Transactions on Modelling and Simulation vol 16, © 1997 WIT Press, www.witpress.com, ISSN 1743-355X

Experimental Evaluation of the Material Properties for Finite Element Analysis of Cold-Formed Steel Sections

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Abstract: Experimental investigations to evaluate the mechanical properties, and the built in residual stresses of channel-shaped cold-roll-formed steel sections are reported in this paper. Tensile coupon tests were used to evaluate the mechanical properties at the flat zones and at the corner zones of the sections. Electrical resistance strain gauges with an "Electrical Discharge Machining" cutting technique was used to establish the magnitudes, and the distributions of residual stresses. Based on the experimental results, analysis models for the stress-strain relationship, the variation of the yield strength, and the residual stresses across the section have been established. The proposed material models have been incorporated within a large deformation elasto-plastic shell finite element to form a model for cold-formed steel sections. The efficiency and the accuracy of the proposed material properties models, as applied to a finite element model has been evaluated against corresponding experimental results of cold-formed steel sections subjected to axial compressive loads.

1. Introduction

Techniques used in the manufacture of cold-formed steel [CFS] sections induce substantial changes on the material characteristics. Large plastic deformations during the forming operations, particularly at the corner zones, result in trapped longitudinal and transversal residual stresses in the section. In addition, the unreleased plastic strains at the corner zones result in significant changes in the mechanical properties of the material. In general, cold-roll-forming of steel sections results in different mechanical properties, and different magnitudes of residual stresses across the different locations of the section. Limited experimental studies on the effects of the cold work on the mechanical properties, and on the magnitude and the variation of the residual stresses of CFS sections exist in the literature.

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Development of any analytical model to predict the behavior of cold-formed steel (CFS) structural members, first requires correct representation of the variation of the material characteristics, such as, [a] mechanical properties (uniaxial stress-strain behavior, including values for the proportional limit, the yield and ultimate strengths, the extent of yielding plateau, and strain hardening parameters), and [b] built in residual stress pattern (initial state of stress). This paper presents the results of two series of experimental investigations, and develops analysis models. The first series is concerned with the evaluation of the mechanical properties, whereas the second series is concerned with the residual stresses. The investigations were performed on two different size zinc-coated lipped channel sections manufactured in Canada. Section:Type (A) [203 mm (8 in.) deep, 1.91 mm (0.075 in.-14 gauge) thick, Grade D steel with a minimum specified yield strength of 345 MPa (50 ksi)] Section:Type(B) [101.5 mm (4 in.) deep, 1.22 mm (0.048 in.-18 gauge) thick, Grade A steel with a minimum specified yield strength of 228 MPa (33 ksi)]. Based on the current results, and as well as the results of previous researchers, this paper proposes analysis models for the variation of the yield strength, the stress-strain relationship, and the distribution of residual stresses across cold-formed channel shaped steel sections. The paper also compares the results based on a finite element analysis incorporating the proposed material models, to the corresponding experimental results on CFS sections subjected to axial compressive loads.

2. Mechanical Properties of Cold-Formed Steel Sections

The mechanical properties of the cold-formed steel channel sections were evaluated based on 41 tensile coupon tests. The coupons were cut along the longitudinal direction of the web, flanges, corners, and lips of the two channel sections. For each position, a minimum of two coupons were tested. The coupons were tested in a 250-kN capacity MTS (Material Test System) machine. A calibrated extensometer of 50 mm gage length was used to measure the axial elongation. A strain range of 10% was adopted for the initial part of the test in order to increase the accuracy of the elongation readings during the elastic behavior of the coupons. Beyond an equivalent strain limit of 0.02, the strain range was increased to 50% in order to monitor the large strain plastic behavior of the coupons up to failure. The stress-strain relationship of a tensile coupon was derived from the load-elongation relationship using the original cross-sectional area and the gage length. The cross-sectional area of a flat coupon was determined by measuring the actual minimum width, and the thickness within the gage length to the nearest 0.01 mm. The minimum base metal thickness was determined by excluding the zinc coating thickness. The study of the resulting stress-strain curves showed that the tensile coupons from flat parts of the web, flange and the lip, have approximately the same stress-strain relationship, yield strength, ultimate strength, and elongation at failure. This behavior of the flat parts is fairly consistent with the mechanical properties associated with the virgin steel sheet, suggesting that the cold-roll forming operation did not affect the flat parts of the section. However, substantial changes in the material behavior were noticed at and around the corner regions as a result of the large plastic deformations caused by the cold forming operation. A considerable increase in the yield and ultimate strengths occur at the corner regions. This increase, however, is accompanied by a severe decrease in ductility and the disappearance of the yielding plateau and the strain hardening range. These results are consistent with the earlier observations made by Karren (1967).

2.1 Analysis Model for Variation of Yield Strength

To incorporate the variation of the yield strength into an analytical model of the cold-formed steel material, it is proposed that a lipped channel CFS section be divided into two zones; a corner zone and a flat zone. Figure 1(a) identifies the proposed corner zone and the flat zone of a lipped channel section. The corner zone consists of all the four curved areas of the section, two equivalent flat areas on both sides of each curved area, and the two lips of the section. The flat zone includes the remaining portions of the web and flanges of the section. Based on the results of the tensile coupons, the yield strength of the flat zone (F_y) is proposed to be uniform, having a value of the specified yield strength of the steel grade of the section. Therefore, no increase in the yield strength is to be considered in the flat zones of the section. The yield strength of the corner zone (F_{yc}) is, however, proposed to have higher value than the corresponding strength of the flat zone. The increase in the corner yield strength (ΔF_y) is proposed to be as follows:

$$\Delta F_y \ \underline{(\text{corner zone})} = 0.60 \left[\frac{B_c}{(r/t)^m} - 1.0\right] F_y \qquad [1]$$

where,

$$B_c = 3.69 \left(\frac{F_u}{F_y}\right) - 0.819 \left(\frac{F_u}{F_y}\right)^2 - 1.79 \ , \qquad m = 0.192 \left(\frac{F_u}{F_y}\right) - 0.068$$

This model suggests that the increase in yield strength at corners is dependant on the ratio between the ultimate strength (F_u) and yield strength (F_y) of the virgin steel material, the inside bending radius of the corner (r), and the thickness of the flat steel sheet (t). This model can be used to predict the increase in the yield strength of the corner area only and is not valid for areas adjacent to corners (which also showed increased yield strengths). The Equation (1) is of the form proposed by Karren (1967), however the coefficient proposed by Karren (1967) was 1.0, instead of 0.60 proposed here in. The current test results and the results given by Karren and Winter (1967), for different shapes of rolled CFS sections, were compared to Equation (1). It was observed that the average increase in the yield strengths measured within the corner zone, as compared to the flat zone yield strength (F_y), usually ranges between 0.82 and 1.23 of the values predicted by Equation (1). Figures 1(b) shows the proposed simplified analysis model for the distribution of the yield strength across the lipped channel section, and the corresponding measured distribution obtained by the tensile coupon tests for both Section type (A) and type (B).

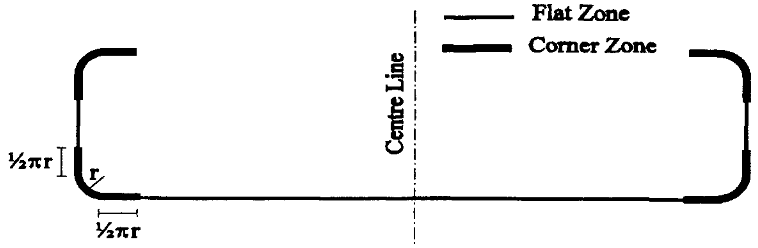
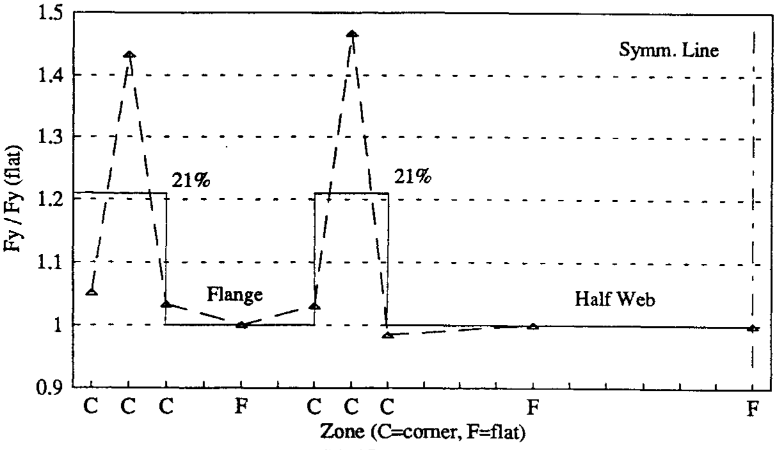
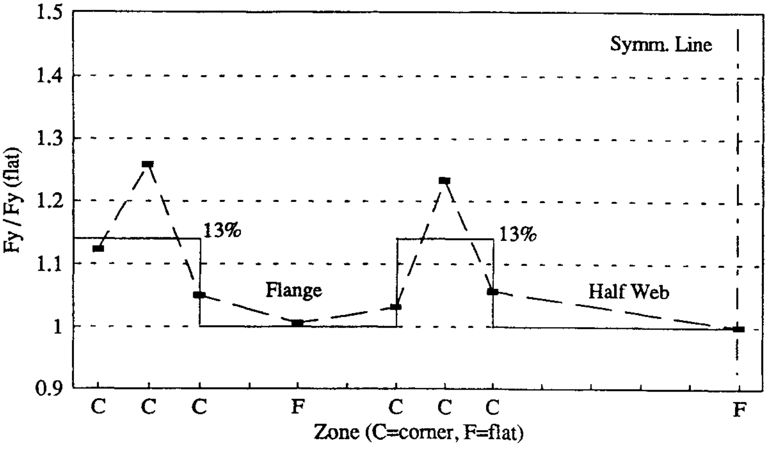


Figure 1(a) Definition of flat and corner zones of a lipped channel section



(b) (Grade D Steel)



(c) (Grade A Steel)

Figures 1(b), (c) Measured and idealized yield strength for channel sections of Grades D and A steels

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2.2 Analysis Model for Stress-Strain Relationship

The stress-strain behavior observed in most of the tensile coupons may be described as initially linear and then a gradual yielding behavior. Thus, an idealized elasto-plastic stress-strain model with a multi-linear isotropic strain hardening rule may be used to account for this behavior. It is proposed that the idealized stress-strain model, as shown in Figure 2, be considered for analysis which is based on the Huber-von Mises elasto-plastic stress-strain model. In this idealized model, the elastic stress-strain behavior is represented by a linear segment up to a proportional strength limit (F_p), which is equivalent to the initial yielding point of the material. The slope of this linear segment equals to the modulus of elasticity (E) The gradual yielding behavior can be idealized using a bi-linear representation (with tangent moduli E_{T1} and E_{T2}) between the proportional limit (F_p) and the yield strength (F_y) with an intermediate point having a stress value of (F_{ym}). This intermediate stress (F_{ym}) is taken as the half-way point strength between (F_p) and (F_y). The behavior beyond (F_y) is characterized as a strain hardening behavior and is represented by a linear segment with a tangent moduli (E_{T3}). Obviously the defining strengths of the idealized stress-strain relationship (F_p, F_{ym}, and F_y) for the corner zones, and the flat zones of the channel section follow the idealization of the yield strength variations presented in the previous section. Based on the test results for both the flat zone and the corner zone of the section, a ratio of (F_p/ F_y) equals to 0.75 is considered appropriate. The modulus of elasticity (E) is considered equal to 203,000 MPa. The proposed values for the tangent moduli (E_{T1}, E_{T2}, and E_{T3}) are 100,000 MPa, 20,000 MPa, and 1,000 MPa, respectively, which are the best approximation based on the stress-strain results of the tensile coupons.

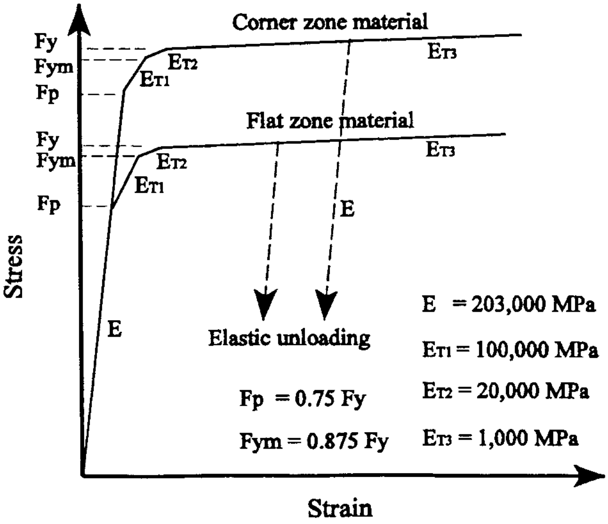


Figure: 2 Idealized Stress-Strain Relationships for Cold-Formed Steel

3. Residual Stresses in Cold-Formed Steel Sections

The magnitudes and distributions of longitudinal and transversal residual surface strains at different positions of cold-formed steel channel sections were investigated in this part of the study. The surface strains were released by slicing the sections into strips using the method of Electrical Discharge Machining (EDM), and the strains were measured using electrical resistance strain gauges. This machining process for metals uses electrical sparks which occur in the gap between the cutting tool (electrode) and the test specimen (work piece), and in an environment of ionized dielectric fluid. The use of the EDM method for a residual stress test, which has many inherent advantages for this application (Abdel Rahman, 1997), is considered a relatively new technique as most of the earlier studies were based on conventional saw cutting. The cutting tool was made of brass, as it is an excellent electric conduction material, and the tool was shaped as a rectangular plate having a thickness of 1 mm. Since the brass cutting tool erodes during the cutting process, a new tool had to be used after every 3 or 4 cuts. A hydrocarbon oil was used as a dielectric fluid, which was continuously circulated during the cutting process to flush away the dusty metal particles from the cut.

Residual stress tests were performed on two identical specimens for each of Section:Type (A)[Length: 600mm] and Section:Type (B)[Length: 300mm]. Strain gauges were mounted on the specimens, after removing the zinc coating layer at the positions of the gauges. See Figure 3(a). Section:Type (A) contained 14 strain gauges, where as 12 strain gauges were mounted on each test specimen of Section:Type (B). In general, the gauges were mounted on both the inside and outside surfaces of the specimens at each position. However, no gauges were mounted on the inside surface at the lip and at the corner adjacent to the lip, since it was difficult to reach the inside surface. All strain gauges were of 5 mm length and were mounted in the longitudinal direction of the section at the mid-length of the test specimen. One 5 mm rosette strain gauge was also mounted at position (8) of one of the test specimen of Section:Type (A) to measure the surface strains in the longitudinal, transversal, and 45 degrees directions of the specimen. The specimen, along with the attached strain gauges, was placed inside the work pan of the machine and lightly clamped to the bed of the pan at its edges. The work pan was then filled with the hydrocarbon oil and the brass cutting tool was mounted in its place. The specimen was supported underneath each cutting path to prevent any local deformations in the surrounding area of the cut. When the cutting sequence was completed, the cut strips were taken out of the work pan, and were left for about 3 minutes to cool down to the normal room temperature. The readings of all the strain gauges were then recorded using the strain indicator.

3.1 Residual Stress Test Results

The measured values of the released surface strains of cold-formed steel channel sections indicate that significant surface residual stresses exist in these sections due to the cold roll-forming operation. Tensile residual stresses were recorded on the outside surface, and compression residual stresses were recorded on the inside surface on all of the channel sections test specimens considered. The location of the highest magnitudes of residual stresses for all the test specimens, is found to be at the web area next to the curved corner (gauges 4 and 5). The lip area (gauge 1) and the flange-lip corner (gauge 14) also show relatively high magnitudes of residual stresses. The web-flange corner (gauges 10 and 11) shows lower magnitudes of residual stresses compared to the flange-lip corner. This variation may be attributed to the forming technique and the arrangement of forming rolls.

One of the important observation from the test results is that the magnitude of the tensile residual stresses on the outside surface is very close to the magnitude of the compressive residual stresses on the corresponding inside surface. Similar observations were reported in the tests performed by Weng and Pekoz (1990). This observation can be interpreted and stated as, the residual stress distribution in a thin cold-formed steel section changes from tensile to compression through the thickness with a linear variation, and having a zero stress at the center line of the section. The residual stresses in both the longitudinal and transversal directions were investigated using the strain rosette readings. The principal strains at this location were found to be (-286.5 $\mu\epsilon$) and (+13.5 $\mu\epsilon$). The difference between the major principal strain and the recorded longitudinal strain (-284 $\mu\epsilon$) at that location is less than 1%. This suggests that the principal residual stress direction is the longitudinal direction of a cold-formed steel section. It also indicates that the magnitudes of transversal residual strains for structural CFS sections are not significant compared to the longitudinal residual strains, and thus may be ignored.

3.2 Analysis Model for Residual Stress Distribution

Based on the current results it is proposed that the residual stress distributions for Sections:Type (A) and Type (B) be modeled as shown in Figures 3(b) and (c). Accordingly, the longitudinal residual stress for the corner zone is about 40% of the yield strength, which represents the average of the measured residual stresses in this zone for all the test specimens considered in the current study. Weng and Pekoz (1990) suggested a value of 50%. For the flat zone, an average residual stress ratio (F_{rl} / F_y) equals to 12% was found to represent the flat areas of Section:Type (A), whereas an average residual stress ratio (F_{rl} / F_y) equals to 18% was found to represent the flat areas of Section:Type (B). These ratios indicate that the cold work, and consequently the residual stresses, tend to increase on the sections having narrower webs. Hence, it is suggested that the ratio (F_{rl} / F_y) in the flat zone of a roll-formed channel sections having any other web width can be interpolated using the above given two ratios as guidelines. As indicated previously, the residual stress distribution through the thickness can be considered linear for the whole cross section of a cold-formed steel member, with tensile stress on the outside surface and equal compression stress on the inside surface at the same location. The residual stress at any layer through the thickness can then be obtained from this linear distribution.

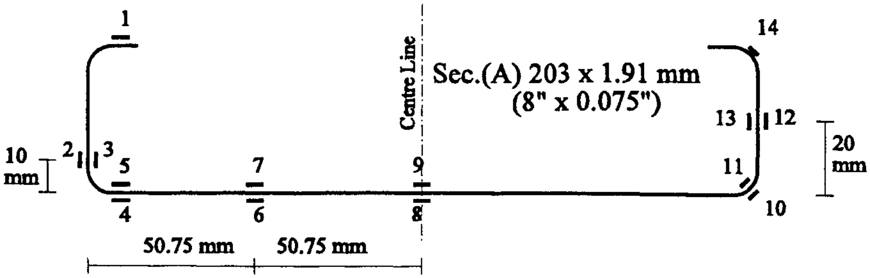
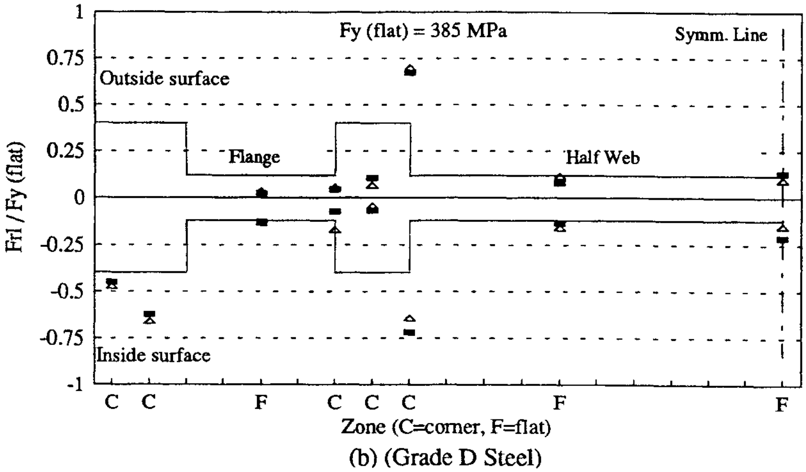
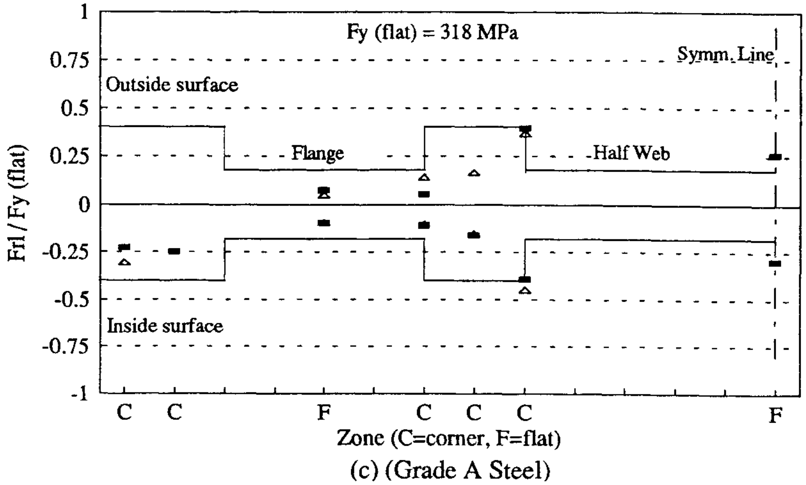


Figure 3(a) Positions of strain gauges for residual strains measurement



(b) (Grade D Steel)



(c) (Grade A Steel)

Figures 3(b), (c) Measured and idealized residual stresses for channel sections of Grades D and A steels

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4. Application of the Proposed Material Models in a Finite Element Analysis

The proposed material properties models for the variation of the yield strength, the stress-strain relationship, and the residual stress distribution in cold-formed steel sections were incorporated within a large deformation elasto-plastic finite element computer model for analysis of such members. The finite element model for the stub-columns utilizes a large deformation degenerated displacement-based isoparametric shell finite element based on the method of "assumed transverse shear and membrane strain fields". The element has nine mid-surface nodes, with three mid-surface displacements, and the two rotations of the mid-surface normals of the element expressed as quadratic polynomials as nodal variables. The method of "assumed strain fields" is used in the current study to eliminate the transverse shear and membrane locking of the general 9-node degenerated shell element (Abdel-Rahman, 1997). Figure 4 shows the finite element mesh for one quarter of the lipped channel stub-column. Symmetric boundary conditions were imposed at the symmetry lines of the one quarter of the stub-column. At the loading edge, the stub-column was subjected to a uniform displacement condition, rather than a uniform loading condition. In order to determine the precise ultimate load, and the post-ultimate behavior of the CFS members in compression, a displacement control algorithm was included within the general finite element program. Initial geometric imperfections were imposed on the finite element model as a double sine wave distribution in the web plate, with a half-wave length equals to the web plate width, which is the expected local buckling shape of the web plate.

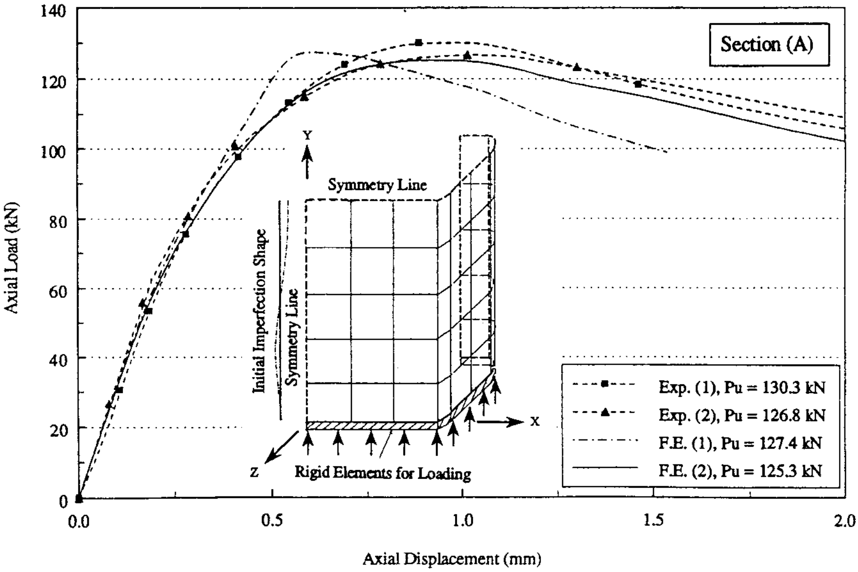

Figure: 4 Axial Load - Axial Displacement Relations for Stub Columns Type (A)

In order to identify the efficiency of the proposed material models two similar cold-formed steel stub-columns of Section:Type (A) were tested under concentric axial loading, till failure. The stub-columns were 475 mm long, which was chosen such that to study the post-local buckling behavior, while retaining the residual stresses, and while excluding the overall buckling mode. The axial loads and the corresponding axial shortening of the stub-columns and the corresponding strain distribution across the stub-column were recorded during the tests. The experimental program consisted of 20 tests on Section:Types (A) and (B), with some members with web opening of various shape and size (Abdel-Rahman, 1997).

Figure 4 shows the axial load-axial displacement curves obtained from the two stub-column tests [Exp. (1) and Exp. (2)] of Section:Type (A), and from two different finite element models [F.E. (1) and F.E. (2)]. The finite element model [F.E. (1)] does not consider any residual stresses, and considers an idealized elastic-perfectly plastic stress-strain relationship with a yield strength equals to the flat yield strength value (Grade D, F_y=385.2 MPa) across the whole section. The second finite element model [F.E. (2)] considers the material properties models proposed in the current study. Both finite element models appear very efficient in predicting the deformations of the CFS section prior to yielding. Both models also predicted somewhat similar ultimate loads, which are in good agreement with the experimental ultimate loads. However, a significant difference can be noticed between the predicted post-yield behavior of the two models. Model [F.E. (1)] could not predict the gradual yielding of the section, and exhibited about 60% of the expected experimental axial displacement at the ultimate load level. However, Model [F.E. (2)] showed a gradual yielding behavior, and post-ultimate behavior, which are in excellent agreement with the experimental results.

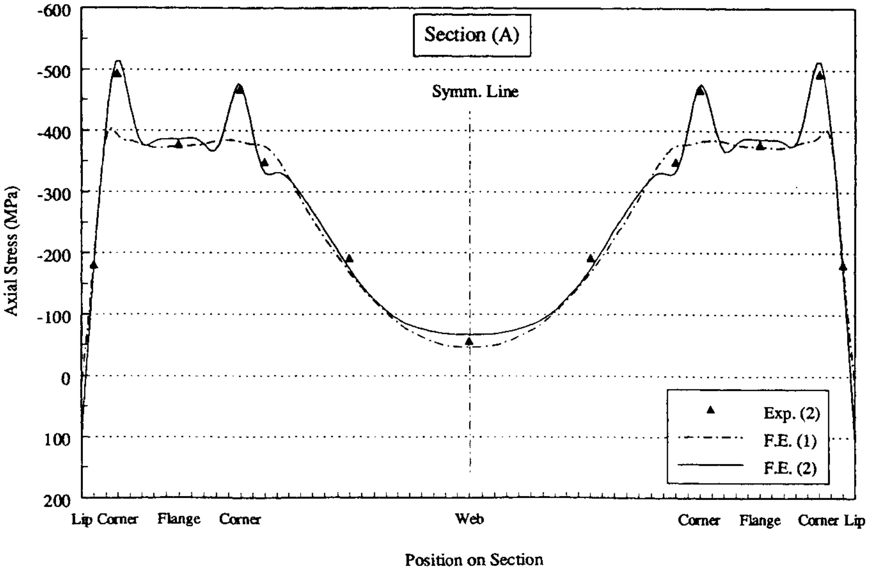

Figure: 5 Axial Stress Distribution at Ultimate Load Levels

Figure 5 shows the axial stress distributions, corresponding to the ultimate load of a stub-column, and the two finite element models. These stress distributions were recorded at the mid-height positions for both the test and the models. The figure shows that the model [F.E. (2)] well predicted the axial stress values across the whole section, specially at the corners and in the buckled web area. Model [(F.E. (1)] could not predict the stress peaks at the corner since the increase in the yield strength and the residual stresses at the corner zones were neglected.

5. Conclusions

The results of 41 tensile coupon tests to evaluate the mechanical properties of cold-formed steel channel sections have been presented. Also the results of four tests to establish the magnitudes and distributions of residual stresses within the channel sections were presented. Both series of tests showed that the cold bending operation alters the virgin material properties of the steel sheet, particularly at the corners and at locations around the corners of the sections. Models for the distribution of yield strength, and residual stresses across channel sections have been presented and discussed. The models were used within a finite element computer model of sections in compression, and the results showed that the proposed models can effectively help in obtaining the true deformations and stress distribution across CFS sections. The model gives accurate stress distribution at ultimate loads, which is needed for "effective width" calculations, a design concept used in codes (CSA, 1994 and AISI, 1991).

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Acknowledgment

The support of the Natural Sciences and Engineering Research Council of Canada is gratefully acknowledged.