STRENGTH ENHANCEMENT OF AUSTENITIC STEEL SECTIONS DUE TO COLD-FORMING

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ABSTRACT

Austenitic grade is the most common type of stainless steel which can be hardened significantly by cold working. The manufacturing process of the cold-formed thin walled sections leads to a notable change in the mechanical properties. These changes of the properties are characterized by the co-existent residual stresses and equivalent plastic strains due to cold forming and has a significant effect on their structural behaviour and strength. This paper determines the effect of cold-forming on the properties by developing an analytical model using software Maple. The increased material strength is determined at different stages of cold forming (coiling, uncoiling including flattening and cold bending) considering the residual stresses and plastic strain. The analytical model is validated with the previous test results. A parametric study is presented to investigate the effect of increase of yield strength ($\sigma_{0.2}$) with the change of the bending radius and the result is compared with the previously published predictive models of strength increase.

Keywords: *Austenitic steel, analytical modelling, cold forming, residual stresses, plastic strain, yield strength enhancement.*

1. INTRODUCTION

Stainless steels have not been widely used in building and civil engineering work as traditional structural materials. It has been mainly used where there has been some other very important concerns driving the design, generally corrosion resistance, sanitary qualities or architectural requirements rather than the inherent structural properties of the steel.

Austenitic grades are the most commonly in use for stainless structural applications accounting for up to 80% of all stainless steel production. They are non magnetic and the most general austenitic alloys are iron-chromium-nickel steels. At room temperature it has austenitic microstructure and contains comparatively soaring amounts of nickel (greater than 10%). The presence of high chromium and nickel, are the most corrosion resistant affording unusually fine mechanical properties of the stainless group. It has high ductility, formability, are readily weldable and offer good corrosion resistance, but prone to stress corrosion cracking. Their strengths are reasonable and they cannot be hardened by heat treatment, but can be hardened (i.e. made stronger) significantly by cold-working due to the high ratio between the ultimate strength to the yield strength. It can absorb significant impact without fracturing due to its outstanding ductile property and their strain hardening characteristics (SCI, 2003; SCI, 2006).

The strength enhancement at corner of the austenitic steel section due to cold working is studied by many researchers from their and previous experimental results for different grades of stainless steel and propose the model for predicting the 0.2 % proof strength ($\sigma_{0.2}$) which depends on the bending radius and annealed material properties (Van den Berg and Van der Merwe, 1992; Rasmussen and Hancock, 1993; Gardner, 2002; Ashraf *et al.,* 2005; Cruise and Gardner, 2008; Rossi *et al.,* 2013). The flat faces of the cold-rolled box sections also experience the strength increase which depends on the geometry of the sections (Cruise and Gardner, 2008; Rossi *et al.,* 2013) and for the pressed-braked section, the flat faces experiences the plastic strain only due to coiling and uncoiling process which can be neglected.

This paper describes the analytical modelling which is done for determining the residual stresses due to cold bending of sheet following several stages, namely coiling, uncoiling including flattening and the cold-forming process including springback. The result from the tensile coupon test of austenitic (1.4404) grade is used for the determination of increased material properties with respect to induced plastic strain. With these new material properties, the increased 0.2% proof strength ($\sigma_{0.2}$) for a cold-formed section is determined and compared with the existing predictive formulas for cold formed stainless steel sections.

2. ATALYTICAL MODELLING

The laboratory measurements of residual stresses in cold-formed thin-walled sections are time-consuming, difficult and it is not possible to establish a perceptible relationship between residual stresses and various steps of the fabrication process (coiling, uncoiling including flattening and formation of sections by cold rolling or press-breaking) by an examination of the measurement results. From this shortcoming, an analytical model is developed by considering the pure plastic bending of a wide plate as a plane strain problem with the steel assumed to obey the von Mises yield criterion and the Prandtl-Reuss hardening rule. Such analytical model was developed for residual stress prediction by e.i. Ingvarsson, 1975; Kato and Aoki, 1978; Rondal, 1987 and most recently for stainless steel by Quach, 2005.

Maple 18.01 was used in this analysis. In this study, the direction of coiling and uncoiling of sheet (Fig. 1) is referred to as longitudinal direction, denoted by *z* axis. The width direction of the sheet is referred to as transverse direction, denoted by *x* axis. The direction normal to the sheet is referred to as through-thickness direction, denoted by *y* axis.

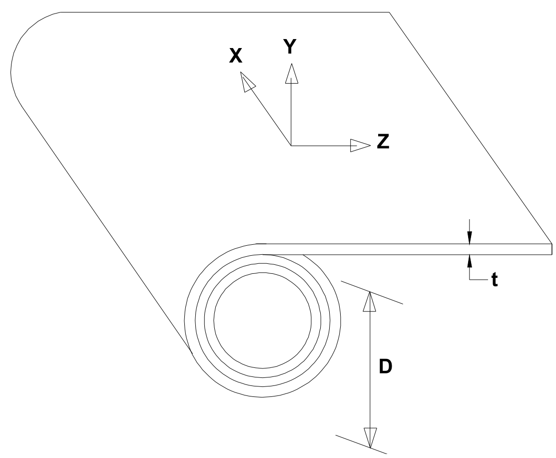


Figure 1: Direction of sheet axis.

2.1 Assumptions and Overview of the Analytical Modelling

Austenitic steel alloy is characterized by a nonlinear stress-strain relationship and material isotropy as anisotropy is small and can be ignored for austenitic alloys. The flat steel sheet is assumed to be free from residual stresses before it is coiled for storage, hence the effect of cold work prior to coiling is assumed to have been removed during annealing. Here the nonlinear stress-strain behaviour is presented by a 3-stage stress-strain model, which is developed by Quach, 2005. This 3- stage model which can measure the full range of stress-strain curve for both tensile and compressive strain is given below in Eq. 1. In the equation the upper sign is used for tension and lower sign for compression.

$$\varepsilon = \left\{ \begin{array}{l} \dfrac{\sigma}{E_0} + 0.002\left(\dfrac{\sigma}{\sigma_{0.2}}\right)^n, \sigma \le \sigma_{0.2} \\ \left[\begin{array}{l} \dfrac{\sigma - \sigma_{0.2}}{E_{0.2}} + \left[0.008 + \left(\sigma_{1.0} - \sigma_{0.2}\right)\left(\dfrac{1}{E_0} - \dfrac{1}{E_{0.2}}\right)\right] \\ \left(\dfrac{\sigma - \sigma_{0.2}}{\sigma_{1.0} - \sigma_{0.2}}\right)^{n'_{0.2,1.0}} + \varepsilon_{0.2} \end{array} \right], \sigma_{0.2} < \sigma \le \sigma_{2.0} \\ \dfrac{\sigma - a}{b \mp \sigma}, \sigma > \sigma_{0.2} \end{array} \right\} \quad (1)$$

The coiling of the sheet into a coiling curvature κ_c which follows the uncoiling of sheet including flattening is modelled as plane strain pure bending in the y-z plane. Through thickness an arbitrary point in the sheet undergoes elastic or elastic-plastic deformation due to coiling and uncoiling of steel sheet, depending on the coiling curvature κ_c and its location y away from the neutral axis of the section.

In the present solution, for the material up to elastic limit the stresses and strains are expressed using the following formulas.

$$\varepsilon_{z,c/u} = \frac{\left(\sigma_{z,c/u} - \nu\sigma_{x,c/u}\right)}{E_0} \tag{2}$$

$$\varepsilon_{x,c/u} = \frac{\left(\sigma_{x,c/u} - \nu\sigma_{z,c/u}\right)}{E_0} = 0 \tag{3}$$

When the material points undergoing plastic straining, the Von Mises yield criterion is satisfied in case of plane stress condition.

$$\sigma_{z,c/u} = \pm\frac{\sigma_{yc/u}}{\sqrt{\left(1-\omega_{c/u}+\omega_{c/u}^{2}\right)}} \tag{4}$$

$$\sigma_{x,c/u} = \pm\frac{\omega_{c/u}\sigma_{yc/u}}{\sqrt{\left(1-\omega_{c/u}+\omega_{c/u}^{2}\right)}} \tag{5}$$

Where,

$$\omega_{c/u} = \left(\sigma_{x,c/u} / \sigma_{z,c/u}\right) \tag{6}$$

The equivalent plastic strain is given by:

$$\overline{\varepsilon}_{p,c/u} = \varepsilon_{p,c/u} = \varepsilon_{yc/u} - \frac{\sigma_{yc/u}}{E_0} \tag{7}$$

For the cold bending of the sheet, the induced strain level is larger than coiling-uncoiling stage. At larger strains, the nominal stress-strain relationship deviates from the "real" stress-strain response (Yu and Zhang, 1996). Hence, at large curvature, the stress strain relationship *ε=f(σ),* is to be represented by the relationship between true stress σ_t and true strain ε_t.

From the relation between the true stress-strain and the nominal stress-strain, the true plastic strain ε_{tp} can be written as:

$$\varepsilon_{tp} = \varepsilon_t - \frac{\sigma_t}{E_0} = \pm\ln\left(1\pm\varepsilon_n\right) - \frac{\sigma_n\left(1\pm\varepsilon_n\right)}{E_0} \tag{8}$$

Where, the plus sign correspond to tension and the minus sign correspond to compression and σ_n, ε_n, σ_t, ε_t, ε_{tp} are the absolute value for both tension and compression coupon test.

3. MATERIAL PROPERTIES WITH RESPECT TO PLASTIC STRAIN

For determining the effect of cold bending on the mechanical properties of sheet, a commonly used austenitic steel grade of 1.4404 is taken. The tensile material property of the sheet without introducing any plastic strain is shown in Table 1, which is considered as the annealed material properties in the Maple. Here the tension coupon test was performed in both parallel to the rolling direction which is denoted by 'P' and the transverse to the rolling direction denoted by 'T' of the sheet. As anisotropy is not considered in the analysis, so the average value of the two directions is used.

Table 1: Summary of tensile material properties for austenitic steel sheet [Marik and Jandera, 2014]

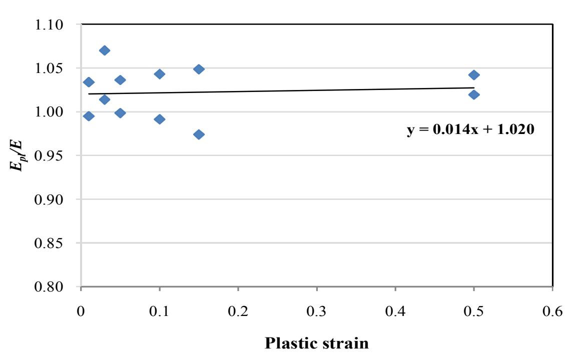
Grade	Rolling direction	E (GPa)	$\sigma_{0.2}$ (MPa)	$\sigma_{1.0}$ (MPa)	σ_u (MPa)	$\varepsilon_{pl,u}$ (%)	n	$n'_{0.2,1.0}$
1.4404	P	191.00	257.2	307.7	620.6	49.5	3.9	2.2
	T	199.80	279	322	635.1	57.1	8.8	2.3
Average		195.40	268.1	314.85	627.85	53.3	6.35	2.25

The cold bending of sheet occurs transverse to the rolling direction, so the data of plastic strain induce in the transverse to the roiling direction is presented in Table 2. In the table 'RD' means the rolling direction, 'LPSI' means the level (magnitude) of the induced plastic strain and 'PSI' means the plastic strain induced direction.

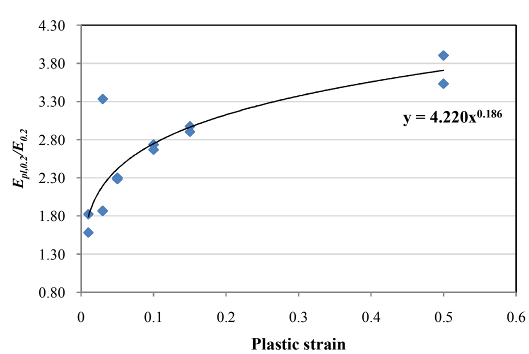
Table 2: 1.4404 grade tensile material properties with induced plastic deformation [Marik and Jandera, 2014]

RD	LPSI (%)	PSI	E (GPa)	$\sigma_{0.2}$ (MPa)	$\sigma_{1.0}$ (MPa)	σ_u (MPa)	$\varepsilon_{pl,u}$ (%)	n	$n'_{0.2,1.0}$
P	1	T	194.41	296.1	365.4	654.3	60.1	3.5	3
P	3	T	198.10	336.6	425.7	666.5	56.9	1.8	3.2
P	5	T	195.10	362.1	461	678	54.9	3.2	3.4
P	10	T	193.70	413.8	534.9	699.4	51.6	2.9	3.6
P	15	T	190.30	452.3	586	716.5	44.4	2.9	3.8
P	50	T	199.20	610	--	--	--	3.0	--
T	1	T	202.00	312.1	370.8	663.6	66.5	4.4	3
T	3	T	209.10	359.7	420.1	670.8	64.1	4.2	3.3
T	5	T	202.50	399.1	473.5	688.2	62.1	3.6	4.3
T	10	T	203.80	474.2	553.5	712.6	54.9	3.5	4.9
T	15	T	204.90	517.2	618.7	743.1	46.8	3.3	4.8
T	50	T	203.60	679.7	850.9	891.8	26.4	2.9	4.5

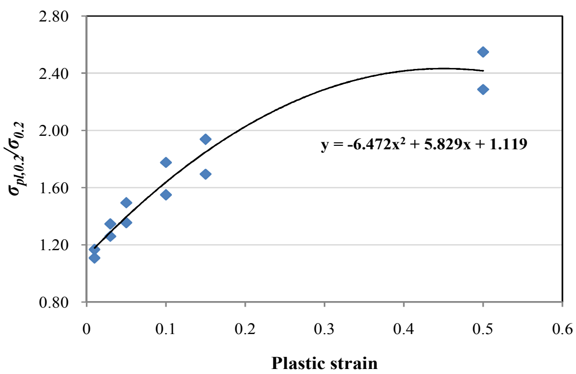
The values of material properties say as, modulus of elasticity (E), 0.2% proof strength ($\sigma_{0.2}$), 1.0% proof strength ($\sigma_{1.0}$), ultimate strength (σ_u), ultimate strain (ε_u), Ramberg-Osgood hardening exponent(n), compound Ramberg-Osgood model hardening exponent (n') from the coupons with various percentage of induced plastic deformation are compared with the initial value of material. Then the data are plotted against with the induced plastic strain (E_{pl}, $\sigma_{pl,0.2}$, $\sigma_{pl,1.0}$, $\sigma_{pl,u}$, $\varepsilon_{pl,u}$, n_{pl}, $n'_{pl,0.2,1.0}$) to get the equation of material properties with respect to initial value and induced plastic strain (Fig. 2). As for higher strain it is necessary to use the true stress-strain behaviour so the values of $\sigma_{0.2}$, $\sigma_{1.0}$, σ_u, ε_u are converted to true stress and strain.



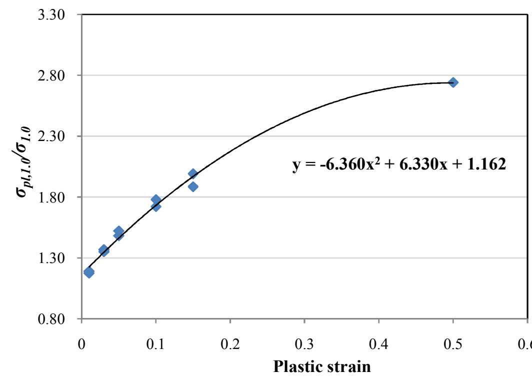
(a) For modulus of elasticity (E)



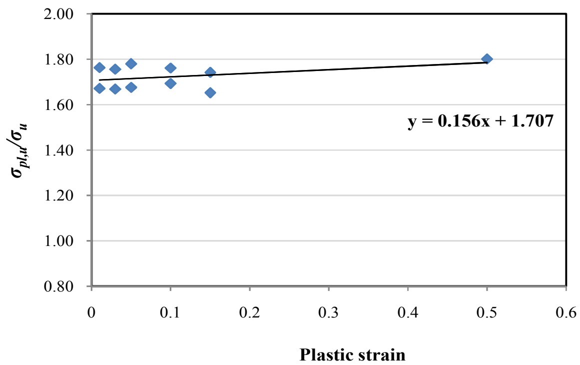
(b) For the tangent modulus at the 0.2% proof stress ($E_{0.2}$)



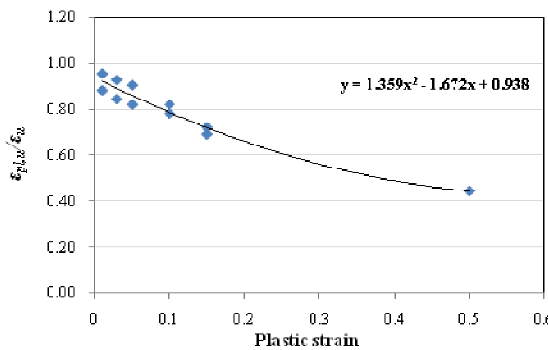
(c) For 0.2% proof stress ($\sigma_{0.2}$)



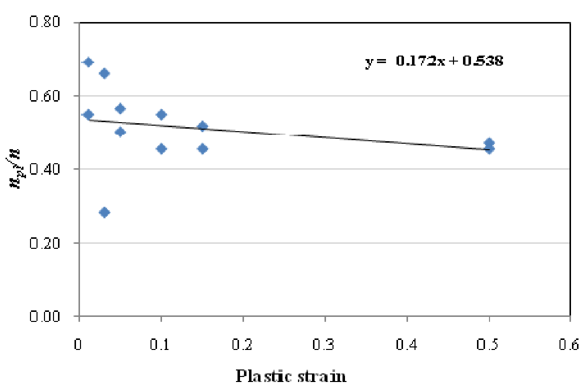
(d) For 1.0 % proof stress ($\sigma_{1.0}$)



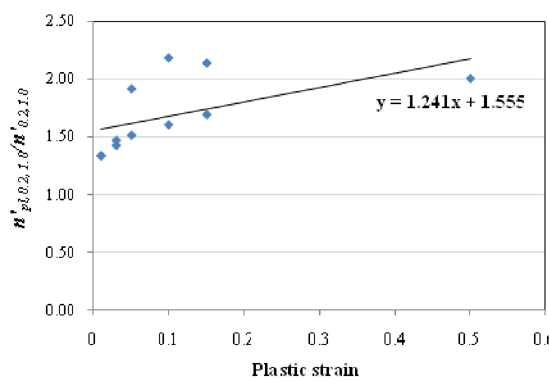
(e) For ultimate strength (σ_u)



(f) For ultimate strain (ε_u)



(g) For Ramberg-Osgood hardening exponent (n)



h) For compound Ramberg-Osgood hardening exponent ($n_{0.2,1.0}$)

Figure 2: Variation of material properties with respect to induced plastic strain.

4. VALIDATION OF MODEL BASED ON STRESS STRAIN DIAGRAM

The validation of the model in terms of the material diagram prediction was based on the tests of Gardner, 2002, where also annealed (virgin) material properties existed. These tests were carried out on austenitic steel grade and therefore the predictions for 1.4404 grade was used.

The corner and the flat part properties of the specimen due to cold forming are analysed. Here, sheet is divided into 10 parts through thickness and the material properties is calculated from the value of plastic strain after cold bending for each part. With the new material properties, for small increment of strain, the stress is calculated and by averaging the data stress strain curve is plotted and compared with the Gardner, 2002 stress strain curve for the corner and flat part in the following Fig. 3 and Fig. 4. Despite some difference in the prediction may be seen, it is regarded to be comparatively small and mostly on the safe side. The model was therefore used for more extensive comparison of existing prediction formulas.

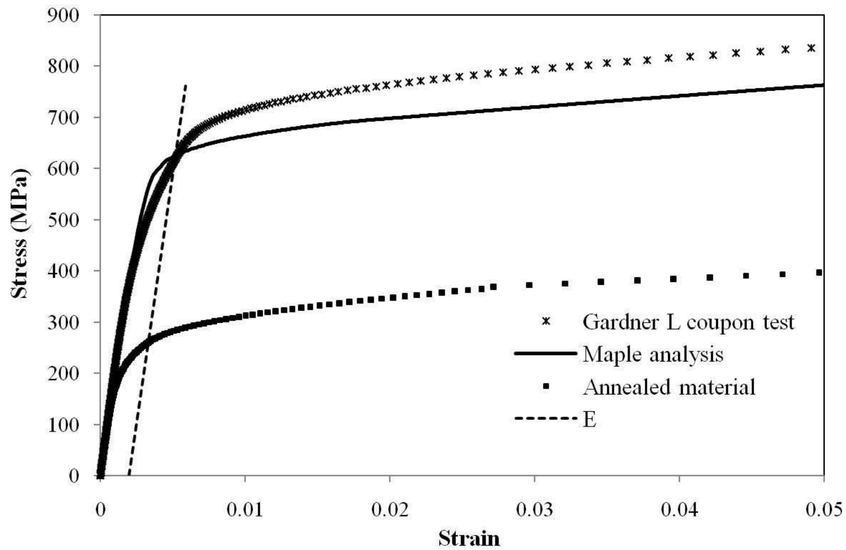


Figure 3: Stress strain diagram at corner of the specimen.

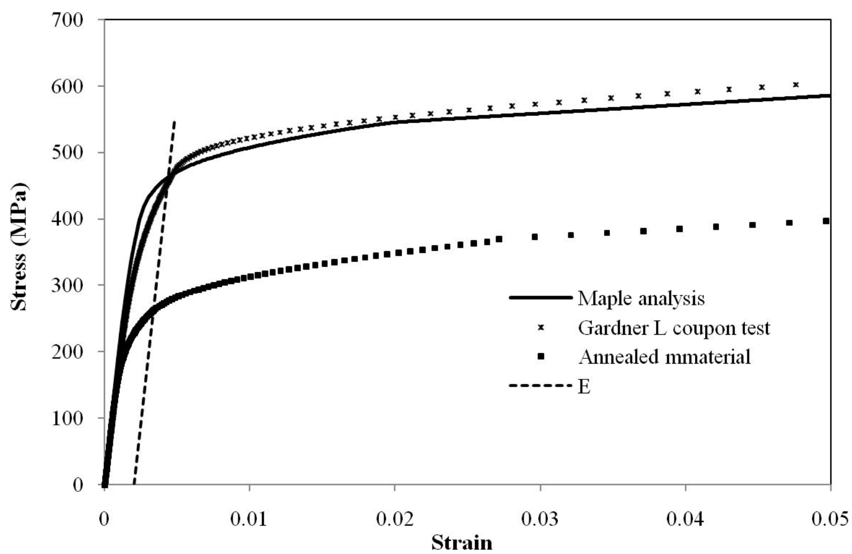


Figure 4: Stress strain diagram at flat face of the specimen.

5. COMPARISON OF THE ANALYTICAL RESULT WITH THE EXISTING DESIGN FORMULAS

From the stress-strain relationship of material after cold bending, the 0.2% proof strength ($\sigma_{0.2}$) is calculated for each bending radius to thickness (r_i/t). The ratio of 0.2% proof strength at corner and annealed material ($\sigma_{0.2,c}/\sigma_{0.2,a}$) is plotted against the ratio of internal corner radius and thickness (r_i/t) and compared with the previous model in Fig. 5 below. The value of r_i/t varies from 0.5 to 7.0 as all the previous test data of cold working are within this ranges.

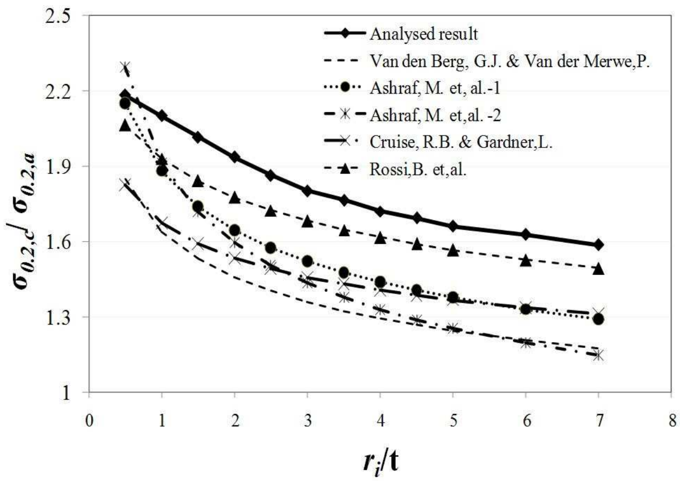


Figure 5: Relationship between increased corner strength with the corner bending radius.

The ratio of increased 0.2% proof strength at corner to the 0.2% proof strength of the annealed material ($\sigma_{0.2,c}/\sigma_{0.2,a}$) from the analysis is compared to the existing models in Table 3. The mean variation and standard deviation of the compared values is shown.

Table 3: Comparison of the analysed result with the previous predictive model for the 0.2% proof strength of the corner regions of cold-formed sections ($\sigma_{0.2,c}/\sigma_{0.2,a}$)

Steel Type	Grade		Van den Berg and Van der Merwe	Ashraf *et al.*-1	Ashraf *et al.*-2	Cruise and Gardner	Rossi *et al.*
Austenitic	1.4404	Mean	1.32	1.17	1.24	1.23	1.07
		SD	0.05	0.06	0.12	0.02	0.01

For predicting the increased strength in the flat parts of the cold-rolled SHS/RHS, it is assumed the section is firstly formed into a circle. The 0.2% proof strength ($\sigma_{0.2}$) is calculated depending on the circle radius to thickness (R_i/t). The ratio of 0.2% proof strength at flat faces and annealed material ($\sigma_{0.2,f}/\sigma_{0.2,a}$) is plotted against the ratio of internal circle radius and thickness (R_i/t) in Fig. 6 below. The value of R_i/t varies from 5 to 100 which can satisfy for all the square or rectangular section made by cold rolling. Here the internal circle radius $R_i = (b+h-2t)/\pi$, where b is the width and h is the height of the section and t is the thickness of the sheet.

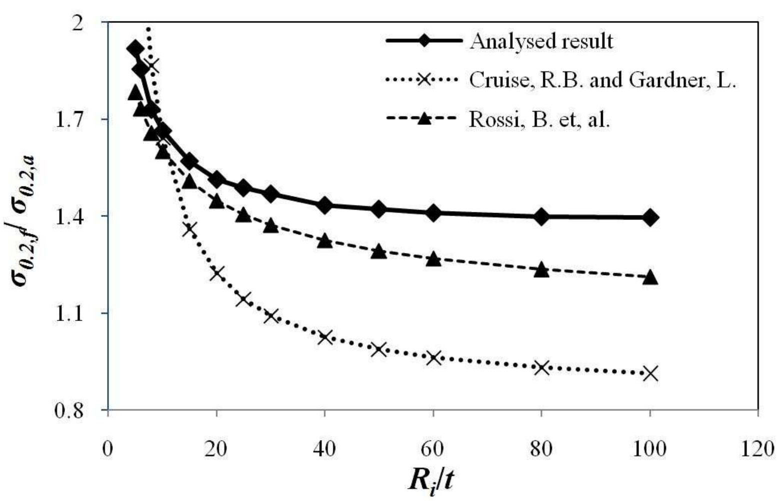


Figure 6: Relationship between increased strength in the flat face with the internal circle radius.

From the analysis, it is shown that the Cruise and Gardner, 2008 model for predicting the increased strength at the flat faces due to cold rolling for R_i/t > 50 represent unexpected result where the value of $\sigma_{0.2,f}/\sigma_{0.2,a}$ is less than 1.0. Also, this value is larger for R_i/t <10. They have predicted the model by using the test result of certain dimension of square and rectangular sections (100×50×2, 100×100×2, 100×50×3, 100×100×3, 100×50×4, 100×100×4, 150×150×3), where the R_i/t ranges from 11.25 to 31.2 and where the model shows good results. The Rossi, B. et, al. (2013) results are in good agreements with the analysed results with good mean variation value 8%.

Table 6: Comparison of the analysed result with the previous predictive model for the 0.2% proof strength of the flat regions of cold-formed sections ($\sigma_{0.2,f}/\sigma_{0.2,a}$)

Steel Type	Grade		Cruise and Gardner	Rossi *et al.*
Austenitic	1.4404	Mean	1.22	1.08
		SD	0.27	0.04

6. CONCLUSIONS

This paper focus on the analytical modelling for predicting the strength increase of corner and flat faces of the cold-formed sections where coiling-uncoiling of the sheet and cold bending considering springback is considered. The strength increase is determined according to the induced plastic strain due to cold forming. The model is validated with the previous test results.

For comparison of the analytical result for strength increase at corner and the flat faces with the previous predictive model for strength increase a parametric study is carried out by varying the internal bending radius to thickness ratio (r_i/t) for corner and the internal circle radius to thickness ratio (R_i/t) for flat faces.

From the result, it is seen that the 0.2% proof strength increase is greater than 100% for austenitic steel with mostly used r_i/t value 1.5 at corner. The analysed result is compared with the previous model for predicting the strength increase. The latest predictive model of Rossi *et, al.* (2013) shows the best results among all which satisfy for all ranges of r_i/t and R_i/t value at corner and flat parts respectively.

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