RESIDUAL STRESSES IN COLD-FORMED STEEL MEMBERS

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ABSTRACT: An extensive experimental investigation of the residual stresses in cold-formed steel members is presented. The electrical discharge machining (EDM) technique is used to cut coupons for residual stress measurement. As compared to the conventional saw-cutting method, the EDM technique greatly reduces the external disturbance during the machining of a thin-walled section caused by heating, clamping, and vibration. The experimental results provide a further understanding of the magnitude and distribution of the residual stresses in cold-formed steel sections, which are found to be quite different from the residual stresses in hot-rolled steel shapes. Based on the experimental findings, an idealized distribution pattern of the residual stresses in a cold-formed channel section is outlined. Finally, the yielding propagation in an axially compressed cold-formed steel section is described, and an equation for predicting the extent of yielding is derived.

INTRODUCTION

Residual stress plays an important role in the design of structural steel members. In structural steel, residual stresses may be due to several causes, including: (1) Uneven cooling of shape after hot-rolling; and (2) fabrication operations such as cold-bending, welding, flame-cutting, and punching, etc. For a hot-rolled wide-flange section, the residual stresses are mainly due to uneven cooling after hot-rolling. The studies conducted at Lehigh University by Yang (1952), Huber (1954), Beedle (1960), Tebedge (1973), and other researchers found that the magnitude of the maximum residual stress in hot-rolled shapes of moderate strength steels is approximately equal to 30% of the yield stress of the material and the residual stresses are assumed to be uniformly distributed through the plate thickness. An idealized typical residual stress distribution pattern is shown in Fig. 1.

For a cold-formed steel section, the residual stresses are mainly caused by a cold-bending effect during the forming process. Due to the difference in the manufacturing process between these two groups of sections, the residual stresses in a cold-formed section may be quite different from those in a hot-rolled shape.

It is noted that the design formulas for flexural buckling strength of cold-formed steel columns used in the AISI (American Iron and Steel Institute) *Specification* (1986) are based on the CRC (Column Research Council) column curve. The CRC column curve was obtained based on the residual stresses measured in hot-rolled steel shapes and was originally developed for the design of hot-rolled steel columns (1976). Therefore, it is felt that the direct use of the CRC column curve for the design of cold-formed steel columns may not be appropriate because of the difference in the residual stresses

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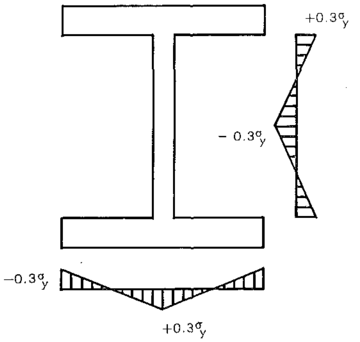

FIG. 1. Idealized Residual Stress Distribution in Hot-Rolled Steel Shape

between these two groups of columns.

The objective of this study is to investigate experimentally the magnitude and distribution of the residual stresses in cold-formed steel sections such that a better understanding of the behavior of the residual stresses in cold-formed steel members can be achieved.

SPECIMEN DIMENSIONS AND MATERIAL PROPERTIES

The cross section dimensions and material properties of all sections tested in this study are given in Table 1, where *a*, *b*, and *c* are the overall width of the web, flange, and lip of the channel sections, respectively. The thickness of the specimens ranged from 0.064 to 0.121 in. (1.626 to 3.073 mm) including 11-, 12-, 13-, 14-, and 16-gage steels. These specimens were ob-

TABLE 1. Cross Section Dimensions and Material Properties

Specimen (1)	t (in.) (2)	A (in.) (3)	a (in.) (4)	b (in.) (5)	c (in.) (6)	r (in.) (7)	σ_y (ksi) (8)	σ_u (ksi) (9)	2-in. elongation (%) (10)
RFC13	0.096	0.674	3.067	1.629	0.715	0.156	51.85	62.21	33
RFC14*	0.075	0.533	2.998	1.756	0.694	0.219	55.09	76.55	30
R13*	0.086	0.573	3.010	1.635	0.605	0.219	50.15	70.63	27
R14*	0.075	0.511	3.015	1.658	0.610	0.219	49.73	69.32	30
PBC14	0.071	0.493	3.001	1.632	0.605	0.156	36.30	50.07	33
P11	0.121	1.328	5.037	2.491	0.878	0.125	33.60	51.91	34
P16	0.064	0.395	2.645	1.377	0.623	0.094	32.06	45.09	32
P3300	0.105	0.397	1.625	0.875	0.375	0.156	55.89	65.04	23
P4100	0.075	0.285	1.625	0.813	0.375	0.156	51.65	59.81	25
DC12	0.105	1.110	1.625	1.625	0.375	0.156	44.31	53.12	36
DC14*	0.075	0.610	1.250	1.250	0.281	0.156	44.95	59.20	35

Note: RFC and R both stand for roll-formed channel; PBC and P both stand for press-braked channel; P3300 and P4100 are roll-formed 12- and 14-gage channel sections; DC12 and DC14 are roll-formed 12- and 14-gage double channels; 11, 12, 13, 14, and 16 are gage-numbers of steel; * represents gradual yielding material; 1 in. = 25.4 mm; 1 ksi = 6.89 N/mm^2.

tained from four different manufacturers and included both roll-formed and press-braked sections.

The material properties of the specimens were determined according to the procedures of the standard tension tests recommended by the ASTM (*Standard* 1975). The yield stress of the material and the percentage of elongation in a 2-in. (50.8-mm) gage length were determined from the uniaxial tensile coupon tests. Coupons were saw-cut from the flat portions of the test specimens, and at least three coupons were tested for each type of section to obtain an average value. For gradual yielding material, the yield stress was determined by the 0.2% offset method.

CONVENTIONAL SAW-CUTTING METHOD

The use of the saw-cutting (sectioning) method for determining residual stresses was first reported by Kalakoutsky in 1888. He cut a steel bar into long strips and measured their changes in length, from which he then determined the residual stresses locked in the bar. Since the 1950s, the sectioning method has been used extensively for measuring residual stresses in wide-flange shapes, welded box sections, and circular tubes. Results of the measured residual stresses from these sections were reported by Huber and Beedle (1954), Beer and Tall (1970), Ross and Chen (1975), etc. This method was also used to measure residual stresses in cold-formed steel sections by Ingvarsson (1977) and Dat (1980). In 1984, Weng used this method to measure residual stresses in cold-bent thick steel plates.

At the beginning of this study, the conventional saw-cutting method was used to measure residual stresses in cold-formed steel sections. In the saw-cutting process, the specimen is clamped with a vise, and cutting is performed by using a slitting saw or band saw with fluid coolant supplied. The residual strains released after each cut are recorded. Based on the measured strains, the residual stresses can be determined.

Although the saw-cutting technique can be used for measuring residual stresses in thin-walled sections, it was found that this method is very tedious and has many drawbacks. Based on several tests conducted by the writers, the following problems were observed.

1. Excessive vibrations may occur during the saw-cutting process due to the thinness of the thin-walled sections. The vibrations may disturb the strain gage readings, and sometimes cause a misalignment of the cutting path.
2. In order to hold the specimen in a tight and steady position for sectioning, it is necessary to apply a clamping force on the specimen. However, an excessive clamping force may result in a permanent deformation on the thin-walled section. Great care in each step of the sectioning process is required to avoid the possible over-squeezing effect.

The electrical discharge machining (EDM) practically eliminates the aforementioned problems. This technique has been used since 1950s for high-precision machining of metals. The principle and applications of this method were discussed by Springborn (1967), Kalpakjian (1967), and Armarego and Brown (1969). In addition to its use for high-precision machining, the writers found that the EDM technique can be used for measuring residual stresses in the thin-walled steel sections. This is possible because the external disturbance during the machining process caused by the EDM method were found to be much smaller than that due to the conventional saw-cutting technique.

METHOD OF ELECTRIC DISCHARGE MACHINING (EDM)

Principle and Advantages of EDM

Electric discharge machining is sometimes known as electro-erosion machining. It is based on the principle of erosion of metals by electric discharges. In the EDM process, as illustrated in Fig. 2, material is removed by a series of discrete electrical discharges that occur in the machining gap between the electrode (cutting tool) and the workpiece (test specimen). The dielectric fluid creates a path for the discharge as the fluid becomes ionized between the two closest points. The initiation of the discharge occurs when a sufficient amount of voltage is applied across the machining gap to cause the dielectric fluid to ionize and the current to start to flow.

This process is applicable to all materials that are good conductors of electricity. The cutting tool is usually made of brass because of its excellent electric conductivity. The dielectric fluid, usually a hydrocarbon-based liquid, has the additional functions of providing a cooling medium and carrying away debris produced by the machining process. The electric discharge can be repeated rapidly, and each time a minute amount of the workpiece material is removed.

As shown in Fig. 2, the cutting tool and the specimen do not contact during the sectioning process. Thus, there is no mechanical cutting effect, as from machining by a saw blade. In addition, the specimen is totally immersed in the dielectric fluid, which also serves as a coolant. Thus, the heat problem due to sectioning is minimized. Furthermore, when applying the EDM technique to measure residual stresses in a thin-walled section, the specimen need not be held very tightly by the vise during sectioning. Therefore, the problem of over-squeezing the thin section can be easily avoided.

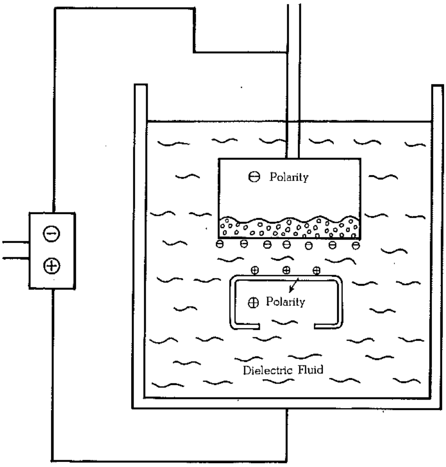

FIG. 2. Measurement of Residual Stresses by EDM Method

TABLE 2. Measured Residual Strains: EDM versus Saw-Cutting

Strain gage number (1)	Residual Strains ($\mu\epsilon$) EDM method (2)	Saw-cut (3)	EDM/saw-cut ratio (4)
1	−832	−855	0.97
2	−848	−891	0.95
3	−1,244	−1,191	1.05
4	−458	−446	1.03
5	−902	−1,014	0.89
6	−356	−369	0.96

Note: Strain-gage locations are shown in Fig. 5; specimens were from same piece of R14 section.

For comparison, both the EDM technique and the saw-cutting method were used to measure the residual stresses in two specimens that were taken from the same piece of cold-formed channel section. The results of the measured residual strains are shown in Table 2. It is seen that the differences are quite small. Therefore, instead of the conventional saw-cutting method, the EDM technique is used in this investigation because of its advantages.

Measurement of Residual Strains by EDM

For this investigation, the sectioning of the specimens was performed by using a knee-type, quill-head EDM machine manufactured by the Ex-Cell-O Corporation. The EA-type electric resistance strain gages and the M-bond 200 adhesive made by Measurements Group, Inc., Raleigh, North Carolina, were used.

The test specimen was saw-cut from the steel columns provided by the manufacturers, then electric resistance strain gages were mounted on the inner and outer surfaces of the specimen along the longitudinal direction. Fig. 3 shows a typical arrangement of strain gages on a channel section. The dashed lines and numbers shown in the figure indicate the sequence of sec-

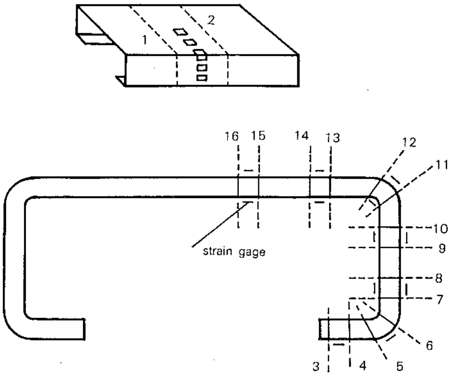

FIG. 3. EDM Sectioning—Cut Sequences Are Indicated by Dashed Lines and Numbers

tioning. To protect strain gages from damage, a thick layer of protection coating, M-Coat A, was applied on the strain gages before machining. The strain gage wires were connected before the sectioning and remained connected throughout the entire procedure.

The residual stresses were measured on one-half of each section, due to the symmetry of the channel sections. Since the inner surface of the lip and the adjacent corner are difficult to reach, no strain gage could be applied on these areas. The sectioning of each specimen was done in a single day to minimize any time-drifting of the strain gage readings. Readings of all gages were taken twice initially and after each cut by using a strain indicator and a switch and balance unit.

EXPERIMENTAL RESULTS

Figs. 4–8 show the results of the measured surface residual strains along the longitudinal direction of the test specimens. It is noted that a measured negative residual strain corresponds to a tension residual stress in the specimen, and a measured positive residual strain corresponds to a compression

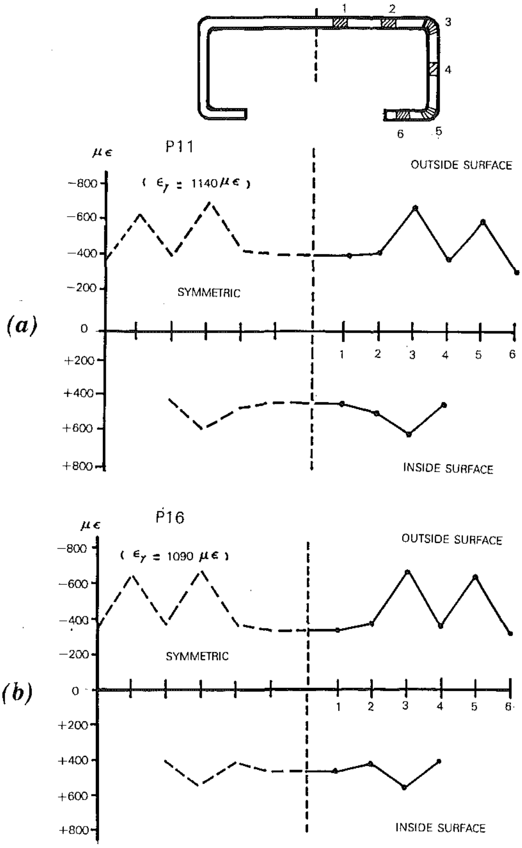

FIG. 4. Measured Residual Strains: (*a*) Section P11; and (*b*) Section P16

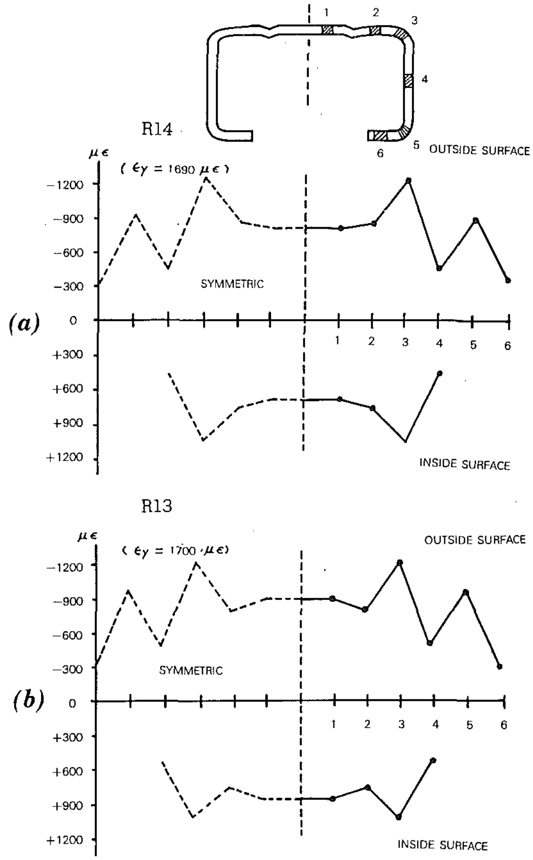

FIG. 5. Measured Residual Strains: (*a*) Section R14; and (*b*) Section R13

residual stress in the specimen. Based on the experimental findings, the following observations can be made:

1. Compression residual stresses (positive residual strains) were found on the inside surface of the sections, and tension residual stresses (negative residual strains) were found on the outside surface. This observation was made consistently in all specimens. (The residual stress distribution through the plate thickness is discussed in a later paragraph.)
2. The magnitudes of the surface residual stresses of the sections ranged approximately between 25 and 70% of the yield stress of the material.
3. The magnitudes of the residual stresses on the flat portions of the section were found to be approximately uniform along the perimeter of the section.
4. The magnitudes of the residual stresses on the corner regions were higher than those on the flat portions. The differences ranged approximately from 15 to 30% of the yield stress of the material.
5. At the same location, the magnitudes of the residual stresses on the inside

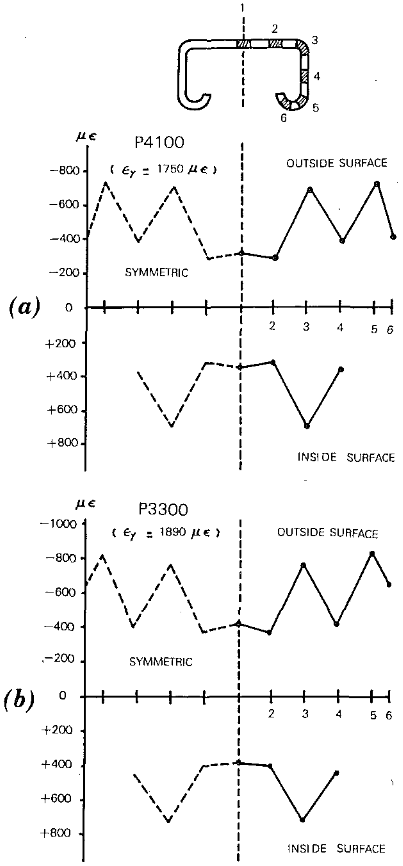

FIG. 6. Measured Residual Strains: (*a*) Section P4100; and (*b*) Section P3300

and outside surfaces of the flat portions of the section were found to be quite close.

6. The general shape of the distribution of residual stress followed a consistent pattern for all specimens.

As mentioned in item 4, higher residual stresses were found in the corner regions than in the flat portions. This is reasonable, since more cold work was introduced in the corners during the manufacturing process. Experimentally, it is observed that both the magnitudes of the residual stresses and yield stresses are higher in the corner regions. The increase of the yield stress at corners due to strain hardening was investigated extensively by Karren (1967) and Dat (1980). It was found that the percentages of the increase of yield stress and residual stress at the corners were quite close. This observation indicates that the increase of residual stress at the corner may be negated by the increase of yield stress for certain types of structural behavior.

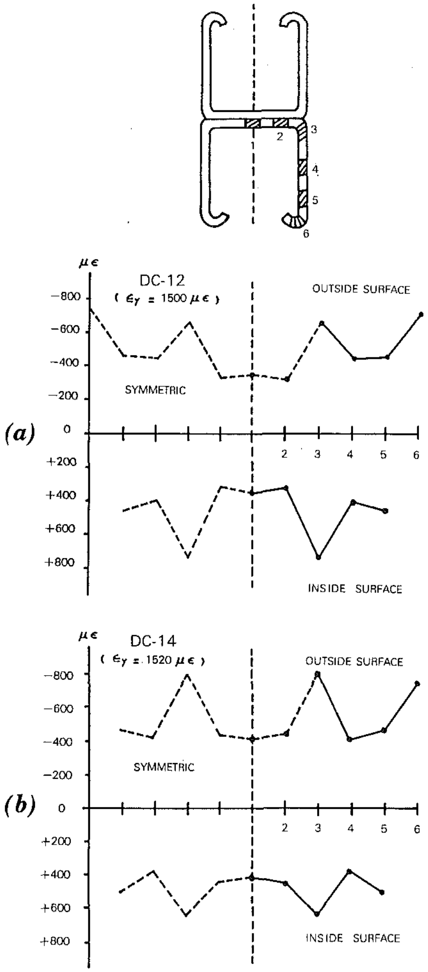

FIG. 7. Measured Residual Strains: (*a*) Section DC12; and (*b*) Section DC14

It is also observed that for both the roll-formed 13- and 14-gage sections, R13 and R14, the magnitudes of the residual strains on the webs were higher than those on the flanges, as shown in Figs. 5(*a*) and (*b*). This may be due to the effect of the cold work applied on the web during the roll-forming process, which caused two indented lines on the web of the section.

For a better qualitative understanding of the residual stresses in the cold-formed steel section, a channel section was cut into several long strips along the longitudinal direction of the section. As shown in Figs. 9(*a*) and (*b*), the long strips did not remain straight but bent into a single curvature. This phenomenon indicates that the cutting process released bending stresses that were locked in the cold-formed section. Inspection of Figs. 9(*a*) and (*b*) shows that the residual stresses are tensile on the outside and compressive on the inside. Furthermore, based on these experimental observations, it would

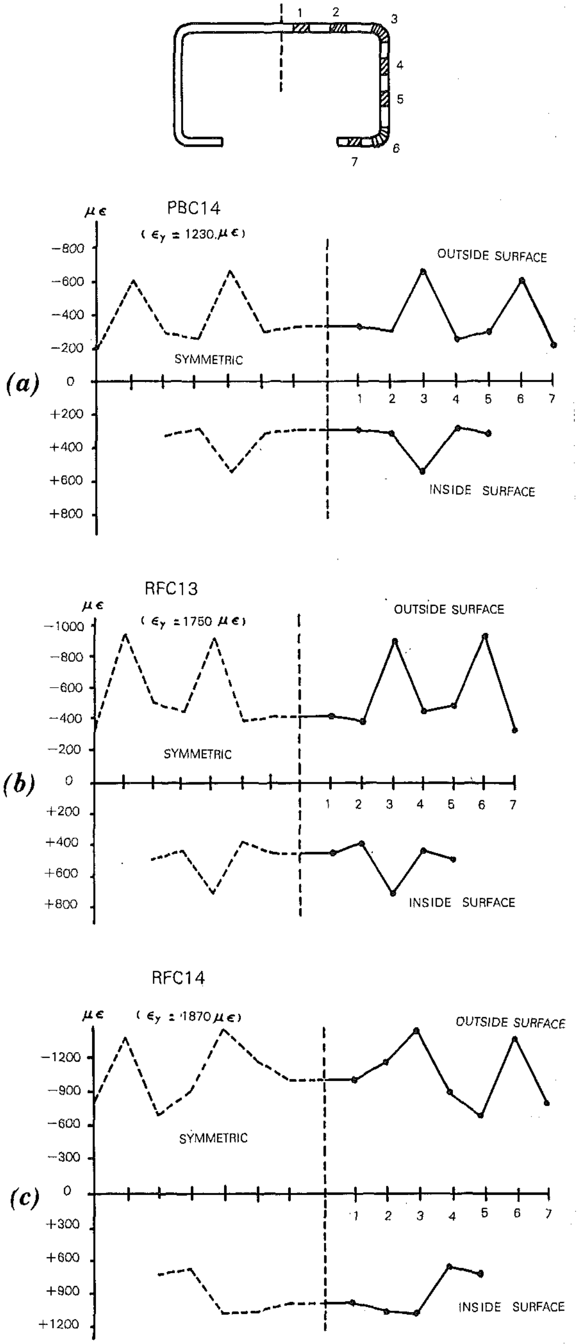

FIG. 8. Measured Residual Strains: (*a*) Section PBC14; (*b*) Section RFC13; and (*c*) Section RFC14

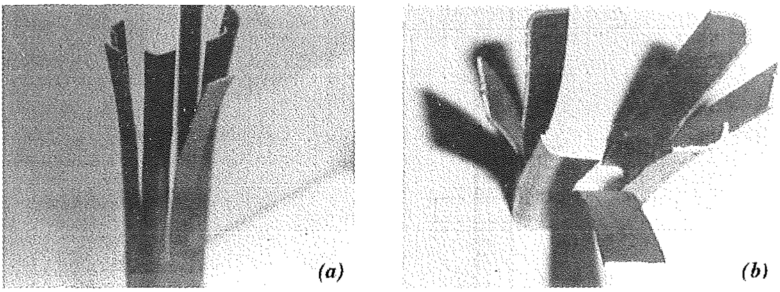

FIG. 9. Effect of Residual Stress on Saw Cut Channel Section: (*a*) Side View; and (*b*) Top View

be reasonable to assume that the residual stresses are linearly distributed through the thickness of the plate element.

However, it is noted that the nature of residual stresses in a cold-formed section is very complex because of the details of the actual manufacturing process. The measurement of the residual stress distribution through the plate thickness of a thin-walled section is virtually impossible in the present study because of the limitation of the available measuring techniques.

Based on the aforementioned, the magnitude and distribution of the residual stresses in a cold-formed steel channel section are simplified and idealized as follows.

1. There are tension residual stresses on the outside surface of the channel section, and compression residual stresses on the inside surface.
2. Residual stresses are assumed to be varied linearly through the plate thickness.
3. The increase of residual stress at the corner regions may be negated by the increase of yield stress. Thus, the residual stresses can be assumed to be uniformly distributed along the perimeter of the section by neglecting the variations of the residual stresses at the corners.
4. The magnitudes of the maximum tension and compression residual stresses are assumed to be the same and are conservatively taken as 50% of the yield stress of the material.

YIELDING PROPAGATION AND EXTENT OF YIELDING

An axially compressed cold-formed steel section starts to yield when the sum of the applied stress and the compression residual stress reaches the yield stress of the material. From the aforementioned idealized residual stress distribution pattern, the yielding of the section starts from the inside surface at the peak of the compression residual stress zone, and propagates as the load increases. As a result of the yielding propagation, the section becomes partially elastic and partially plastic with one layer of elastic zone and one layer of plastic zone. This is illustrated in Fig. 10. It is seen that the elastic part of the plate is decreased from the original thickness, t, to an elastic thickness, t_e. The extent of the yielding depends on the level of the applied stress and the magnitude of the residual stress.

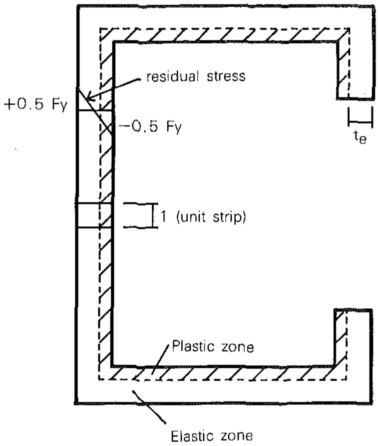

FIG. 10. Residual Stress Distribution, Unit Width Considered in Derivation of Elastic Thickness

Since the residual stresses are assumed to be uniformly distributed along the perimeter of the section, the extent of yielding of an axially compressed channel section can be determined easily. As shown in Fig. 10, a unit length of the perimeter of the channel section is considered for the derivation of an equation for the elastic thickness, t_e. If the load applied on the unit strip is P, the average stress on this area is

$$\sigma_A = \frac{P}{t} \qquad (1)$$

When the sum of the applied stress and the compression residual stress is higher than the yield stress of the material, the plate becomes partially elastic and partially plastic, as detailed in Fig. 11. From this figure, the load acting on the unit length of the section, P, is found to be

$$P = \sigma_y(t - t_e) + \frac{\sigma_0 + \sigma_y}{2}(t_e) \qquad (2)$$

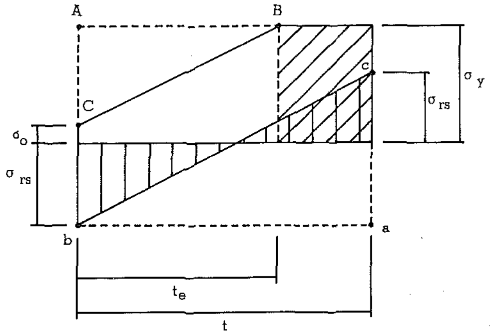

FIG. 11. Partial Yielding due to Residual Stress

where t_e and σ_0 = unknowns to be determined. From the similar triangles, $\Delta ABC \sim \Delta abc$, as shown in Fig. 11, the following relationship is found:

$$\frac{\overline{AC}}{\overline{ac}} = \frac{\overline{AB}}{\overline{ab}} \qquad (3)$$

This leads to

$$\frac{\sigma_y - \sigma_0}{2\sigma_{rs}} = \frac{t_e}{t} \qquad (4)$$

Thus

$$\sigma_0 = \sigma_y - 2\sigma_{rs}\left(\frac{t_e}{t}\right) \qquad (5)$$

By substituting σ_0 and t_e into Eq. 2, the load acting on the unit length of the section, P, can be expressed in terms of the elastic thickness, t_e, and the residual stress, σ_{rs}, as follows:

$$P = \sigma_y t - \sigma_{rs}\left(\frac{t_e^2}{t}\right) \qquad (6)$$

Eqs. 1 and 6 can be solved simultaneously for the elastic thickness t_e while eliminating the load P. This gives

$$t_e = t \cdot \sqrt{\frac{\sigma_y - \sigma_A}{\sigma_{rs}}} \qquad (7)$$

From the experimental results, it was observed that the magnitudes of the measured residual stresses vary approximately from 25 to 70% of the yield stress of the material. A value of $\sigma_{rs} = 0.5\ \sigma_y$ can be used such that Eq. 7 is further simplified. Thus the elastic thickness can be calculated using the following equation:

$$t_e = t \cdot \sqrt{2\left(1 - \frac{\sigma_A}{\sigma_y}\right)} \qquad (8)$$

SUMMARY AND CONCLUSIONS

This paper presents a detailed description of the experimental study of residual stresses in cold-formed steel sections. The results provide useful information for a further study on the effect of residual stresses on the strength of cold-formed steel members. The EDM method used in this study is found to be a convenient way to measure residual stresses in thin-walled sections.

From the experimental findings, it is apparent that the residual stresses in cold-formed sections are quite different from those in hot-rolled shapes. The CRC column curve used in the present AISI *Specification* (1986) for cold-formed steel columns was derived for hot-rolled sections. The validity of this use is the subject of another paper by Weng.

This study also provides a means for predicting the extent of the yielding propagation of an axially compressed cold-formed section. It is shown by Weng that this type of yielding propagation may weaken not only the overall column buckling strength but also the local buckling strength of the component plate elements of the section. This effect results in a further reduction of the overall buckling strength of the column. Though the residual stress magnitudes and patterns were generally consistent, the details of the creation of these residual stresses need further study.

APPENDIX I. REFERENCES

Armarego, E. J. A., and Brown, R. H. (1969). "The machining of metals." Prentice Hall, Englewood Cliffs, N.J.

Beedle, L. S., and Tall, L. (1960). "Basic column strength." *J. Struct. Div.*, ASCE, 86, 139–173.

Beer, G., and Tall, L. (1970). "The strength of heavy welded box columns." *Fritz Engrg. Lab. Report 337.27,* Lehigh Univ., Bethlehem, Penn.

Dat, D. T. (1980). "The strength of cold-formed steel columns." Thesis presented to Cornell University, at Ithaca, N.Y., in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Huber, H. W., and Beedle, L. S. (1954). "Residual stress and the compressive strength of steel." *Welding J.*, 33, Dec., 589–614.

Ingvarsson, L. (1977). "Cold-forming residual stresses." *Bulletin 121,* Dept. of Building Statics and Struct. Engrg., The Royal Inst. of Techn., Stockholm, Sweden.

Johnston, B. G. (1976). *Guide to stability design criteria for metal structures.* 3rd Ed., John Wiley and Sons, New York, N.Y.

Kalakoutsky, N. (1888). *The study of internal stresses in cast iron and steel.* London, U.K.

Kalpakjian, S. (1967). *Mechanical processing of material.* D. Van Nostrand Co., Princeton, N.J.

Karren, K. W. (1967). "Corner properties of cold-formed steel shapes." *J. Struct. Div.*, ASCE, 92(1), 401–432.

Ross, D. A., and Chen, W. F. (1975). "Residual stress measurement in fabricated tublar steel columns." *Fritz Engrg. Lab. Report 393.4,* Lehigh Univ., Bethlehem, Penn.

Specification for the design of cold-formed steel structural members. (1986). Amer. Iron and Steel Inst., Washington, D.C.

Springborn, P. K. (1967). *Non-traditional machining processes.* Amer. Soc. Tool and Manufacturing Engrs., Dearborn, Mich.

"Standard methods of tension testing of metallic materials." (1975). *ASTM E8-69,* Amer. Soc. for Testing and Materials, Philadelphia, Penn.

Tebedge, N., Alpsten, G. A., and Tall, L. (1973). "Residual stress measurement by the sectioning method." *Exp. Mech.*, 13, Feb., 88–96.

Weng, C. C. (1984). "Cold-bending of thick steel plates at low R/t ratios." Thesis presented to Cornell University, at Ithaca, N.Y., in partial fulfillment of the requirements for the degree of Master of Science.

Yang, C. H., Beedle, L. S., and Johnston, B. G. (1952). "Residual stress and the yield strength of steel beams." *Welding J.*, 31(4), 205–229.

APPENDIX II. NOTATION

The following symbols are used in this paper:

A = gross section area;
P = applied load;
t = plate thickness;

t_e = elastic plate thickness;
σ_A = average stress;
σ_{rs} = residual stress;
σ_u = tensile strength;
σ_y = yield stress; and
$\mu\epsilon$ = micro-strain