3D FEM to Predict Residual Stresses of Press-Braked Thin-Walled Steel Sections

Ayad Mutafi, N. Yidris, M. R. Ishak and R. Zahari

Abstract Cold-formed steel sections are normally produced by cold work manufacturing processes. The amount of cold work to form the sections may have induced residual stresses in the section especially in the area of bending. Hence, these cold work processes may have significant effects on the section behaviour and load-bearing capacity. There was a lack of studies in investigating the effects of residual stresses raised by press-braking operations unlike the roll-forming operation. Therefore, a 3D finite element simulation was employed to simulate this forming process. This study investigated the magnitude of the maximum residual stresses along the length of the corner region and through-thickness residual stress variations induced by the press-braking forming process. The study concluded that residual stresses are not linear longitudinally (along the corner region). Maximum residual stresses exist near the middle surface of the plate. The comparison of the 3D-FE results with the 2D-FE results illustrate that 3D-FE has a variation in transverse and longitudinal residual stresses along the plate length. In addition, 2D-FE results overestimate the residual stresses along the corner region.

Keywords Cold-formed steel · FEM · Residual stresses

1 Introduction

Cold-formed steel sections are produced by cold work manufacturing processes. It is known that these processes have significant effects on the section behaviour and load-bearing capacity. This is due to the amount of cold work to form the sections that produce residual stresses. The high amounts of the residual stresses reduce the load capacity of the section, as stated by Quach [1].

There were many attempts to measure the residual stresses. These attempts varied between the experimental and numerical methods. Batista and Rodrigues [2]

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indicated that sections produced by the roll-forming process have residual stresses higher than the press-braking process. Their experiment measured the longitudinal stresses of both processes of the same section geometry. Moreover, Weng and Peköz [3] attempted to measure the longitudinal residual stresses of cold-formed sections. Their experiment showed that residual stresses at corner regions are higher than the flat ones. Also, their findings stated that the inner surface is subjected to compressive residual stresses while the outer one is subjected to tensile residual stresses. Weng and White [4] have conducted an experimental study to measure surface residual stresses. The study also measured through-thickness residual stresses on thick cold bent steel plates using the sectional method. It was reported that through-thickness residual stress distribution was of the zigzag type and the maximum residual stress either occurs at the inside surface of the bend or near the neutral surface of the plate.

Numerical attempts to predict the residual stresses have been done by few researchers [5–9]. These works were intended to introduce alternatives in measuring the residual stresses because measurements by destructive methods have limitations in accuracy and are time-consuming. Moen et al. [5] presented an analytical method for predicting residual stresses in sections formed by the roll-forming process. The study also included several analytical approaches for determining residual stress distribution through the thickness of rolled sheet. Their motivation of the study is to define residual stresses of cold formed steel at its initial state. Quach et al. [6, 7] established a closed-form analytical method for predicting residual stresses and equivalent plastic strains from coiled, uncoiled, and mechanical flattening of carbon steel sheets. Then he implemented the finite element 2D technique for press-braked sections as an alternative of laboratory measurements to predict residual stresses distribution. The outcomes showed good agreement with experimental values.

Most of the studies investigated the effects of roll-forming operations on steel section behaviours. Press-braking was not of much interest to many researchers except for [7–9]. These studies confirmed the residual stresses variation through the thickness by 2D FE model. However, Quach et al. [1, 10] stated that stress distribution changes in a narrow region close to the member edges which are free of stresses. Therefore, this makes the 2D-FE insufficient for determining the residual stresses distribution. This study aims to investigate the residual stresses along the corner region by simulating a 3D finite element model. The main motivation of this study is to establish a comparison between 2D and 3D FEM in the determination of the maximum residual stresses.

2 Simulation of Press-Braking Process

2.1 Scope

Press-braking is a simple section forming process where flat sheet material is placed between a punch and die and folded along the length of the member as shown in Fig. 1. The investigation into the finite element modelling technique for estimating residual stresses introduced by the press-braking process is restricted to the corner region where it experiences the stamping force due to punch movement. Residual stresses at the flat regions are introduced by coiling and uncoiling. This study simulated a section tested by Weng and Peköz [3]. Their experiment results are important to validate finite element results.

2.2 Model Description

An explicit finite element code in ABAQUS [11] was employed to simulate the forming process (Press-braking process). As mentioned earlier, finite element modelling is restricted to the corner region where it experiences the stamping force due to punch movement. Residual stresses at the flat regions are raised by coiling and uncoiling. The implementation of explicit analysis is more effective in quasi-static problems such as metal forming.

The model contains three parts: Punch, Die, and Steel sheet. The punch and die were modelled by an analytical model and the steel sheets were deformable shells with a four-node, quadrilateral, stress/displacement shell element with reduced integration and a large-strain formulation (S4R) [11]. This element can handle large strains and rotations. Simpson's rule with 11 integration points was used for integration across the shell wall thickness. The interaction between the model parts was simulated by general contact.

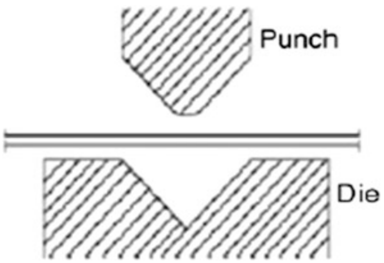


Fig. 1 Press-braking process of cold formed steel

2.3 Geometrical Properties

The section properties were extracted from [3]. A thin-walled lip channel section with 3.96 mm corner radius was investigated for residual stress distribution through thickness. Full details on geometrical properties of the section are presented in Table 1, Fig. 3.

2.4 Material Properties

The modelling of material nonlinearity in ABAQUS [11] required the definition of a true stress—logarithmic plastic strain relationship up to the ultimate point, which was converted from the nominal stress–strain data. Figure 2 shows the nominal stress–strain curves, true stress–strain curves and true stress-logarithmic plastic strain curves that were extracted from the following equations. Regarding Ref. [3] experiment, specimen PBC14 did not provide experimental stress–strain curves [7]

$$\sigma = E\varepsilon, \quad \varepsilon \leq {}^{\sigma_y}\!/_{E} \tag{1}$$

Table 1 Geometrical and material properties of lipped channel sections

Specimen	t (mm)	a (mm)	b (mm)	c (mm)	R (mm)	σ_y (MPa)	σ_u (MPa)	$\varepsilon_y(\times 10^{-6})$	E (GPa)	n ($\times 10^{-2}$)	ε_u^a%
PBC 14	1.80	76.23	41.45	15.37	3.96	250.1	345	1230	203.3	9.56	33

Where R is the corner radius, σ_y is yield stress, σ_u is ultimate stress, ε_y is yield strain, ε_u is ultimate strain and E is modulus of elasticity

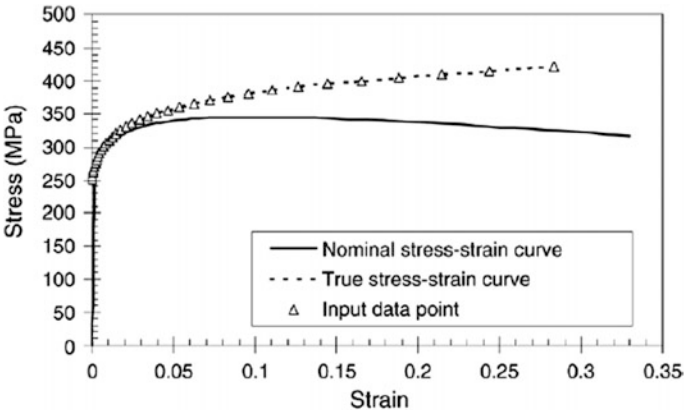


Fig. 2 Weng and Peköz specimen PBC14 [7]

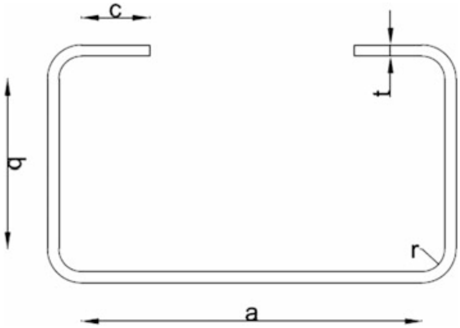


Fig. 3 Dimensions of a lipped channel section

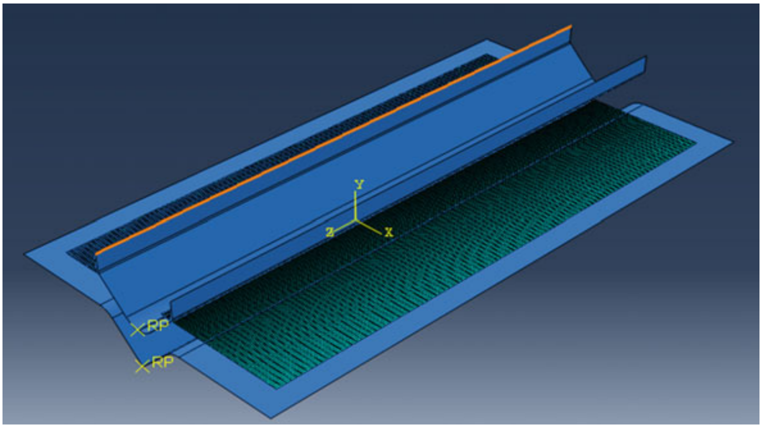


Fig. 4 FE model

$$\sigma = \sigma_y \left(\frac{E_\varepsilon}{\sigma_y} \right)^n, \quad \varepsilon > \sigma_y / E \tag{2}$$

Full details on geometrical, material properties of the section and FE model are presented in Table 1, Figs. 3 and 4.

2.5 Mesh Convergence Study

Mesh convergence studies have been performed for a rectangular metal sheet subjected to metal forming by press-braking in order to determine the optimal density of mesh in the sheet metal model. Four mesh densities were examined and the residual stresses of the steel sheets were noted. The shorter edge of the plate had

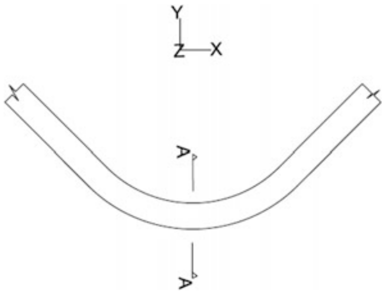


Fig. 5 The selected longitudinal lines

number of seeds that was higher than the longer edge as at this location, the metal sheet had interaction with the punch and the die, hence experienced large bending.

In this study, the stress results of three longitudinal node lines—mid-corner line A-A was monitored and shown in Fig. 5. The steel sheet can be divided into three regions: a corner region and two flat regions. The location of point A is at the middle of the bend curve. This location was selected in order to verify the finite element results with those of Refs. [3, 7].

In this convergence study, maximum compressive residual stresses are taken into account as these stresses have influence in the section buckling strength [12]. This study examined the stresses at the mid-corner line (A-A) only. Table 2 summarizes the results on the convergence test.

From Table 2, a mesh of 300 × 150 is taken as a reference to evaluate the accuracy of the other three meshes. It can be seen that the mesh with 200 × 150 showed results closer to the reference mesh. Therefore, the mesh with 200 × 150 is the adopted mesh for this study.

Table 2 Comparison of maximum compressive stresses for PBC14 at mid-corner line (A-A)

Mesh	No. of elements	Max. compressive residual stresses			
		$\sigma_{Tran.}$ (MPa)	Diff. %	$\sigma_{Long.}$ (MPa)	Diff. %
(150 × 100)	15,000	278.74	0.75	164.58	0.22
(200 × 100)	20,000	275.95	−0.26	164.35	0.08
(200 × 150) Adopted	30,000	276.83	0.06	162.66	−0.95
(300 × 150)	45,000	276.66	0.0	164.22	0.00

3 Results and Discussions

3.1 Validation of the Results

When performing numerical simulations, it is essential that the results from the finite element analyses be compared with independent published work. Consideration has been given to the work of Weng and Peköz [3] and also Quach's 2D finite element simulation [7]. Quach et al. [6] concluded that the magnitudes of residual stresses were sensitive to the coiling radius and the yield stress of the material; the larger the radius the smaller the stresses. Hence, this study assumed that residual stresses arising from the coiling and uncoiling process is negligible by considering that the coil diameter has the magnitude of 1100 mm [7].

The residual strain at flat regions were determined by the closed-form analytical solution presented in [6] that predicts residual stresses and equivalent plastic strains from the coiling-flattening process. Transverse to longitudinal stress ratio is expressed as a function of the distance from the mid-plane and the material behaviour is assumed to be elastic-perfectly plastic.

Figure 6 shows a good agreement between this study and results of plastic strain in Refs. [3, 7]. Therefore, the 3D FE results of this study are validated. Comparing the results in Fig. 6, 3D-FE longitudinal strains give a good prediction than the results in 2D-FE.

3.2 Results Comparison

Previous numerical studies agreed that maximum residual stresses location is near the middle surface of the corner region [3, 5, 7]. Earlier experimental study suggested that the magnitude of longitudinal residual stresses at the corner area is in the

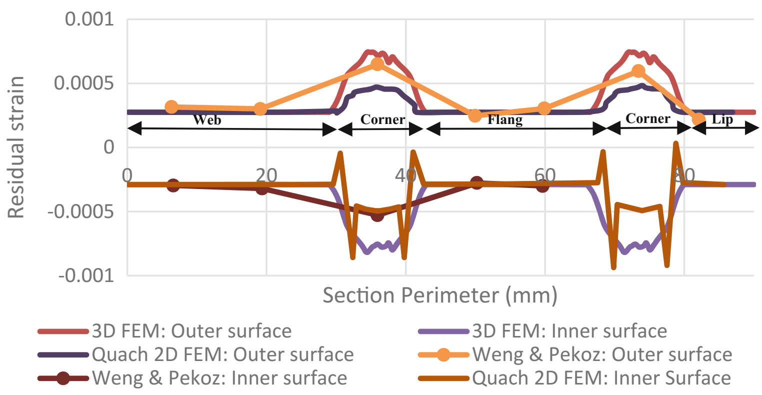


Fig. 6 Comparison of residual strain of section PBC14

Table 3 Comparison of residual stresses (PBC14 Specimen)

	A-A (Mid-corner)			
	σ_z/σ_y		σ_x/σ_y	
	Tensile	Comp.	Tensile	Comp.
Experiment [3]	0.25–0.7	0.25–0.7	–	–
2D-FE [7]	0.5	0.9	0.8	1.4
3D-FE	0.68	0.65	1.28	1.11

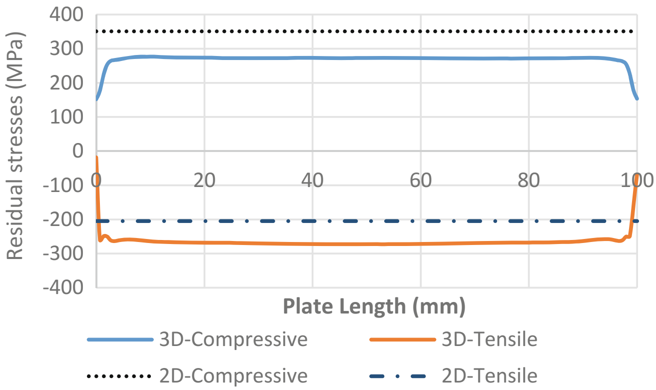
range of 0.25–0.7σ_y yield stress [3]. Also, compression residual stresses were found at the inner surface and tensile residual stresses found at the outer surface. Meanwhile the 2D-FE analysis results in [7] showed that peak longitudinal and transverse compression residual stresses at the mid-corner (A-A) were 0.9σ_y and 1.4σ_y respectively and peak longitudinal and transverse tensile residual stresses were 0.5σ_y and 0.8σ_y at the mid-surface.

In the present study, maximum residual stresses were located near the middle layer of the plate. At the mid-corner, maximum longitudinal compressive and tensile residual stresses are about 0.68σ_y and 0.65σ_y respectively and are located near the mid-layer of the plate. Additionally, peak transverse compressive and tensile residual stresses are found near the mid-layer and they are 1.28σ_y and 1.11σ_y respectively. The summary of the comparison between the current work and Refs. [3, 7] is shown in Table 3.

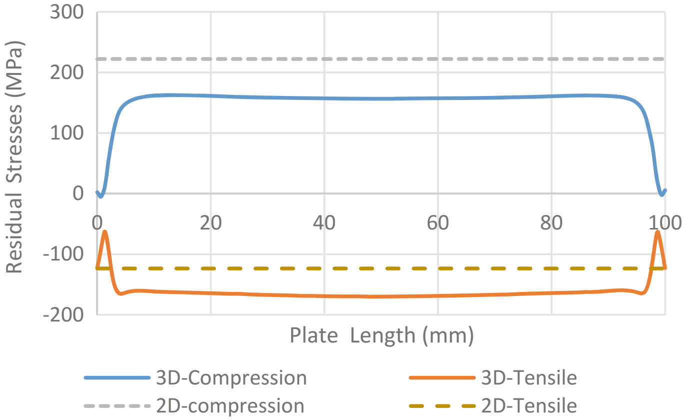
Figure 7 shows that the 2D-FE results predicted residual stresses to be linear along the corner region. However, 3D-FE shows that residual stresses are not linear especially near the plate edges where it is lower than the rest of the plate.

4 Future Work

There will be future work implementing the same finite element technique to investigate the effects of geometrical properties (Corner radius and sheet thickness) on the prediction of maximum residual stresses.



a) Maximum Transverse residual stresses



b) Maximum Longitudinal residual stresses

Fig. 7 Maximum residual stresses in 3D-FE versus 2D-FE

5 Conclusion

Cold formed steel sections are normally produced by cold work manufacturing processes. The amount of cold work to form the sections may have induced residual stresses in the section especially in the area of bending. Studies by researchers in the past on the effects of local buckling on the failure mechanics of thin-walled compression members have shown that ultimate failure will occur when the yielding has reached most of the middle surface in the corner region of the sections. Hence, these cold work processes may have significant effects on the section behaviour and load-bearing capacity. Most of the studies have investigated the effects of residual stresses arising from roll-forming operations and its influence on steel section behaviour. Press-braking has not been of much interest to researchers. Therefore, a 3D finite element simulation was employed to simulate this forming process. This study investigated the magnitude of the maximum residual stresses along the length of the corner region and through-thickness residual stress variations induced by the press-braking forming process. The study concluded that residual stresses are not linear longitudinally (along the corner region). Maximum residual stresses exist near the middle surface of the plate. The comparison between the 3D-FE results with existing 2D-FE results illustrate that 3D-FE results show a variation in transverse and longitudinal residual stresses along the plate length. In addition, 2D-FE results overestimated the residual stresses along the corner region.

References

1. Quach, W.M., Teng, J.G., Chung, K.F.: Effect of the manufacturing process on the behaviour of press-braked thin-walled steel columns. Eng. Struct. **32**(11), 3501–3515 (2010)
2. Batista, E.D.M., Rodrigues, F.G.: Residual stress measurements on cold-formed profiles. Exp. Tech. **16**(5), 25–29 (1992)
3. Weng, C.C., Pekoz,T.: Residual stresses in cold-formed steel members. J. Struct. Eng. **116**(6), 1611–1625 (1990)
4. Weng, C.C., White, R.: Residual stresses in cold-bent thick steel plates. J. Struct. Eng. **116**(1), 24–39 (1990)
5. Moen, C.D., Igusa, T., Schafer, B.W.: Prediction of residual stresses and strains in cold-formed steel members. Thin-Walled Struct. **46**(11), 1274–1289 (2008)
6. Quach, W.M., Teng, J.G., Chung, K.F.: Residual stresses in steel sheets due to coiling and uncoiling: a closed-form analytical solution. Eng. Struct. **26**(9), 1249–1259 (2004)
7. Quach, W.M., Teng, J.G., Chung, K.F.: Finite element predictions of residual stresses in press-braked thin-walled steel sections. Eng. Struct. **28**(11), 1609–1619 (2006)
8. Quach, W.M., Teng, J.G., Chung, K.F.: Residual stresses in press-braked stainless steel sections, I: coiling and uncoiling of sheets. J. Constr. Steel Res. **65**(8–9), 1803–1815 (2009)
9. Quach, W.M., Teng, J.G., Chung, K.F.: Residual stresses in press-braked stainless steel sections, II: press-braking operations. J. Constr. Steel Res. **65**(8–9), 1816–1826 (2009)
10. Abambres, M., Quach, W.-M.: Residual stresses in steel members: a review of available analytical expressions. Int. J. Struct. Integrity **7**(1), 70–94 (2016)
11. ABAQUS 6.13-4: Dassault Systèmes Simulia Corp., Providence, RI (2013)
12. Loughlan, J., Yidris, N., Cunningham, P.R.: The effects of local buckling and material yielding on the axial stiffness and failure of uniformly compressed I-section and box-section struts. Thin-Walled Struct. **49**(2), 264–279 (2011)