
970	13	14	21	23

$F_{uv\text{-}T}$: ultimate strength of virginal sheet at elevated temperature; $F_{yv\text{-}T}$: yield strength of virginal sheet at elevated temperature

Table 7 Comparison of proposed model predicted yield strength with test results at elevated temperatures

Temperature (°C)	Inner corner			Outer corner		
	$\Delta F_{yc\text{-test}}$ (MPa)	$\Delta F_{yc\text{-predicted}}$ (MPa)	$\Delta F_{yc\text{-test}}/\Delta F_{yc\text{-predicted}}$	$\Delta F_{yc\text{-test}}$ (MPa)	$\Delta F_{yc\text{-predicted}}$ (MPa)	$\Delta F_{yc\text{-test}}/\Delta F_{yc\text{-predicted}}$
80	32	45	0.71	60	48	1.25
180	31	61	0.51	88	56	1.57
320	9	98	0.09	13	75	0.17
450	45	107	0.42	65	77	0.84
550	17	47	0.36	26	37	0.70
660	19	50	0.38	57	21	2.71
970	1	3	0.33	<0	3	<0

$\Delta F_{yc\text{-test}}$: corner strength enhancement obtained from test results; $\Delta F_{yc\text{- predicted}}$: corner strength enhancement obtained by prediction

strength enhancement generally decreases as the temperature increases.

CONCLUSION

The corner strength enhancement of high-strength cold-formed steel was investigated in this study. Two kinds of cold-formed steel, steel grade G550 and G450, were investigated both at the normal room and elevated temperatures. The suitability of current Australian/New Zealand and North American standards for high strength cold-formed steel corner strength enhancement was investigated. It is shown that these two standard predictions are generally accurate for outer corner specimen but very conservative for inner corner specimen. Therefore, an analytical model was proposed for cold-formed steel grade G450 and G550. The strength coefficient *k* and the strain-hardening exponent *n* were obtained from the measured stress-strain curves. The proposed model accurately predicted the corner strength enhancement. In addition, the proposed model was also used to predict the corner strength enhancement of high strength cold-formed steel at elevated temperatures by substituting the reduced material properties. And the predictions are proved to be generally unconservative. Therefore, the effect of temperature on the corner strength enhancement could not be neglected. The corner strength enhancement decreases when the temperature increases.

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