



## Nonlinear finite element analysis of cold-formed steel plain angle columns

Mustafa Durmaz <sup>a,\*</sup>, Ayşe Daloğlu <sup>b</sup>

<sup>a</sup> Department of Civil Engineering, Gümüşhane University, 29100 Gümüşhane, Turkey

<sup>b</sup> Department of Civil Engineering, Karadeniz Technical University, 61080 Trabzon, Turkey

### ABSTRACT

The main objective of this paper is to provide an efficient and accurate finite element model to understand the behavior of cold-formed steel plain angle columns. The effects of initial local and overall geometric imperfections have been taken into consideration in the analysis. The material nonlinearities of flat and corner portions of the angle sections were incorporated in the model. Failure loads and buckling modes as well as load-shortening curves of plain angle columns were investigated in this study. The nonlinear finite element model was verified against experimental results. The finite element analysis was performed on plain angles compressed between fixed ends over different column lengths, and column curves were obtained.

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### 1. Introduction

Cold-formed steel structures have many advantages in terms of their superior strength-to-self-weight ratio, ease of construction, and economic design. In recent years, developed manufacture techniques and increased strength of materials gave the edge to cold-formed steel over traditional hot rolled steel in the construction of a wide range of structures (Ellobody and Young, 2005).

Some researchers carried out experimental investigation to study the behavior of cold-formed steel angle columns. Madugula et al. (1983) carried out 16 tests on single equal-leg angles 45x45x3 mm and 65x65x4 mm with hinged end conditions. The nominal slenderness ratios of the test specimens varied from 90 to 250 and comparison of test results with design strengths predicted from different codes of practice was investigated. Popovic et al. (1999) presented the results of 12 fixed-ended and 18 pin-ended compression tests performed on cold-formed plain angle columns. The nominal sizes of angles were 50x50x2.5, 50x50x4, and 50x50x5 with  $b/t$  ratios (flat flange width-to-thickness ratio) of 20.6, 12.2, and 9.6, respectively. Young (2004) conducted a series of tests on cold-formed steel plain angle columns compressed between fixed ends. The angle sections were brake-pressed

from high strength structural steel sheets and had a  $b/t$  ratio ranging from 35.8 to 57.9. The test results were compared with design strengths obtained from the AISI Specification (1996) and AS/NZS standard (1996) for cold-formed steel structures. It is concluded that the design strengths are generally very conservative for all column lengths. Hence design equations for cold-formed steel plain angle columns were proposed.

The behavior of cold-formed steel columns is affected by initial geometric imperfections and residual stresses. Weng and Pekoz (1990) carried out a detailed experimental study of residual stresses effect on the strength of cold-formed steel members. It is found that the residual stress distribution in cold-formed steel sections is different from that in hot-rolled steel sections. Jiao and Zhao (2003) investigated the effect of initial geometric imperfections, residual stresses, and yield slenderness limit on the behavior of very high strength circular steel tubes.

An accurate finite element model is needed to predict the complex behavior of thin-walled structures. It can be quite costly and time consuming for experimental investigation. A detailed finite element study was carried out by Young and Yan (2002) for the analysis and design of fixed-ended plain channel columns. A finite element program ABAQUS was used in the analysis. The four-

node doubly curved shell element with reduced integration and hourglass control (S4R5) was used in the model. The element has five degrees of freedom per node. The results of the finite element analysis were compared with the results of experimental investigation. Durmaz and Daloğlu (2007, 2009) provided a nonlinear finite element model to investigate the behavior of hot-rolled steel angles subjected to concentric and eccentric axial loads. It was found that the finite element model generally provided good predictions of the experimental failure loads.

The main objective of this paper is to simulate the behavior of cold-formed steel plain angle columns using the finite element method. The finite element program ABAQUS 6.13 (2013) was used in the analysis. The results obtained from the model are verified against test results carried out by Young (2004).

## 2. Experimental Investigation

### 2.1. General

The experimental investigation of cold-formed steel plain angle columns performed by Young (2004) provided the experimental ultimate loads and failure modes of columns compressed between fixed ends. The test specimens were brake-pressed from high strength zinc-coated grades G500 and G450 structural steel sheets having nominal yield stresses of 500 and 450 MPa, respectively. Each specimen was cut to a specified length of 250, 1000, 1500,

2000, 2500, 3000 and 3500 mm. Three series of plain angles were tested, having a nominal flange width of 70 mm. The nominal plate thicknesses were 1.2, 1.5, and 1.9 mm. The three series were labeled P1.2, P1.5, and P1.9 according to their nominal thickness. The measured inside corner radius was 2.6 mm for all specimens. The measured cross-section dimensions of the test specimens are detailed in Young (2004).

The Young's modulus ( $E$ ) was measured as 208, 207, and 208 GPa for Series P1.2, P1.5, and P1.9, respectively. The measured static 0.2% proof stress ( $\sigma_{0.2}$ ) was 550, 530, and 500 MPa for Series P1.2, P1.5, and P1.9, respectively. The initial overall geometric imperfections of the specimens were measured prior to testing. The maximum overall imperfections at mid length were 1/2950, 1/2150, and 1/1970 of the specimen length for Series P1.2, P1.5, and P1.9, respectively. A servo controlled hydraulic testing machine was used to apply compressive axial force to the specimen. The fixed-ended bearings were designed to restrain against the minor and major axis rotations as well as twist rotations and warping.

The initial local geometric imperfections, residual stresses, and corner material properties of the tested plain angle specimens were not reported by Young (2004). However, the values of these measurements are important for finite element analysis. Hence the initial local imperfections, residual stresses, and corner material properties of the angle specimens belonging to the same batch as the column test specimens were measured by Ellobody and Young (2005) and used in this paper.

### 2.2. Initial local geometric imperfections

Measurements of initial local imperfections were carried out by Ellobody and Young (2005) by using the coordinate measuring machine. A plain angle test specimen of 300 mm in length for Series P1.5 was used for the measurement of local imperfections. The measurements were taken at the middle and quarter lengths of the specimen. Readings were taken at regular intervals and maximum magnitude of local plate imperfection was 0.0021 mm, which is equal to 0.14% of the angle thickness. The same factor was used to predict the initial local geometric imperfections for Series P1.2 and P1.9.

### 2.3. Residual stresses

The same plain angle specimen used in measuring the initial local geometric imperfections was used by Ellobody and Young (2005) in measuring the residual stresses. The common method to determine the residual stresses is the method of sectioning that requires cutting the plain angle into strips to release the internal residual stresses. By measuring the strains before and after cutting, consequently residual stresses can be determined. The angle specimen was marked into strips of 10 mm width as shown in Fig. 1.

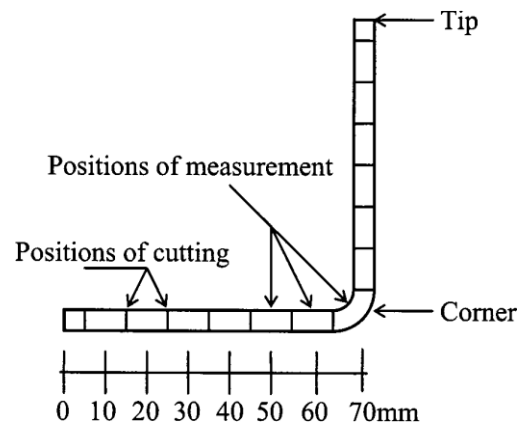


Fig. 1. Positions of wire cutting and measurements for the determination of residual stresses.

Residual stresses are calculated by multiplying residual strains by Young's modulus of the test specimen of Series P1.5. Table 1 summarizes the membrane and bending residual strains at the measurement sections with reference to the plain angle tip. The distribution of membrane and bending residual stresses in the cross section of the test specimen is shown in Fig. 2.

### 2.4. Material properties

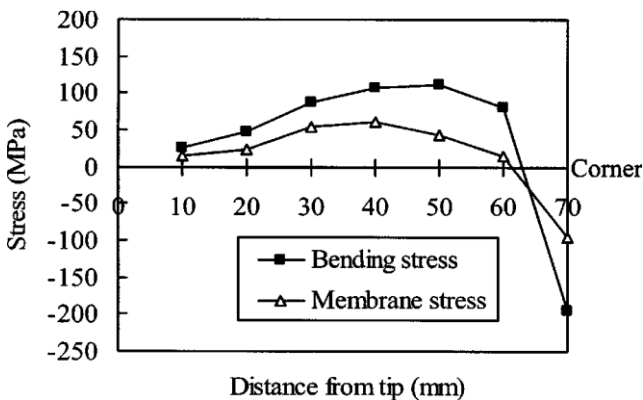
The material properties in the corner of the angle section were determined for Series P1.5 by Ellobody and Young (2005) by carrying out a tensile coupon test. The corner coupon specimen was taken from the corner strip after the wire cutting of the specimen used to measure the residual stresses. The corner coupon specimen was curved before testing, and the effect of bending residual

stresses is included in the stress-strain curve of the corner tensile coupon test. The material properties of the corners of Series P1.2 and P1.9 were extrapolated from the material properties of the Series P1.5 according to the measured 0.2% tensile proof stress ( $\sigma_{0.2}$ ) in the flat portions of each series. The measured and predicted ma-

terial properties of the corner coupons can be summarized as follows: Young's modulus ( $E$ ) of 203 GPa for the three series. The static 0.2% proof stress ( $\sigma_{0.2}$ ) was 635, 610, and 575 MPa for Series P1.2, P1.5, and P1.9, respectively. The tensile strain after fracture ( $\epsilon_u$ ) was 3% for the three tests series.

**Table 1.** Measured membrane and bending residual strains for series P1.5.

Distance from tip (mm)	Membrane strain ( $\mu$ strain)	Bending strain ( $\mu$ strain)
10	75	125
20	115	235
30	260	420
40	300	520
50	210	540
60	75	395
70 (corner)	-460	-940



**Fig. 2.** Distribution of membrane and bending residual stresses along the cross section of Series P1.5.

### 3. Finite Element Modeling

#### 3.1. General

In this study, the finite element program (ABAQUS, 2013) was used in the analysis of plain angle columns tested by Young (2004). The model used the nominal sizes, initial local and overall geometric imperfections, residual stresses, and material properties. Finite element analysis for buckling requires two types of analyses. The first is known as eigenvalue analysis that estimates the buckling modes and loads. Such an analysis is a linear elastic analysis performed using the (\*BUCKLE) procedure available in the ABAQUS library with the live load applied within the step. The buckling analysis provides the factor by which the live load must be multiplied to reach the buckling load. For practical purposes, only the lowest buckling mode predicted from the eigenvalue analysis is used. The second is called load-displacement nonlinear analysis and follows the eigenvalue prediction. It is necessary to consider whether the post buckling response is stable or unstable.

#### 3.2. Finite element type and mesh

It is mentioned in the ABAQUS manual that the four-noded doubly curved shell element with reduced integration S4R is suitable for complex buckling behavior (ABAQUS, 2013; Nandula, 1998; Young, 2004). The S4R element has six degrees of freedom per node and provides accurate solutions to most applications. The element also accounts for finite strain and is suitable for large strain analysis. Since buckling of plain angle columns is very sensitive to large strains, the S4R element was used in this study to ensure the accuracy of the results. In order to choose the finite element mesh that provides accurate results with minimum computational time, convergence studies were conducted. It is found that a 10 mm x 10 mm (length by width) ratio provides adequate accuracy in modeling the angles.

#### 3.3. Boundary conditions and load application

Following the testing procedures for Series P1.2, P1.5, and P1.9, the ends of the columns were fixed against all degrees of freedom except for the displacement at the loaded end in the direction of the applied load. The nodes other than the two ends were free to translate and rotate in any direction. The load was applied in increments using the modified RIKS method available in the ABAQUS library. The RIKS method is generally used to predict unstable and nonlinear collapse of a structure such as post buckling analysis. It uses the load magnitude as an additional unknown and solves simultaneously for loads and displacements. The load was applied as static uniform loads at each node of the loaded end which is identical to the experimental investigation. The nonlinear geometry parameter (\*NLGEOM) was included to deal with the large displacement analysis.

### 3.4. Material modeling

The measured stress-strain curves for flat portions of Series P1.2, P1.5, and P1.9 were used in the analysis. In addition, the measured and predicted stress-strain curves of the corner coupons for the same series were used. The material behavior provided by ABAQUS allows for a multilinear stress-strain curve to be used. The first part of the multilinear curve represents the elastic part up to the proportional limit stress with measured Young's modulus and Poisson's ratio equal to 0.3. Since the analysis of post buckling involves large inelastic strains, the nominal (engineering) static stress-strain curve was converted to a true stress and logarithmic plastic strain curve. The true stress ( $\sigma_{true}$ ) and plastic true strain ( $\varepsilon_{true}^{pl}$ ) were calculated using Eqs. (1) and (2).

$$\sigma_{true} = \sigma(1 + \varepsilon), \quad (1)$$

$$\varepsilon_{true}^{pl} = \ln(1 + \varepsilon) - \sigma_{true}/E, \quad (2)$$

where  $E$  is Young's modulus while  $\sigma$  and  $\varepsilon$  are measured nominal (engineering) stress and strain values.

### 3.5. Modeling of initial local and overall geometric imperfections

Cold-formed steel plain angle columns with very high  $b/t$  ratio are likely to fail by pure local buckling. On the other hand, columns with very low  $b/t$  ratio are likely to fail by overall buckling. Both initial local and overall geometric imperfections are found in columns as a result of the fabrication process. Hence superposition of local buckling mode as well as overall buckling mode with measured magnitudes is recommended for accurate finite element analysis (Ellobody and Young, 2005). These buckling modes can be obtained by carrying eigenvalue analysis of the column with very high  $b/t$  ratio and very low  $b/t$  ratio to ensure local and overall buckling occurs, respectively. Only the lowest buckling mode (eigenmode 1) is used in the eigenvalue analysis. This technique is used in this study to model the initial local and overall imperfections of the columns. Since all buckling modes predicted by ABAQUS eigenvalue analysis are generalized to 1.0, the buckling modes are factored by the measured magnitudes of the initial local and overall geometric imperfections (Young and Yan, 2002).

### 3.6. Modeling of residual stresses

To ensure accurate modeling of the behavior of plain angle columns, the residual stresses were included in the finite element model although their effect on the ultimate capacity is considered to be small (Schafer and Pekoz, 1998; Gardner, 2002). Measured residual stresses are implemented in the finite element model by using the ABAQUS (\*INITIAL CONDITIONS, TYPE=STRESS) parameter. Only the membrane residual stresses were modeled in this study.

## 4. Results and Discussion

In the verification of the finite element model, a total of 21 cold-formed steel plain angle columns were analyzed. A comparison between the experimental results and the results of the finite element model is carried out. The main objective of this comparison is to verify and check the accuracy of the finite element model. The comparison of the ultimate loads  $P_{test}$  and  $P_{FEM}$  are shown in Table 2. Fig. 3 plotted the relationship between the ultimate load and the column effective length  $L_{eff}=L/2$  for angles reported by Young (2004), where  $L$  actual column length. The column curves show the experimental ultimate loads together with that obtained by the finite element method. It can be seen that good agreement has been achieved between both results for most of the columns.

**Table 2.** Comparison between test and FE results.

Specimen	$P_{test}$ (kN)	$P_{FEM}$ (kN)	$P_{test}/P_{FEM}$
P1.2L250	23.80	30.30	0.79
P1.2L1000	18.70	22.62	0.83
P1.2L1500	15.20	16.86	0.90
P1.2L2000	12.60	12.11	1.04
P1.2L2500	11.60	10.83	1.07
P1.2L3000	8.00	8.40	0.95
P1.2L3500	5.80	5.91	0.98
Mean			0.937
COV			0.011
P1.5L250	39.60	44.29	0.89
P1.5L1000	31.00	34.32	0.90
P1.5L1500	25.20	25.80	0.98
P1.5L2000	17.50	18.61	0.94
P1.5L2500	15.70	15.63	1.00
P1.5L3000	13.10	13.01	1.01
P1.5L3500	11.50	11.41	1.01
Mean			0.962
COV			0.002
P1.9L250	57.70	62.86	0.92
P1.9L1000	47.80	53.37	0.90
P1.9L1500	35.60	37.10	0.96
P1.9L2000	27.10	29.38	0.92
P1.9L2500	22.40	24.49	0.91
P1.9L3000	14.80	20.04	0.74
P1.9L3500	14.40	16.16	0.89
Mean			0.891
COV			0.005

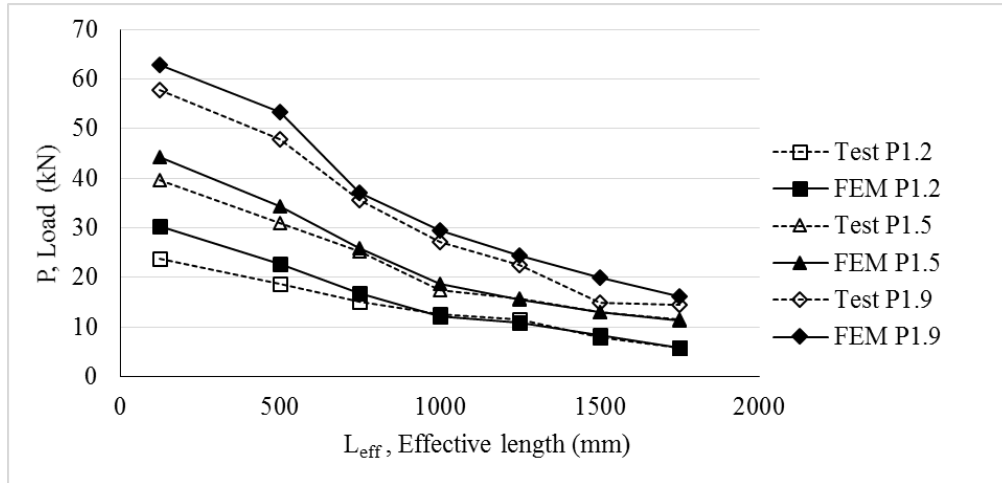


Fig. 3. Ultimate loads of plain angle columns for Series P1.2, P1.5, and P1.9.

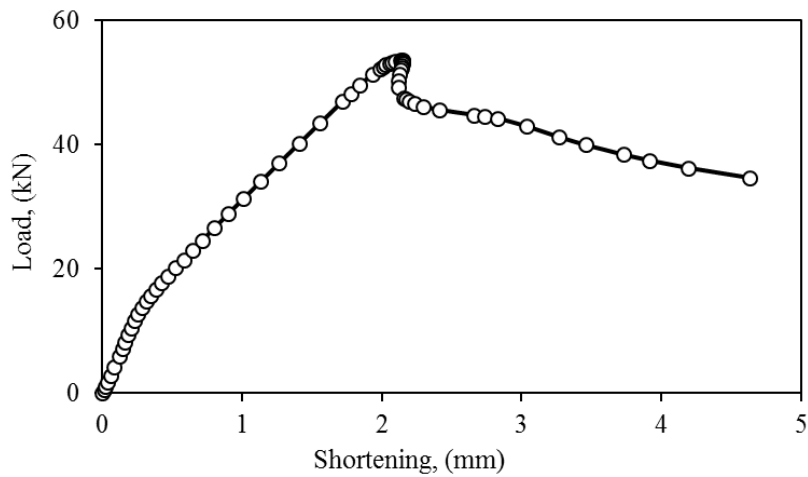


Fig. 4. Load-axial shortening curve for P1.9L1000.

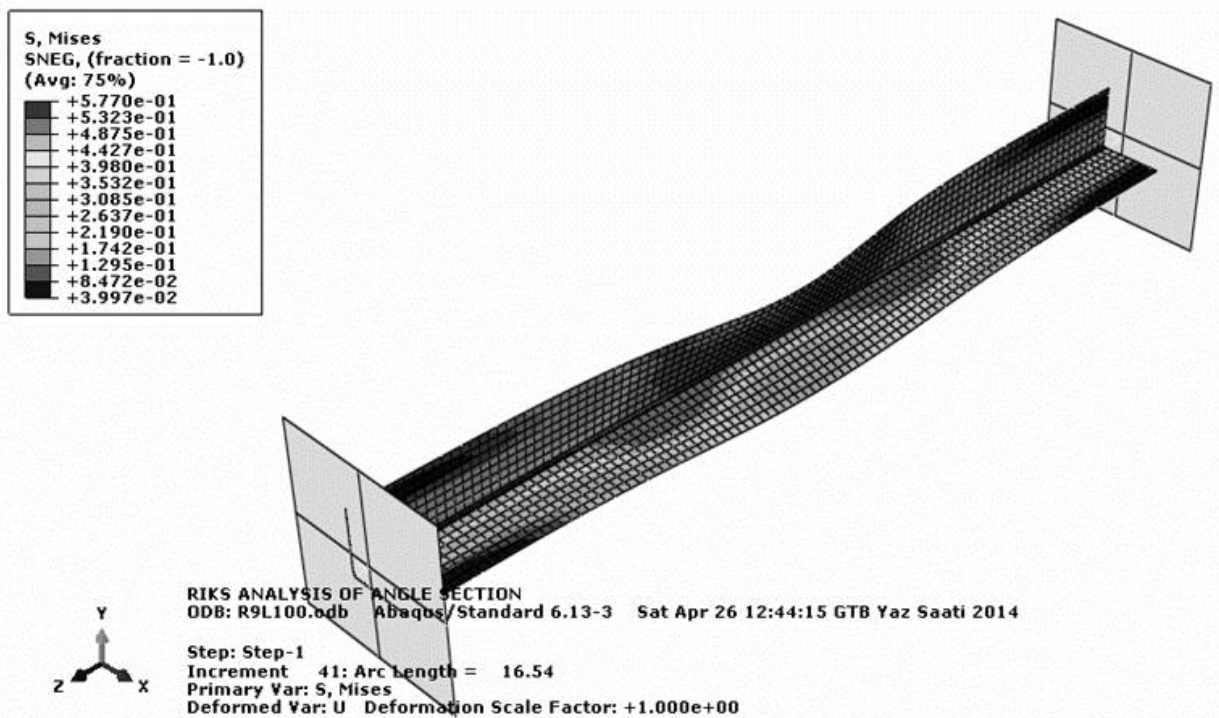


Fig. 5. Failure mode of column P1.9L1000.

## 5. Conclusions

This paper provides an efficient finite element model for the analysis of cold-formed steel plain angle columns. The initial local imperfections, residual stresses, and corner material properties of the cold-formed steel angle test specimens have been measured and reported in this paper. The finite element model includes initial local and overall geometric imperfections and residual stresses. Nonlinear material properties of flat and corner portions of plain angle columns are also considered in the analysis. The comparison between the finite element results and the experimental investigation of 21 columns with different geometric dimensions showed good agreement in predicting the columns behavior. The column strengths, load-shortening behavior, and failure modes have been predicted using the finite element model and compared well with the experimental results.

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## REFERENCES

- ABAQUS (2013). Standard User's Manual. Hibbit, Karlsson and Sorensen, Inc., Vols. 1, 2 and 3, Version 6.13.
- American Iron and Steel Institute (AISI) (1996). Specification for the Design of Cold-Formed Steel Structural Members, Washington, D.C.
- Australian/New Zealand Standard (AS/NZS) (1996). Cold-Formed Steel Structures, AS/NZS 4600:1996, Standards Australia, Sydney, Australia.
- Durmaz M, Daloğlu A (2007). Merkezi yüklü korniyerlerin yük taşıma kapasiteleri. *2<sup>nd</sup> Steel Structures Symposium*, TMMOB Chamber of Civil Engineers, Eskişehir. (in Turkish)
- Durmaz M, Daloğlu A (2009). Eksantrik yüklü korniyerlerin yük taşıma kapasiteleri. *3<sup>th</sup> Steel Structures Symposium*, TMMOB Chamber of Civil Engineers, Gaziantep. (in Turkish)
- Ellobody E, Young B (2005). Behavior of cold formed steel plain angle columns. *Journal of Structural Engineering*, 131(3), 457-466.
- Gardner L (2002). A New Approach to Structural Stainless Steel Design, *Ph.D. Thesis*, Department of Civil and Environmental Engineering, Imperial College of Science, Technology and Medicine, London.
- Jiao H, Zhao XL (2003). Imperfections, residual stress and yield slenderness limit of very high strength (VHS) circular steel tubes. *Journal of Constructional Steel Research*, 59, 233–249.
- Madugula MKS, Prabhu TS, Temple MC (1983). Ultimate strength of concentrically loaded cold-formed angles. *Canadian Journal of Civil Engineering*, 10, 60–68.
- Nandula R (1998). Finite Element Analysis of Eccentrically Loaded Angles, *M.Sc. Thesis*, University of Windsor, Windsor, Ontario, Canada.
- Popovic D, Hancock GJ, Rasmussen KJR (1999). Axial compression tests of cold-formed angles. *Journal of Structural Engineering*, 125(5), 515–523.
- Schafer BW, Pekoz T (1998). Computational modeling of cold formed steel: Characterizing geometric imperfections and residual stresses. *Journal of Constructional Steel Research*, 47, 193–210.
- Weng CC, Pekoz T (1990). Residual stresses in cold-formed steel members. *Journal of Structural Engineering*, 116(6), 1611–1625.
- Young B (2004). Tests and design of fixed-ended cold-formed steel plain angle columns. *Journal of Structural Engineering*, 130(12), 1931–1940.
- Young B, Yan J (2002). Finite element analysis and design of fixed-ended plain channel columns. *Finite Element Analysis and Design*, 38, 549–566.