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EFFECT OF CORNER STRENGTH ENHANCEMENT ON SHEAR BEHAVIOUR OF STAINLESS STEEL LIPPED CHANNEL SECTIONS

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Abstract: During the cold-forming process of manufacturing, stainless steel sheets undergo plastic deformations, in particularly around corner regions of press braked sections. These plastic deformations lead to significant changes in material properties of stainless steel compared to its flat sheet properties. Consequently, yield strength and ultimate strength increments can be envisaged and this process is termed as cold working. Stainless steel exhibits significant level of strain hardening under plastic deformations. This is the main reason for these strength enhancements. In the structural design process of stainless steel sections, these strength increments are required to be considered to harness the benefits arising from it. Therefore, previous research proposed predictive models for these strength enhancements. In this context, the effect of corner strength enhancement on press-braked stainless steel lipped channel sections under shear was examined in this paper. 120 finite element models were developed. Different corner radii and section thicknesses were taken into account. Results highlighted that the effect of cold working on the shear capacity of stainless steel lipped channel sections is more significant in compact sections compared to slender sections where up to 9 % increment was observed. Further analysis was conducted using 40 finite element models to highlight the inelastic reserve capacity available in compact stainless steel lipped channel sections in shear. From the results, it was concluded that when web slenderness is less than 0.25 more than 40 % shear capacity increment can be achieved due to strain-hardening of stainless steel.

Keywords: Cold working; Corner strength enhancement; Stainless steel; Lipped channel sections; Shear capacity

1. Introduction

Stainless steel is becoming an attractive option for structural elements as it provides a range of benefits over the conventional carbon steel. Stainless steel exhibits non-linear stress-strain relationship with gradual yielding unlike carbon steel, which is characterised by a bi-linear stress-strain relationship with a sharp yield point. Therefore, stainless steel has beneficial strain-hardening effect under higher strains. As a result of this, strength enhancements can be seen in stainless steel sections during the forming process. These strength increments are considerably higher than the currently adopted material strengths in the design guidelines such as EN1993-1-4 (2015). Therefore, it is worth to study the effect of these strength enhancements on the structural behaviour of stainless steel sections in view of adopting those in the design process to utilise stainless steel more efficiently. On the other hand, many research has previously been conducted on shear behaviour of cold-formed channel sections. Shear behaviour of cold-formed lipped channel sections has been studied in a number of researches by Keerthan and Mahendran (2013a; 2013b; 2015a; 2015b) while shear behaviour of LiteSteel beams has been investigated by Keerthan and Mahendran (2012) and Mahendran and Keerthan (2013). Moreover, web crippling behaviour of cold-formed lipped channel sections has been studied by Sundararajah et al. (2017a; 2017b). However, limited attention has been given to stainless steel lipped channel sections. Therefore, this paper presents the details of finite element (FE) modelling undertaken to investigate the effect of corner strength enhancement and strain-hardening effect on the shear behaviour of press-braked stainless steel lipped channel sections.

There are two main cold-forming methods of manufacturing for thin-walled structural sections. Those are known as roll-forming and press-braking. Roll-forming is a mass production method where uncoiled sheet material is fed into a series of forming rollers to deform it in to the desired cross section. A typical example for this method is hollow sections. On the other hand, press-braking is relatively simple and semi-manual method involving bending of flat material sheets into shapes such as angles and channels using a standard set of tools and dies. Both methods of manufacturing involve enhancement of material properties of sheets compared to its virgin properties. This is known as cold-working. In the roll-forming process, moderate strength enhancements can be seen in the flat parts of the final section while higher strength increments can be seen in the corner regions. In the press-braking these strength enhancements are confined to corner regions.

2. Predictive Models for Corner Strength Enhancement

The effect of cold-work of forming on corner strength enhancement of stainless steel sections has been investigated by a number of researches previously. Coetsee et al. (1990) were the first to study the cold-working effect on the strength of stainless steel sections. Coupon tests and experimental studies on stainless steel lipped channel sections were conducted to study the effect of cold-working on the strength of stub columns. Van den Berg and Van der Merwe (1992) proposed an equation to predict corner 0.2 % proof strength using press-braked stainless steel corner coupon tests. Further studies have been conducted by Ashraf et al. (2005) and Cruise and Gardner (2008) on strength enhancements of corner regions of stainless steel sections induced during cold-forming.

In the study conducted by Cruise and Gardner (2008), an existing model was modified using comprehensive data base of press-braked and cold-rolled sections for prediction of corner 0.2 % proof strength. This proposed equation is based on a simple power model of internal corner radius (r_i) to material thickness (t) ratio, initially proposed for carbon steel by Karren (1967). Eq. (1) gives the modified equation for corner 0.2 % proof stress ($\sigma_{0.2,c}$) proposed by Cruise and Gardner (2008) for press-braked sections.

$$\sigma_{0.2,c} = \frac{1.673\sigma_{0.2,v}}{\left(\frac{r_i}{t}\right)^{0.126}} \quad (1)$$

where $\sigma_{0.2,v}$ is the 0.2 % proof stress of the virgin material.

Ashraf et al. (2005) proposed an equation to predict corner ultimate strength ($\sigma_{u,c}$) using all available test results on stainless steel. This equation is given by Eq. (2) where $\sigma_{u,v}$ is the ultimate strength of the virgin sheet material.

$$\sigma_{u,c} = 0.75\sigma_{0.2,c}\left(\frac{\sigma_{u,v}}{\sigma_{0.2,v}}\right) \quad (2)$$

Further studies were conducted by Cruise and Gardner (2008) to investigate the extent of corner strength enhancements in stainless steel cross-section. Based on this study it was found that corner strength enhancements extend to a distance of 2×material thickness beyond the corner radius for roll-formed sections while that is confined to corner regions of press-braked sections.

3. Finite Element Modelling

3.1 Model development

This section presents the details of FE modelling undertaken in this study to investigate the shear behaviour of stainless steel lipped channel beams (LCBs). Developed FE models were validated against the experimental results and then utilise in the parametric study to investigate the corner strength enhancement and strain-hardening effects. Commercially available FE software package, ABAQUS CAE 2017 was used for the development of the FE models. Geometric and material properties, loading and boundary conditions were employed in the FE modelling to suitably simulate the experimental conditions. Details of experimental results can be found in Dissanayake et al. (2019a; 2019b) and Fareed et al. (2019). In the FE modelling single LCBs were employed instead of back-to-back setup used in the experimental programme. LCBs were simply supported at the two ends and loaded at the mid-span through shear centre using single web side plates to eliminate torsional effects. Tie constraints were introduced at the contact surface between the LCB web and web side plates. Similar FE models were previously employed by Keerthan and Mahendran (2011) and Keerthan et al. (2014).

S4R shell elements were assigned to the sections to simulate thin section behaviour under shear. Mesh sensitivity analysis results suggested that 5 mm × 5 mm mesh provided the convergence with good accuracy. However, for corner regions of LCBs, 1 mm × 5 mm mesh was introduced to define the corner curvature. Figure 1 illustrates the FE mesh assigned in the modelling.

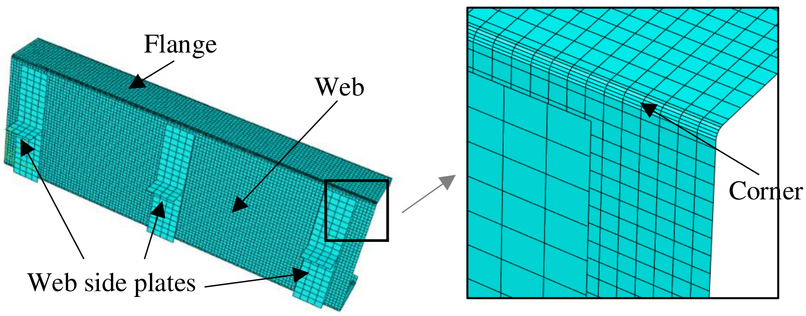


Figure 1: FE mesh of LCB and web side plate

To represent non-linear stress-strain behaviour of stainless steel modified two-stage Ramberg-Osgood material model proposed by Arrayago et al. (2015) was used. Then using Eqs. (3) and (4), true stress

(σ_{true}) and log plastic strain (ε_{ln}^{pl}) were calculated. When defining materials in Abaqus, sufficient number of data points were introduced using these two equations to accurately represent material behaviour. Corner material properties were calculated as described in Section 2. Since this study was on press-braked sections these enhancements were introduced only to corner regions as suggested in Cruise and Gardner (2008).

$$\sigma_{true} = \sigma_{nom}(1 + \varepsilon_{nom}) \tag{3}$$

$$\varepsilon_{ln}^{pl} = \ln(1 + \varepsilon_{nom}) - \frac{\sigma_{true}}{E} \tag{4}$$

where σ_{nom} and ε_{nom} are engineering stress and strain, respectively and E is the young's modulus.

To simulate the simply supported boundary conditions, a pin support and a roller support were assigned to the two ends of LCBs. Equal angle straps were attached to the LCB flanges to avoid distortional buckling and this was appropriately modelled. Figure 2 shows the boundary conditions assigned to the FE model. The details of boundary conditions used in the FE modelling are also summarised below where u_x, u_y and u_z are translations and θ_x, θ_y and θ_z are rotations in the x, y and z directions, respectively while 0 denotes free and 1 denotes restrained conditions.

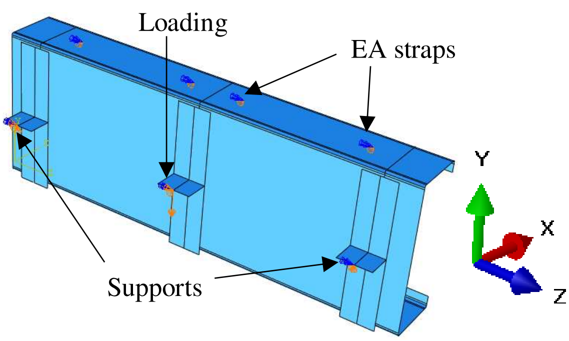


Figure 2: Boundary conditions used in the FE modelling

- Left support : u_x=1 u_y=1 u_z=1 θ_x=0 θ_y=0 θ_z=1
- Right support : u_x=1 u_y=1 u_z=0 θ_x=0 θ_y=0 θ_z=1
- Mid span loading point : u_x=1 u_y=0 u_z=1 θ_x=0 θ_y=0 θ_z=1
- Strap locations : u_x=1 u_y=0 u_z=0 θ_x=0 θ_y=0 θ_z=1

Local geometric imperfection amplitude (ω_0) was calculated using modified Dawson and Walker model proposed by Gardner and Nethercot (2004) and is given in Eq. (5). To identify local geometric imperfection mode shapes, an elastic buckling analysis was initially performed on each FE model. Then, using the modified Riks method, a geometrically and materially non-linear analysis was conducted up to failure to identify ultimate loads and failure modes.

$$\omega_0 = 0.023\left(\frac{\sigma_{0.2}}{\sigma_{cr}}\right)t \quad (5)$$

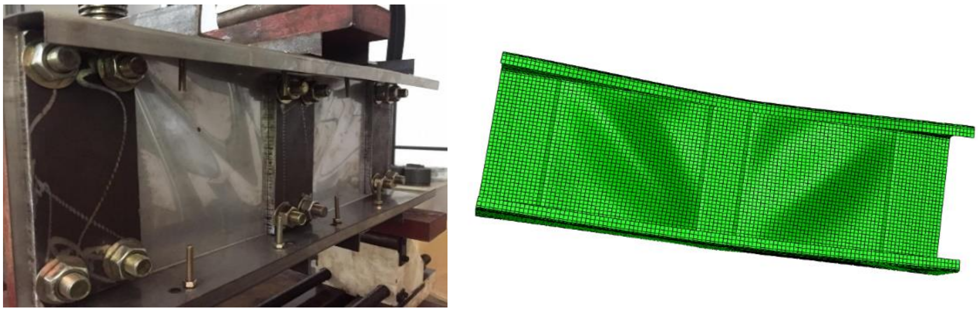
where σ_{cr} is the critical elastic buckling stress of the most slender element of the section.

3.2 Validation

Developed FE models were compared against the corresponding experimental results in terms of ultimate loads and failure modes to assess the performance. Table 1 compares the experimental and FE ultimate loads. Mean and coefficient of variance (COV) of experimental to predicted (FE) shear capacity ratio are 1.02 and 0.073, respectively. Therefore, it can be concluded that developed FE models are able to capture the ultimate shear capacities of stainless steel LCBs with reasonably good accuracy. Moreover, Figure 3 shows the experimental and FE shear failure modes of LCB 200×75×15×1.2 section where the FE model agrees well with the experimental failure mode.

Table 1: Comparison of experimental and FE shear capacities

LCB section	**$V_{Exp.}$(kN)**	**V_{FE} (kN)**	**$V_{Exp.}/V_{FE}$**
LCB 100×50×15×1.2	18.49	16.86	1.10
LCB 100×50×15×1.5	24.44	23.90	1.02
LCB 100×50×15×2.0	36.00	32.72	1.10
LCB 150×65×15×1.2	21.60	20.09	1.08
LCB 150×65×15×1.5	26.26	28.40	0.92
LCB 150×65×15×2.0	43.55	42.60	1.02
LCB 200×75×15×1.2	22.98	22.97	1.00
LCB 200×75×15×2.0	47.05	52.11	0.90
Mean			1.02
COV			0.073



(a) Experiment (b) FE model

Figure 3: Shear failure mode of LCB 200×75×15×1.2 section

4. Parametric study

A detailed parametric study was conducted using the validated FE models to investigate the effect of corner strength enhancement and strain-hardening effect on the shear behaviour of press-braked stainless steel LCBs; the results are discussed in this section.

4.1 Effect of corner strength enhancement

To study the effect of corner strength enhancement 120 FE models were developed. Table 2 summarises these results. r_i/t ratio was varied from 0.4 to 5 herein. Figure 4 compares the shear capacities with and without corner enhancement for LCBs with an internal radius of 5 mm. From the results, it can be concluded that corner strength enhancement has more effect on compact sections than slender sections. This can be explained by the fact that compact sections experience higher strains than slender sections at failure, therefore subjecting to more strain-hardening. Excluding unreliable FE results it was found that up to 9% shear capacity increment can be achieved from corner enhancement for press-braked LCBs. Similar findings were reported by Cruise and Gardner (2008) for press-braked stub columns. Moreover, it showed that the effect of internal radius on the shear capacity is negligible for LCBs. This is illustrated in Figure 5. In Figures 4 and 5 V_u is the shear capacity, V_y is the shear yield capacity and λ_w is the web slenderness of the section.

Table 2: Shear capacities and % increments due to the corner strength enhancement for stainless steel LCBs

Section	r_i=2 mm		r_i=3 mm		r_i=5 mm	
	$V_{FE}^{*,a}$ (kN)	% ^{*,b}	$V_{FE}^{*,a}$ (kN)	% ^{*,b}	$V_{FE}^{*,a}$ (kN)	% ^{*,b}
Grade 1.4301						

LCB 150×65×15×1	15.4	1.03	15.0	1.02	14.7	1.04
LCB 150×65×15×2	40.0	1.04	39.4	1.05	37.9	1.06
LCB 150×65×15×3	68.5	1.05	68.0	1.06	66.4	1.07
LCB 150×65×15×4	96.0	1.06	95.4	1.07	93. 3	1.08
LCB 150×65×15×5	131.8	1.07	130.1	1.08	128.2	1.09
LCB 200×75×15×1	17.2	1.03	18.6	1.13	16.5	1.04
LCB 200×75×15×2	47.3	1.03	47.1	1.05	44.7	1.05
LCB 200×75×15×3	82.5	1.05	81.0	1.05	79.3	1.06
LCB 200×75×15×4	114.6	1.05	113.9	1.06	111.7	1.07
LCB 200×75×15×5	171.2	1.18	151.7	1.06	150.2	1.08
Grade 1.4462						
LCB 150×65×15×1	26.0	1.04	25.6	1.06	26.0	1.04
LCB 150×65×15×2	76.0	1.04	73.4	1.04	68.9	1.05
LCB 150×65×15×3	128.6	1.04	127.7	1.04	124.3	1.06
LCB 150×65×15×4	175.6	1.05	174.2	1.06	170.5	1.06
LCB 150×65×15×5	229.9	1.05	228.0	1.06	225.0	1.06
LCB 200×75×15×1	27.7	1.04	30.3	1.05	26.4	1.08
LCB 200×75×15×2	86.4	1.02	84.9	1.04	79.4	1.04
LCB 200×75×15×3	158.9	1.05	157.1	1.06	150.2	1.05
LCB 200×75×15×4	218.7	1.05	216.6	1.06	211.0	1.06
LCB 200×75×15×5	283.3	1.05	281.4	1.06	276.9	1.06

*Note: a – including corner enhancement, b – increment due to corner enhancement

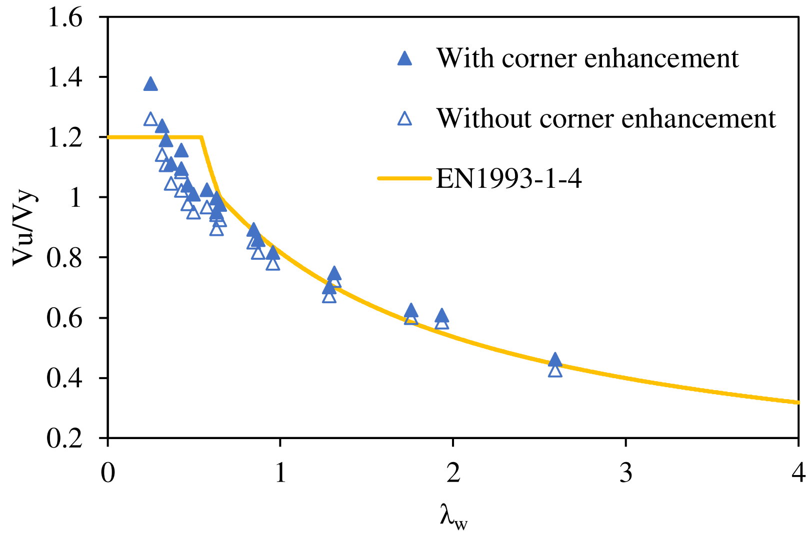


Figure 4: Shear capacities of stainless steel LCBs with and without corner enhancement for r_i=5 mm

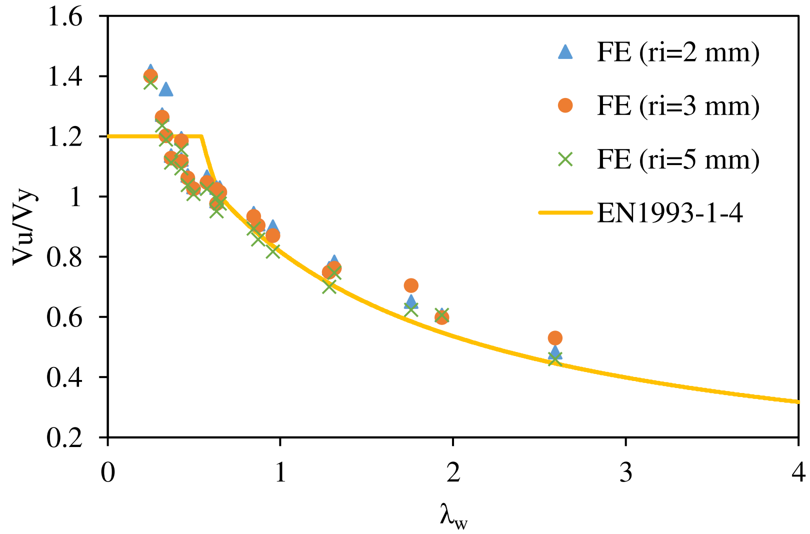


Figure 5: Shear capacities of stainless steel LCBs for ri=2 mm, 3 mm and 5 mm

4.2 Strain-hardening effect

Pronounced strain-hardening effect of stainless steel on the shear behaviour of LCBs were investigated in this section. Shear capacities of stainless steel LCBs were compared against the shear capacities of carbon steel LCBs in this context. In the FE modelling, stainless steel grade 1.4301 was used and for carbon steel FE models elastic-perfectly plastic material model with a yield stress equals to 0.2 % proof stress of stainless steel grade 1.4301 was used. Four LCBs (LCB 100×50×15, LCB 150×65×15, LCB 200×75×15 and LCB 250×75×15) and five material thicknesses (1 mm, 2 mm, 3 mm, 4 mm and 5 mm) were considered herein. Shear capacities are compared in Figure 6. From the results it can be concluded that the effect of strain-hardening is more significant in compact sections where more than 40 % shear capacity increment can be expected in stainless steel sections compared to carbon steel sections when web slenderness (λ_w) is less than 0.25 while that for slender sections are negligible. This capacity increment in compact sections is known as inelastic reserve capacity. However, a value of 1.2 has been introduced in EN1993-1-4 to include this additional capacity in the design process seems to be too conservative.

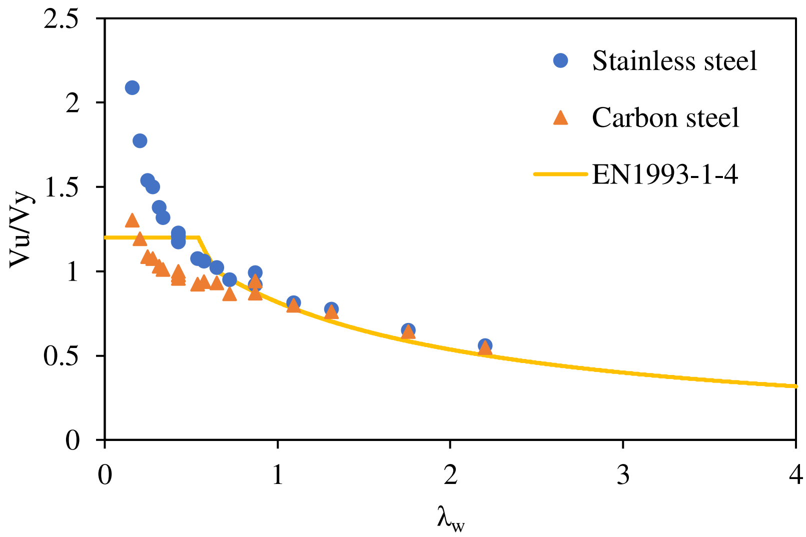


Figure 6: Comparison of shear capacities for stainless steel and carbon steel LCBs

5. Concluding Remarks

Due to the cold-work of forming, stainless steel sections undergo strength enhancements during the manufacturing process. These are localised to corner regions in press-braked sections. Previous research has been conducted to predict these strength enhancements in stainless steel sections. In this study, the effect of corner strength enhancement on shear capacity of LCBs was investigated. The r_i/t ratio of the sections covered in this study varied from 0.4 to 5. From the results, it can be concluded that corner strength enhancement is more pronounced on compact sections where up to 9% shear capacity increment can be observed from corner enhancement for press-braked LCBs. Further, it was demonstrated that the effect of internal radius on the shear capacity is negligible for LCBs. Another study was conducted to investigate the strain-hardening effect on shear behaviour of stainless steel LCBs. Due to the strain-hardening effect, more than 40 % shear capacity increment can be observed for compact sections when web slenderness is less than 0.25 while that for slender sections is negligible.

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