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A COMPUTER PROGRAM FOR CALCULATION OF THE RESIDUAL STRESS DISTRIBUTION AND THE EFFECTIVE STRESS-STRAIN CURVE OF COLD-FORMED STRUCTURAL MEMBERS

by

R.K. Tacey

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STRUCTURES DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

November 1976

Report 76-0141

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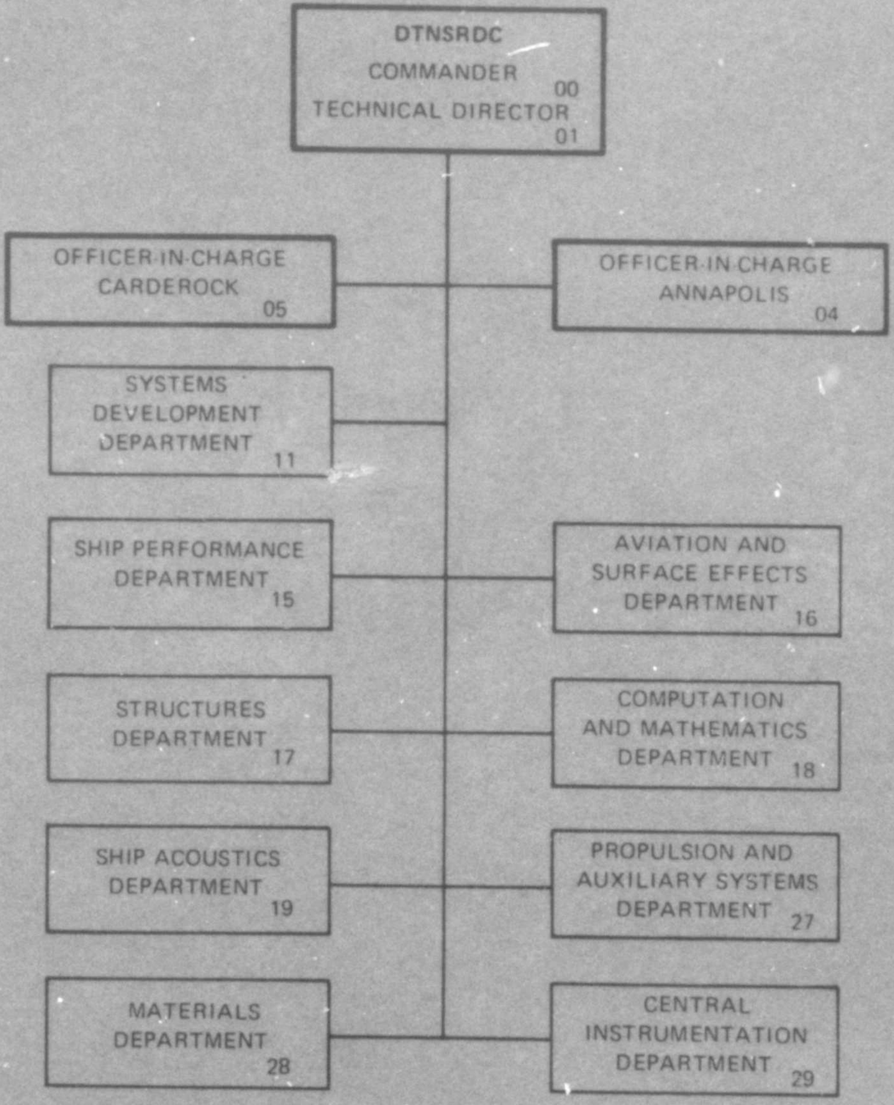
MAJOR DTNSRDC ORGANIZATIONAL COMPONENTS



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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
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1. REPORT NUMBER
DTNSRDC Report 76-0141

2. GOVT ACCESSION NO.

3. ~~RECIPIENT'S CATALOG NUMBER~~
⑨

4. ~~TITLE (and Subtitle)~~
⑥ A COMPUTER PROGRAM FOR CALCULATION OF THE RESIDUAL STRESS DISTRIBUTION AND THE EFFECTIVE STRESS-STRAIN CURVE OF COLD-FORMED STRUCTURAL MEMBERS,

5. ~~TYPE OF REPORT & PERIOD COVERED~~
Final rept.,

6. ~~PERFORMING ORG. REPORT NUMBER~~

7. ~~AUTHOR(s)~~
⑩ Robert K. Tacey

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
David W. Taylor Naval Ship Research
and Development Center
Bethesda, Maryland 20084

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
Task Area SF 43.422.502
1-1720-555-56

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Sea Systems Command Code 035
Washington, D.C. 20362

~~12. REPORT DATE~~
⑪ Nov[redacted] [redacted]76

13. ~~NUMBER OF PAGES~~
77

14. MONITORING AGENCY NAME & ADDRESS (*if different from Controlling Office*)
Naval Sea Systems Command Code 035
Washington, D.C. 20362

⑫ 78p.

15. SECURITY CLASS. (*of this report*)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

⑭ DTNSRDC-76-0141

17. ~~DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)~~
⑯ F43422

D D C
JAN 31 1977
C

18. ~~SUPPLEMENTARY NOTES~~
⑰ SF43422502

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Cold formed structural members
Bauschinger effect
Strain hardening
Effective Stress-strain curves
Residual stress distribution

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

This report describes a computer program which can be used to calculate the cross sectional residual stress distribution and the effective compressive stress-strain relationship of a cold formed structural member. The program

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is user oriented and requires input of only basic geometry and base metal stress-strain data. The program is general as to the shape of the cross section that may be analyzed. It accounts for inelastic material behavior during initial bending and during springback. Strain hardening and unequal compressive and tensile material stress-strain relationships are included in the analysis. Material properties are homogeneous and isotropic within the individual elements. However, they may vary from element to element. The Bauschinger Effect can be accounted for by utilizing non-dimensional experimental data or theoretical formulations. These different methods may be inserted in the program in modular fashion. The program can analyze the forming process as an operation consisting of up to ten individual bends. Graphs are presented that show close agreement between the program predictions and limited experimental results.

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ABSTRACT

This report describes a computer program which can be used to calculate the cross sectional residual stress distribution and the effective compressive stress-strain relationship of a cold formed structural member. The program is user oriented and requires input of only basic geometry and base metal stress-strain data. The program is general as to the shape of the cross section that may be analyzed. It accounts for inelastic material behavior during initial bending and during springback. Strain hardening and unequal compressive and tensile material stress-strain relationships are included in the analysis. Material properties are homogeneous and isotropic within the individual elements. However, they may vary from element to element. The Bauschinger Effect can be accounted for by utilizing non-dimensional experimental data or theoretical formulations. These different methods may be inserted in the program in modular fashion. The program can analyze the forming process as an operation consisting of up to ten individual bends. Graphs are presented that show close agreement between the program predictions and limited experimental results.

ADMINISTRATIVE INFORMATION

Work on this program was initially funded under in-house Independent Research Program, Task Area FR 0230301. Work was completed under Task Area SF 43.422.502 and Work Unit 1-1720-555.

PROGRAM ASSUMPTIONS

1. The behavior of a structural member may be described completely, on a macroscopic scale, by means of its stress to strain relationship.

2. Each longitudinal fiber of the structural member is subjected to uniaxial strain during the cold rolling process.

3. The structural member is initially straight, but may have initial residual stresses in the direction of its longitudinal axis.

4. The material is homogeneous and isotropic within an element. Stress-strain properties may vary from element to element.

5. Plane cross sections remain plane after deformation.

6. The cross section is symmetric about a plane through the center of curvature and the center of gravity of cross section of the member.

7. The material may have different tensile and compressive engineering stress-strain curves. However, the portions of the curves about their respective proportional limits are about the same shape. Young's modulus is the same for both the tensile and compressive base metal curves.

8. Stress increases monotonically with strain.

9. The Bauschinger Effect may be represented for a given family of materials by one set of nondimensionalized experimental data.

10. Material unloading is linear elastic until the zero stress state is reached. If reverse loading occurs material behavior becomes nonlinear.

11. Shear deformation which occurs in the rolling process is not considered.

PROGRAM FEATURES

1. Analysis of many different cross sectional shapes is possible.

2. Material behavior is characterized by its actual engineering stress-strain curve.

3. Different compressive and tensile stress-strain relationships are allowed. Different base metal stress-strain curves may be input for each element. This allows for different base plates used in the cross section and for weld material that may be present.

4. Inelastic material behavior is taken in account on the initial bend and on subsequent springback.

5. The section neutral axis shifts during bending and during springback.

6. Residual stresses in the longitudinal direction of the straight member before bending may be included.

7. Hardening rules may be easily modified.

8. Multibend operation analysis is available.

9. Automatic output includes the stress and strain history of the cold formed member of all bends as well as the effective stress-strain curve of the member.

10. Optional output includes printout of all stress-strain curves of all elements and important iterative quantities. Additionally, the effective stress-strain curves for a segmented tee section may be obtained.

INTRODUCTION

An understanding of the true load carrying ability of structural members is necessary to produce adequate designs involving those members. This strength is characterized by a load-deflection or stress-strain curve. It is obvious that these curves are needed when the design is inelastic in nature. However, the manufacturing history of the member may make use of stress-strain curves necessary even when the member is designed to function in the elastic region. For instance, residual stresses may be introduced during the manufacture of the member or during the fabrication of the structure. These stresses can act as preloads which may cause inelastic behavior near the design loads of the structure. Additionally, the material characteristics of the member may be altered by forming processes or welding. In particular the cold rolling process may reduce the proportional limit and elastic modulus significantly.

The cold rolling process of forming a curved structural member involves bending a straight structural member to a radius smaller than its design radius. The member springs back to the desired radius upon release of external forces. This process changes some important structural properties of the material, and gives rise to a complex state of residual stress. A graphical representation of the stress components of this process is shown in Figure 1. A typical theoretical residual stress distribution for a cold rolled plate is given in Figure 2a; one for a typical cold formed tee section, in Figure 2b. As can be seen from Figure 2, the residual stress distributions of the cold rolled plate and the cold formed tee section are in equilibrium when the complete cross section is considered. However, local areas, such as the flange of a tee section, may exhibit unbalanced stresses.

The determination of an effective stress-strain relationship depends on the calculation of residual stress distribution in the cross section of structural element. In the past this calculation could be performed only after simplifying assumptions had been made. One assumption has been that the material behaves in an elastic-perfectly plastic manner as shown in Figure 3. A related assumption is the absence of the Bauschinger Effect. This phenomena is an apparent loss in the proportional limit stress in one direction of loading after the material has been loaded plastically in the opposite direction. The assumption elastic-perfectly plastic material behavior ignores an apparent strengthening, known as strain hardening, which may occur at high strains in materials which can develop increased stress with increasing strain in the plastic region. This assumption also incorrectly places the proportional limit at the 0.2 percent offset yield point. The exclusion of the Bauschinger Effect from an analysis of cold forming strength decreases the accuracy of the analysis for many important structural materials. Figure 4 shows the Bauschinger Effect on a uniaxial compression specimen of high strength steel with tensile prestrain. The reduction in the compressive proportional limit is obvious.

DISCUSSION

The need for a method to accurately predict the effect of stress-strain curve of a cold rolled structural component was discussed in the Introduction. Theoretical prediction for cold rolled plates is available, but does not include the Bauschinger Effect. Predictions for cold formed sections other than plates are done by hand once the residual stress distribution has been obtained.[1] All of these methods involve the use of simplifying assumptions that affect their accuracy. The program presented here is an attempt to describe, on a macroscopic scale, the response of the structural material to the cold rolling process. Care has been taken to keep assumptions as few and as realistic as possible. These assumptions were listed previously.

The program analyzes the component cross section as a system of rectangular elements. The structural properties of each element are maintained in an array and updated during each phase of the rolling process. This approach is necessary in that the material properties are dependent on the strain history of the element. After the rolling process is completed, a series of incremental strains is applied to each element and its stress response calculated. These stresses are then integrated over the cross section to produce the response of the member as a whole. Since the analysis is performed with a system of elements, the restrictions on the type or shape of cross section are few. Any section may be analyzed which is symmetric about a plane through the center of curvature and the center of gravity of any cross section of the member. Additionally, a perpendicular to this plane may not pass through more than one segment of the member, see Figure 5. Element geometry is automatically generated for three often used cross section geometries. These are shown in Figure 6.

Because the material is described by base metal stress to strain relationships, a section made of practically any homogenous, isotropic material may be analyzed. Different stress-strain curves are used for each element. Because of this, sections made of different materials may be analyzed. The effect of welding on the cross section may be accounted for if the curves for the weld material are known. The curves must always be monotonically increasing. This is a mathematical

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[1] McVee, J., "Residual Stresses in Cold Bent Circular Ring/Frame Segments of Tee Cross Section," NCRE Report N194, Mar 1971. A complete listing of references is given on page 72.

restriction and does not affect results of a plateau type material. A sufficient number of points must be included to adequately describe the shape of the stress-strain curve. Points should be concentrated in the most curvilinear section of the curve. Up to fifty points are allowed for the base metal compressive curves. Young's modulus is calculated from these curves. The tensile base metal curves are calculated from the compressive as a means of facilitating data input. A percentage reduction factor is read and used to calculate stresses for the tensile curves. Strains for the tensile curves are computed by the following equation.

$$\epsilon_{\text{tensile}} = |\epsilon_{\text{comp}}| - |\sigma_{\text{comp}}| * R_F/E$$

where R_F is the input reduction factor and E is the Young's modulus of the curve.

The program accounts for inelastic material behavior on the initial bend and on springback. The neutral axis is shifted on the initial bend and on springback. Any longitudinal residual stresses that are present when the member is straight may be included in the analysis. Additionally, in multibend analysis, residual stress and inelastic effects from each bend are accounted for, and are cumulative.

The Bauschinger Effect is considered both in springback and in final compression phase which determines the material effective stress-strain curve. The user has the option of using hardening rules based on experimental tests or on theoretical considerations. Experimental hardening rules presently included in the program are based on nondimensional uniaxial tests results of high strength steel. Data for curvilinear stress-strain material was generated at DTNSRDC. Data for plateau material specimens was taken from the literature.[2] In those tests

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[2] O'Brien, C.M., "An Investigation to Show the Magnitude and Significance of the Bauschinger Effect in Submarine Hull Plating," Masters Thesis at the Massachusetts Institute of Technology, May 1963.

various specimens prestrained a certain amount in tension or compression. Then loading is reversed and the load-deflection curves recorded. The various prestrained stress-strain curves are obtained and are nondimensionalized by dividing the stress at a given strain by the base metal stress at the same strain. Figure 7 demonstrates the effect of different amounts of prestrain. To nondimensionalize the data, the procedure described below is followed.

Firstly, an arbitrary strain is selected and the corresponding stress on each curve is determined. These stresses are then divided by the corresponding stress from the base metal curve. These ratios and the selected strains constitute nondimensionalized stress-strain curves from which experimental hardening rules are derived.

This process enables the use of one set of nondimensional data for many materials that obey the same hardening rules but that have different stress to strain relationships. The experimental data feature has the advantage of defining hardening rules for materials that may not follow theoretical rules. If the program is used to analyze a member made of material other than high strength steel, the user should determine if the rules defining the Bauschinger Effect are suitable to that material. Different rules, both theoretical and experimental, may be added by simply writing an appropriate subroutine.

The theoretical hardening rule is a combination of the isotropic and kinematic[3] rule and is set up as follows. The maximum difference between the curve suffering the Bauschinger Effect and the base metal curve is calculated. According to the kinematic hardening rule, this difference always occurs at the proportional limit and acts to reduce the proportional limit. It is multiplied by a factor whose default value is 1.0. According to the isotropic hardening rule, the Bauschinger Effect acts to increase the ultimate limit stress. This increase is defined as the maximum difference calculated at the proportional limit multiplied by a factor whose default value is zero. All points on the curve between the proportional limit and the ultimate limit are adjusted by an amount

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[3] Mendelson, A., "Plasticity: Theory and Application," MacMillan Company, 1968.

calculated by linear interpolation. Thus the curve suffers the maximum loss of strength near the proportional limit and may actually increase in strength at the ultimate limit. The calculations are made according to the following equations.

$$\Delta \varepsilon_{max} = (\sigma_I - \sigma_{PLI})/E$$

$$\Delta \varepsilon = \Delta \varepsilon_{max} (\varepsilon_{iA} - \varepsilon_{PLA})/(\varepsilon_{uA} - \varepsilon_{PLA}) * F_{uL}$$

$$- \Delta \varepsilon_{max} (\varepsilon_{uA} - \varepsilon_{iA})/(\varepsilon_{uA} - \varepsilon_{PLA}) * F_{PL}$$

$$\Delta \sigma = \Delta \varepsilon * E$$

where

$\Delta \varepsilon_{max}$	is the maximum strain difference
σ_I	is the stress that occurred in the initial direction of loading
σ_{PLI}	is the proportional limit stress in the initial direction of loading
E	is the Young's modulus
$\Delta \varepsilon$	is the strain difference between the base metal curve and the affected curve
ε_{uA}	is the ultimate limit strain in the reversed direction of loading
ε_{PLA}	is the proportional limit strain in the reversed direction of loading
ε_{iA}	is the applied strain on the base metal curve in the reversed direction of loading
$\Delta \sigma$	is the stress difference between the base metal curve in the reversed direction of loading and the affected curve
F_{PL}	is the proportional limit reduction factor which is user supplied
F_{uL}	is the ultimate limit increase factor which is user supplied

Figure 8 shows the effect of the two curve fitting parameters on the shape of the predicted stress-strain curve of structural member made of high strength steel with a plateau type base metal stress-strain curve. These parameters are input by the user and may vary with a change in geometry of the section or a change in material.

Output includes the residual stress pattern due to the cold forming process and an effective stress-strain curve that incorporates the effects of residual and the Bauschinger Effect with strain hardening. Also, a set of curves is available for a segmented tee cross section. Here the web is divided into three equal area segments and an effective stress-strain curve produced for each. A fourth curve is produced that represents the effective flange strength.

PROGRAM PROCEDURE

DEFINITIONS (All "Y" distances and radii are measured to the innermost fiber of the structural member)

A(I)	element cross sectional area
C	change in curvature due to bending
C_{SB}	change in curvature due to springback
R	fully bent radius
E	Young's modulus
RF	final radius after springback
Y(I)	distance to centroid of element "I"
Y_o	neutral axis after bending prior to springback
Y_{SB}	neutral axis after springback
$\sigma(I)$	residual stress in element "I"
$\sigma_B(I)$	stress due to bending
$\epsilon(I)$	strain due to C
$\epsilon_{SB}(I)$	strain due to C_{SB}

For any given bend in a multibend analysis or for a single-bend analysis the procedure of the program is as follows.

Define change in curvature due to current bend after selecting an arbitrary value for Y_o and R

$$C = 1.0/(R + Y_o) - 1.0/(R_P + Y_{SBP})$$

where R_P and Y_{SBP} are the radius and neutral axis location of the previous bend. On the first bend R_P is infinite for an initially straight member and thus the second term goes to zero. Next elemental strains due to the change in curvature are defined.

$$\epsilon(I) = C * (Y(I) - Y_o) + \sigma_i(I)/E$$

Stresses are now developed for each element by applying the strain to the appropriate element stress-strain curve. Each element has two stress-strain curves associated with it. One is compressive; the other, tensile. Once the stresses are obtained, forces are calculated and equilibrium checked. If the sum of forces in the cross section is not small compared to the average of the absolute values of the tensile and compressive forces then a new Y_o is selected and the above procedure repeated. The applied moment necessary to bend to the chosen radius is computed by summation of elemental moments. The strain in each element due to bending of the structural member is now known for the current value of the fully bent radius. This strain may be thought of as prestrain. Modified stress-strain curves are generated for each element. If the strains are elastic no change is made in the element curves. Otherwise the curves are changed according to the hardening rule used.

The next step is chose an arbitrary value for Y_{SB}, the springback neutral axis. The change in curvature due to springback, C_{SB}, is then defined,

$$C_{SB} = 1.0/(R + Y_o) - 1.0/(RF + Y_{SB})$$

Elastic springback strains are computed next

$$\epsilon_{SB}(I) = C_{SB} * (Y_{SB} - Y(I))$$

Stresses are then obtained from stress-strain curves previously modified for the Bauschinger Effect and strain hardening. These stresses are due to springback only. The total strain after springback is then calculated as follows. See Figure 9.

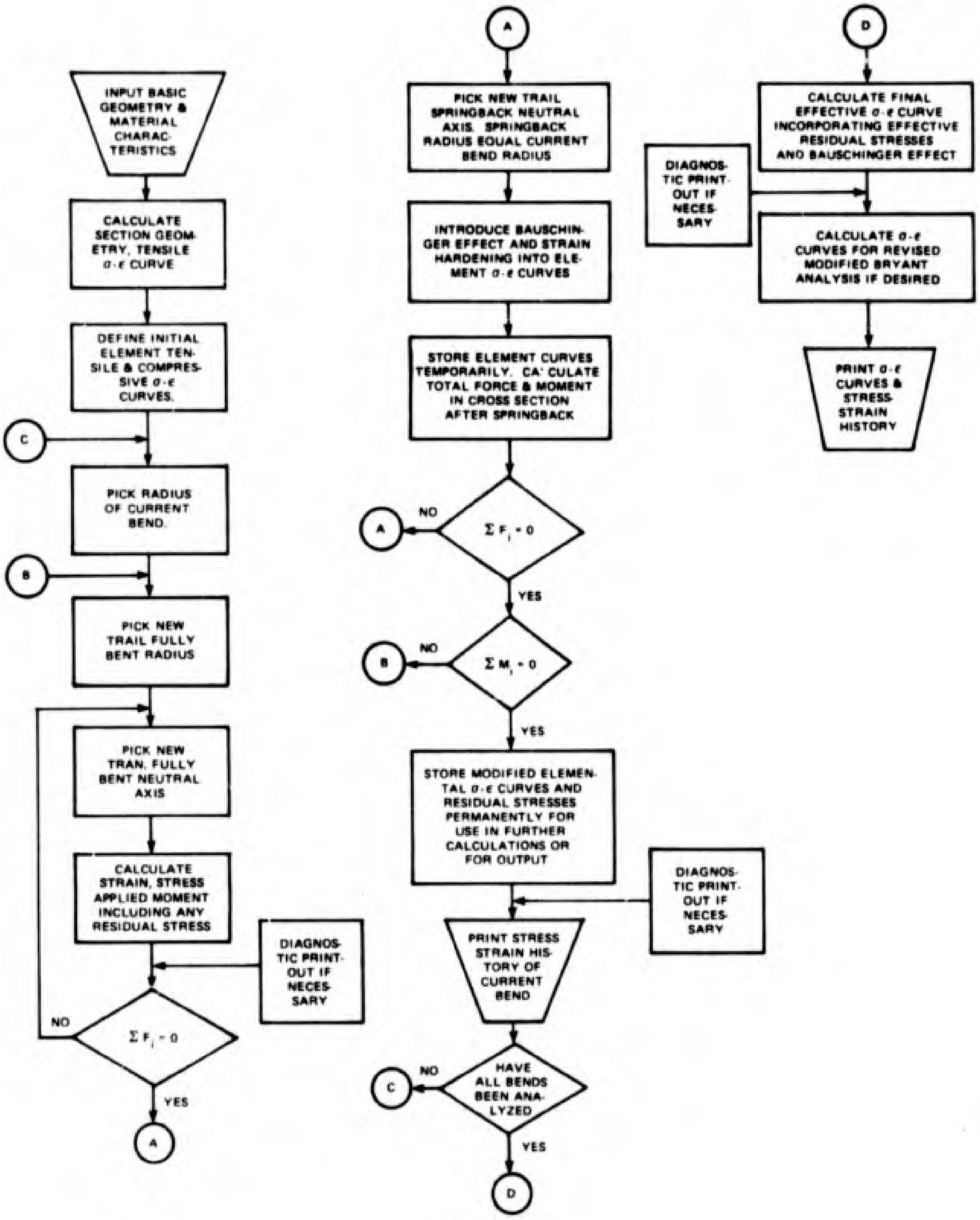
$$\epsilon_T = \epsilon_{SB} - \sigma_B(I)/E$$

This strain is then used to calculate the final residual stress distribution due to bending plus springback. Forces and moments are then calculated and equilibrium conditions checked. If force equilibrium conditions are satisfied then the Y_{SB} assumed is correct. If not, a new Y_{SB} is chosen and the springback computations repeated. Moment equilibrium is checked once Y_{SB} is correct. If moment equilibrium is satisfied the next bend is analyzed using the residual stress distribution and modified element stress-strain curves and initial conditions. If the last bend has been analyzed, the effective stress-strain curve for the cross section is developed.

The effective stress-strain is developed from the final residual stress distribution and the modified element stress-strain curves. A strain is applied to each element and its stress response is calculated. This stress is then weighed by the ratio of the area of the element to that of the total section. These weighted stresses are then integrated over the cross section to give an effective stress that corresponds to the applied strain. A flow chart of the program logic follows.

EXPERIMENTAL WORK

Experimental data needed to evaluate predictions of the program is extremely limited as far as the effect of the cold forming process on the effective stress-strain curve of a structural component is concerned. Such data presented in this report consists of effective stress-strain curves of tee sections made of high strength steel.


INPUT BASIC GEOMETRY & MATERIAL CHARACTERISTICS
CALCULATE SECTION GEOMETRY, TENSILE σ-ε CURVE
DEFINE INITIAL ELEMENT TENSILE & COMPRESSIVE σ-ε CURVES.
C
PICK RADIUS OF CURRENT BEND.
B
PICK NEW TRAIL FULLY BENT RADIUS
PICK NEW TRAN. FULLY BENT NEUTRAL AXIS
CALCULATE STRAIN, STRESS APPLIED MOMENT INCLUDING ANY RESIDUAL STRESS
DIAGNOSTIC PRINT-OUT IF NECESSARY
NO
Σ F_i = 0
YES
A
A
PICK NEW TRAIL SPRINGBACK NEUTRAL AXIS. SPRINGBACK RADIUS EQUAL CURRENT BEND RADIUS
INTRODUCE BAUSCHINGER EFFECT AND STRAIN HARDENING INTO ELEMENT σ-ε CURVES
STORE ELEMENT CURVES TEMPORARILY. CALCULATE TOTAL FORCE & MOMENT IN CROSS SECTION AFTER SPRINGBACK
A
NO
Σ F_i = 0
YES
B
NO
Σ M_i = 0
YES
STORE MODIFIED ELEMENTAL σ-ε CURVES AND RESIDUAL STRESSES PERMANENTLY FOR USE IN FURTHER CALCULATIONS OR FOR OUTPUT
DIAGNOSTIC PRINT-OUT IF NECESSARY
PRINT STRESS STRAIN HISTORY OF CURRENT BEND
C
NO
HAVE ALL BENDS BEEN ANALYZED
YES
D
D
CALCULATE FINAL EFFECTIVE σ-ε CURVE INCORPORATING EFFECTIVE RESIDUAL STRESSES AND BAUSCHINGER EFFECT
DIAGNOSTIC PRINT-OUT IF NECESSARY
CALCULATE σ-ε CURVES FOR REVISED MODIFIED BRYANT ANALYSIS IF DESIRED
PRINT σ-ε CURVES & STRESS-STRAIN HISTORY

One stiffener is made of material that has a plateau stress-strain curve while that of the other is curvilinear. Additionally, data is available on he residual stress distribution in a cold formed tee as shown in Figure 10. The tee was made of high strength steel with a curvilinear stress-strain curve. Experimental data was obtained by hole drilling and slicing techniques. This data provdes a check on the calculated residual stress distribution. Accuracy in this calculation is necessary for accuracy in the subsequent calculation of an effective stress-strain curve. The agreement is very good, especially in the web area which constitutes the upper eighty percent of the figure. Agreement in the flange area is also good. However, difficulties arise in obtaining experimental measurements of stresses in the flange and flange-web intersection., High stress gradients hinder the hole drilling and slicing methods to a large extent. Slicing is also hampered by geometry of the of the cross section near the web-flange intersection.

The experimental effective stress-strain curves were obtained from uniaxial specimens of tee cross section shown in Figure 11. These specimens were cut from straightened segments of external tee ring stiffeners. When a curved external tee section is straightened a strain distribution results which is similar to that of a cold formed internal tee stiffener. This also removes the possibility of local buckling of the web during straightening. The original external ring stiffener was machined from base metal plate. This produces a stress free ring without heat treatment which may affect material properties.

It should be noted that on bending of structural members an elastic core is developed. This is the area of the cross section which remains elastic and in which the neutral axis of the member is located. For the particular geometries presented the elastic core is calculated to be totally in the flange. Other cross sections may develop the elastic core outside the flange and such cases should be investigated.

Figure 12 shows the experimental effective stress-strain curve and the base metal compression plateau stress-strain curve of the tee section. The reduction in proportional limit is approximately fifty five percent. Also shown is a predicted curve using the kinematic-isotroptic hardening rule. The coefficient of ultimate limit increase and the coefficient of proportional limit reduction are equal to 2.0. These numbers were obtained by a trial and error process. To use this hardening rule effectively, one must be able to determine the coefficients more easily. Figure 13 is essentially the same plot as Figure 12 except the predicted effective stress-strain curve has been calculated using experimental hardening rules. Agreement is within five percent. The predicted curve is lower than the experimental one. This may be the result of the nondimensional data used for the plateau hardening rule. This data exhibits a severe reduction in strength at high strain rates. The comparison of theoretical and experimental results for a high strength steel with a curvilinear stress-strain curve does not exhibit the five percent discrepancy of the plateau type material.

Figure 14 shows the base metal stress-strain curve and the experimental effective stress-strain curve of the second tee section. This work was conducted by Bond at DTNSRDC. Observe the base metal curve above the proportional limit is curvilinear rather than plateau in nature. The reduction in the proportional limit stress is approximately sixty percent. Also shown is the predicted effective stress-strain curve using experimental hardening rules. Agreement is within two percent. The kinematic isotropic hardening rule is not shown because it depends on trial and error determination of two necessary constants.

FUTURE WORK

The program documented herein gives the designer an inexpensive and easily used tool not available in the past. However, the program in its present state is limited in the scope of its validation and experimental hardening data. The limitations are both on the number of data available to the program and in fact that the data available represent only one loading cycle. Data should be collected to provide more detailed information on material response in the range of 0.1 percent to 2.0 percent prestrain. This data should represent a loading history that is cyclic in nature.

The experimental data used to asses the program's accuracy is limited to one residual stress distribution and two effective stress-strain curves. More data of this nature should be generated for different cross sections and materials.

There is some experimental indication* that, due to the mechanics of the rolling process, the state of strain in a flanged structural member, does not follow the assumption of planes before deformation remaining plane after deformation. This is not unexpected but should be investigated. Also, the effect of shear deformation normally present in the rolling process should be investigated.

ACKNOWLEDGMENTS

Mr. D.T. McDevitt made many helpful suggestions during the design and testing of the cold formed tee specimens and during the writing of this report.

Mr. C.D. Bond provided technical guidance during coding of the program as did Mr. T.E. Reynolds.

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*Cordinanao, H.V., "Structural Properties of Cold Formed Tee Shapes," DTNSRDC Materials Department Research and Development Report MAT-74-25 August 1974.

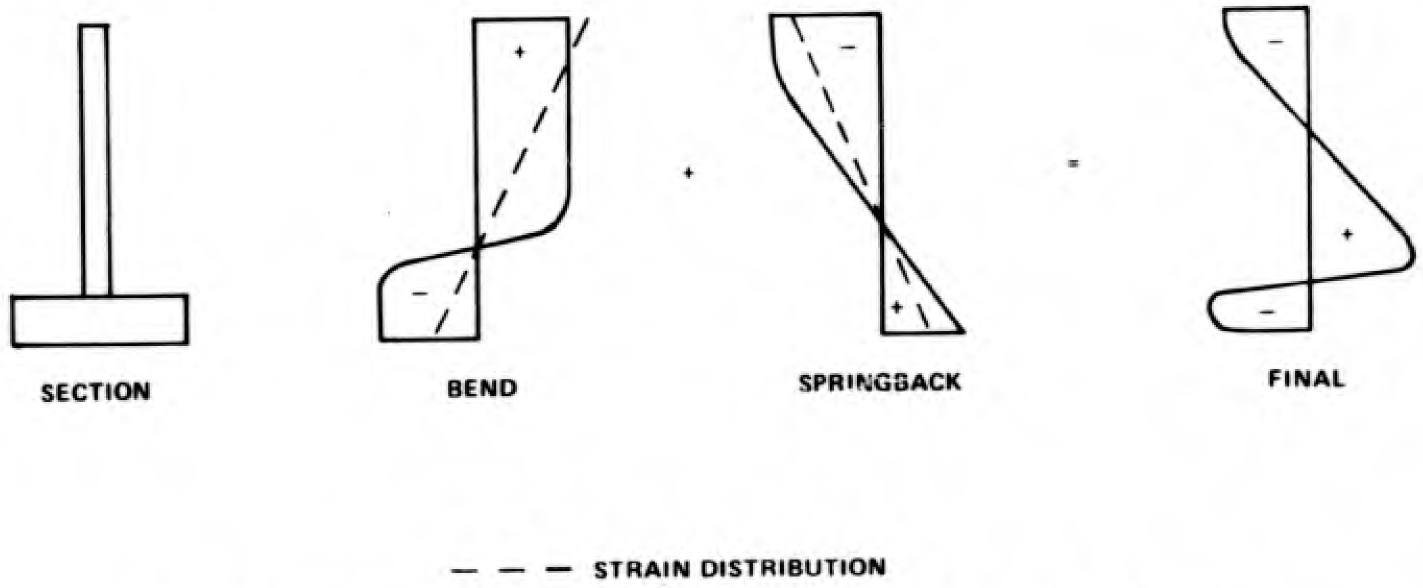


Figure 1 - Stress Patterns due to Cold Rolling of a Tee Section

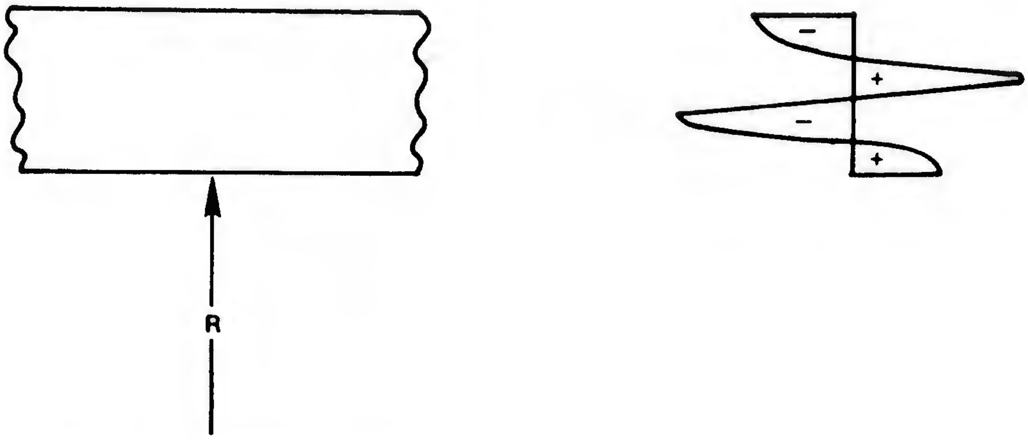


Figure 2a - Typical Residual Stress Pattern for a Cold Rolled Plate

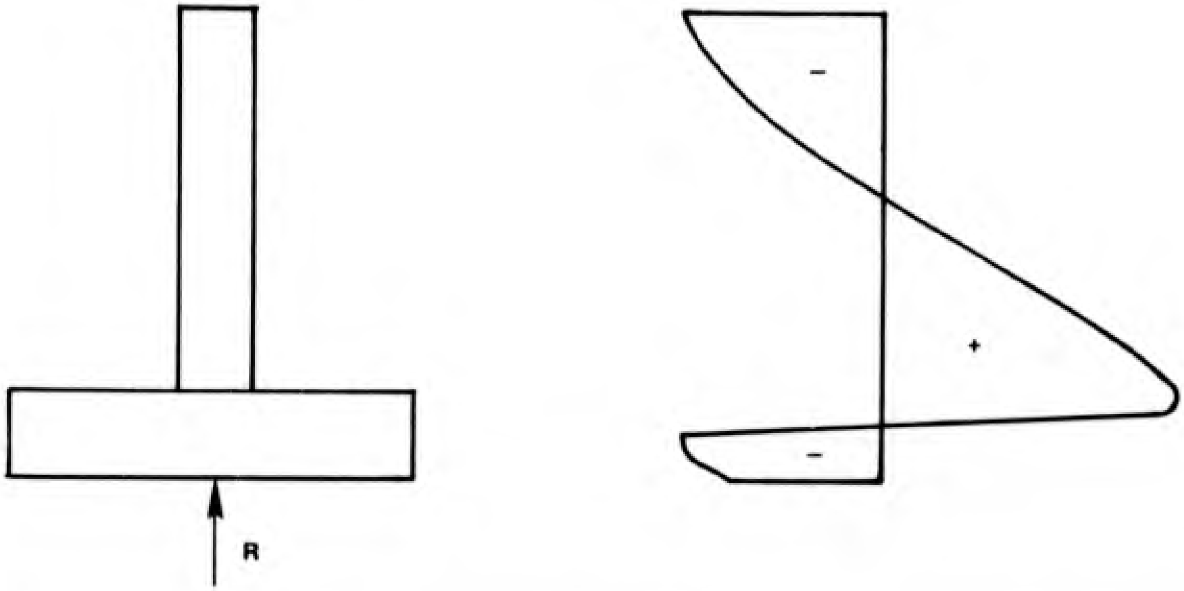


Figure 2b - Typical Residual Stress Pattern for a Cold Formed Tee Section

Figure 2 - Typical Residual Stress Patterns

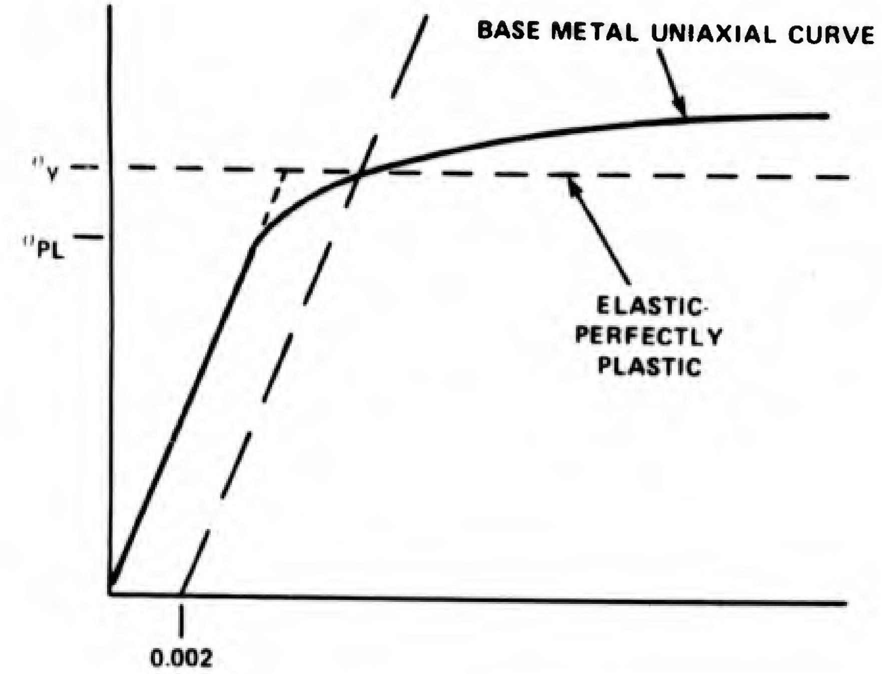


Figure 3 - Stress-Strain Curve of an Elastic-Perfectly Plastic Material

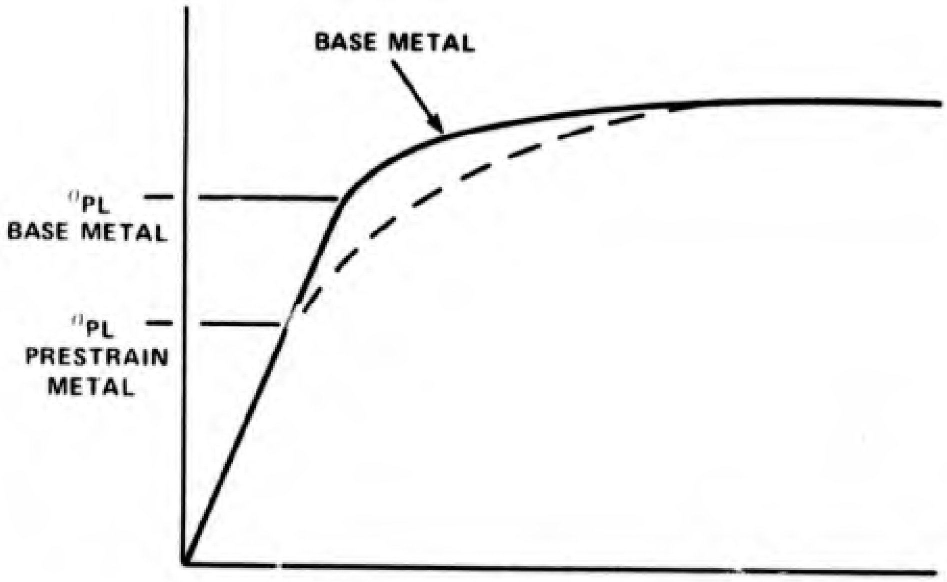
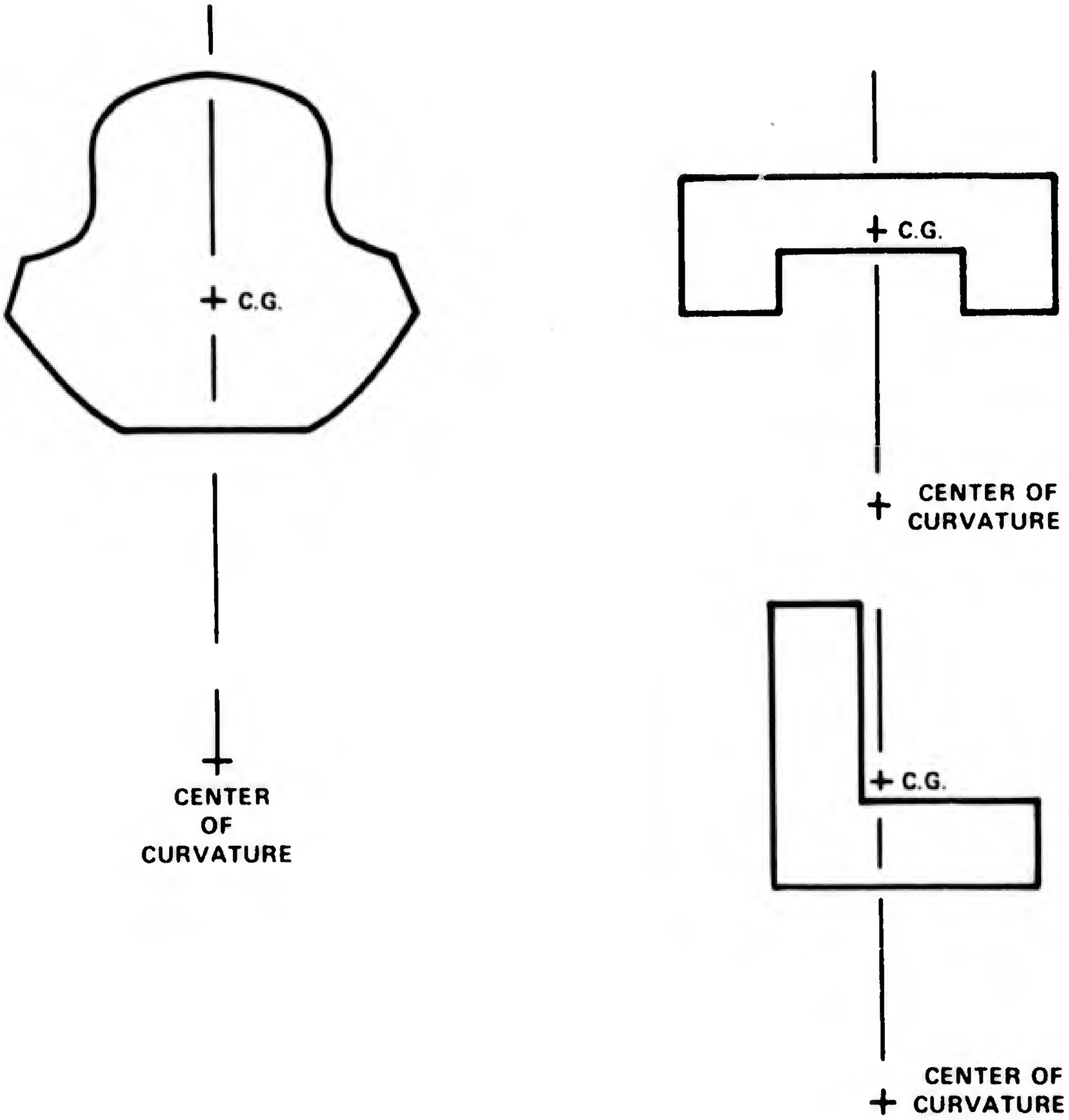


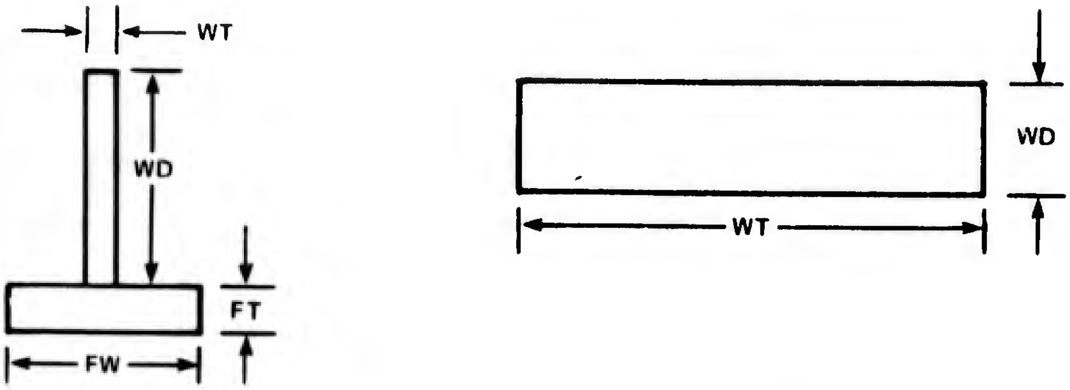
Figure 4 - Bauschinger Effect in a Uniaxial Specimen of High Strength Steel



ALLOWABLE

NOT ALLOWABLE

Figure 5 - Restrictions on Cross Sections that may be Analyzed



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IGEOM = 3

Figure 6 - Cross Section Geometry Options

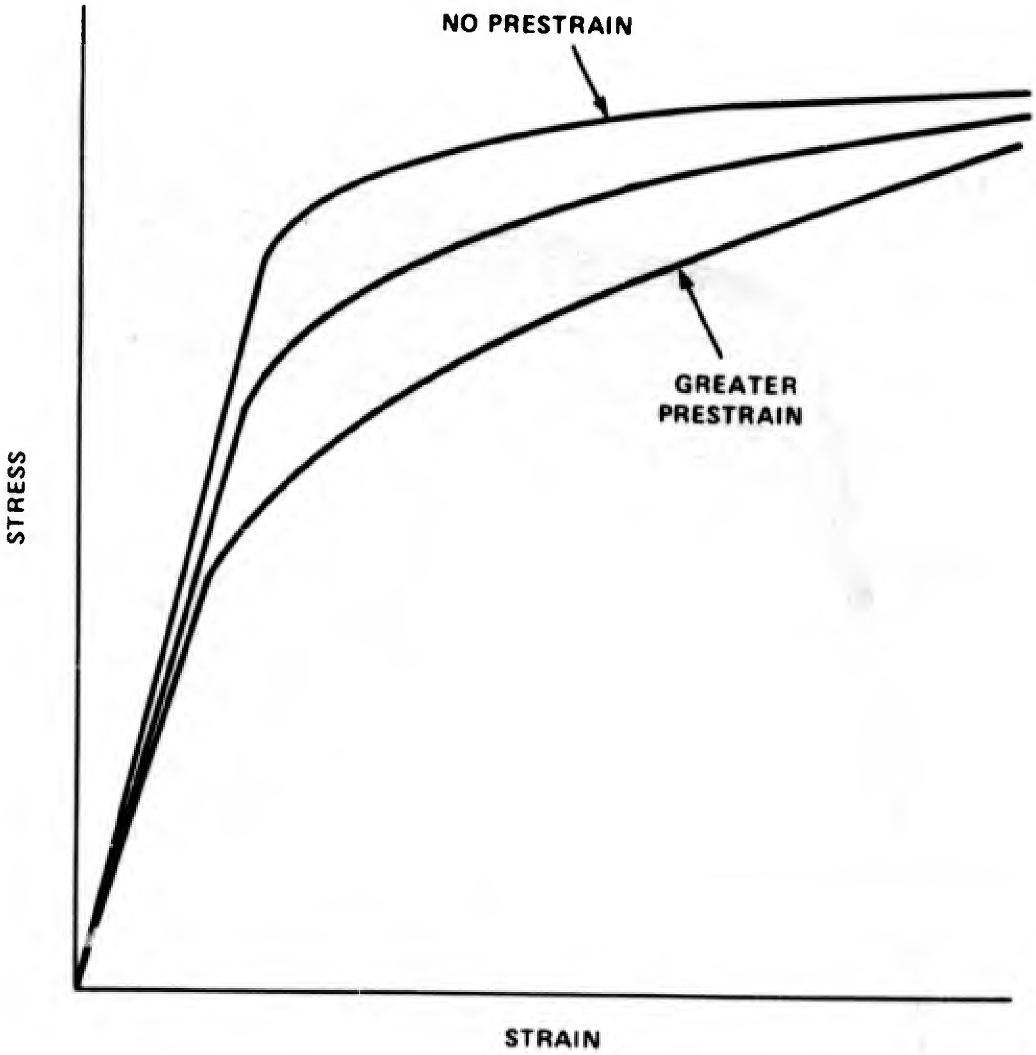


Figure 7 - Representation of the Effect of Prestrain on the Effective Stress-Strain Curve

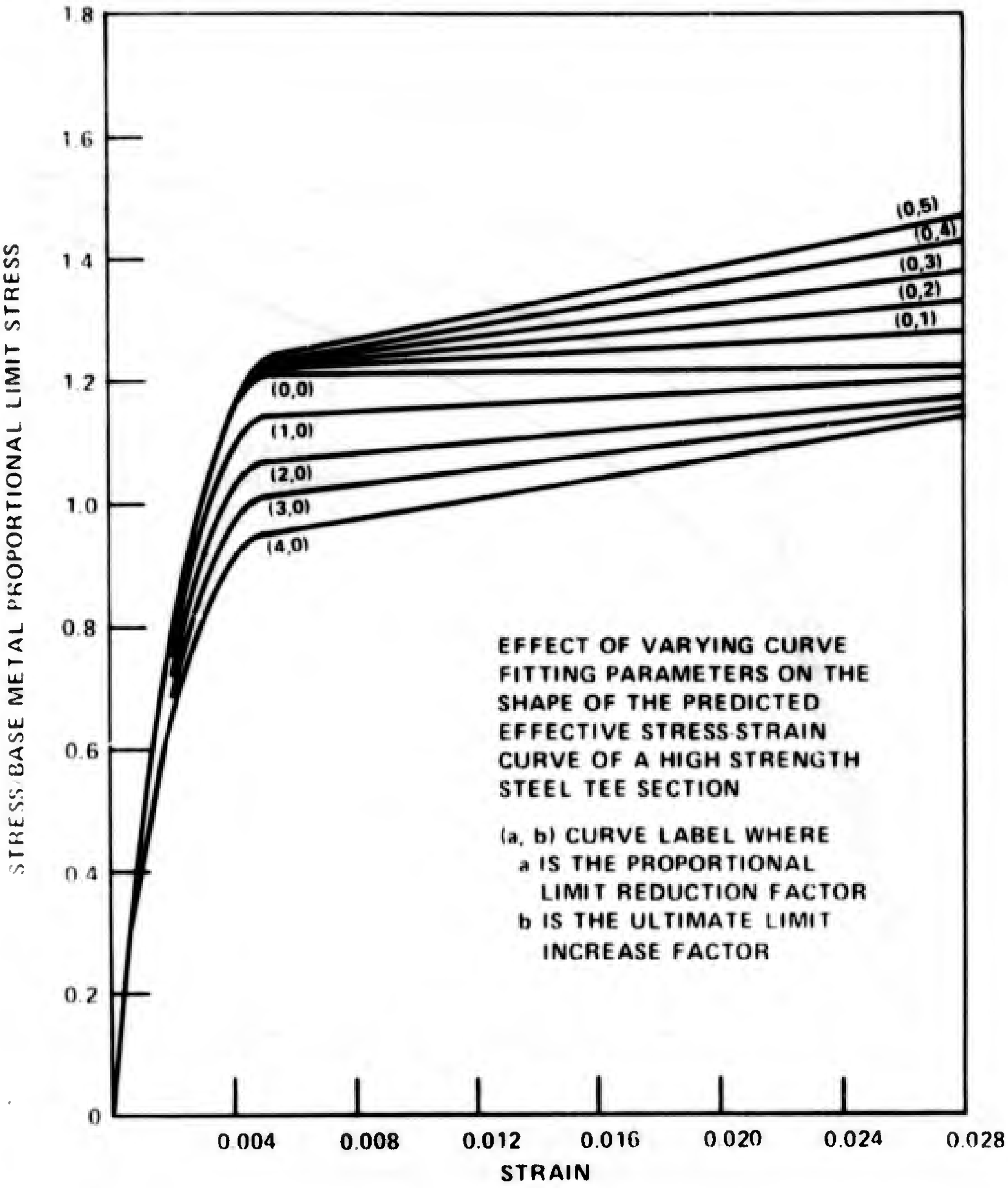
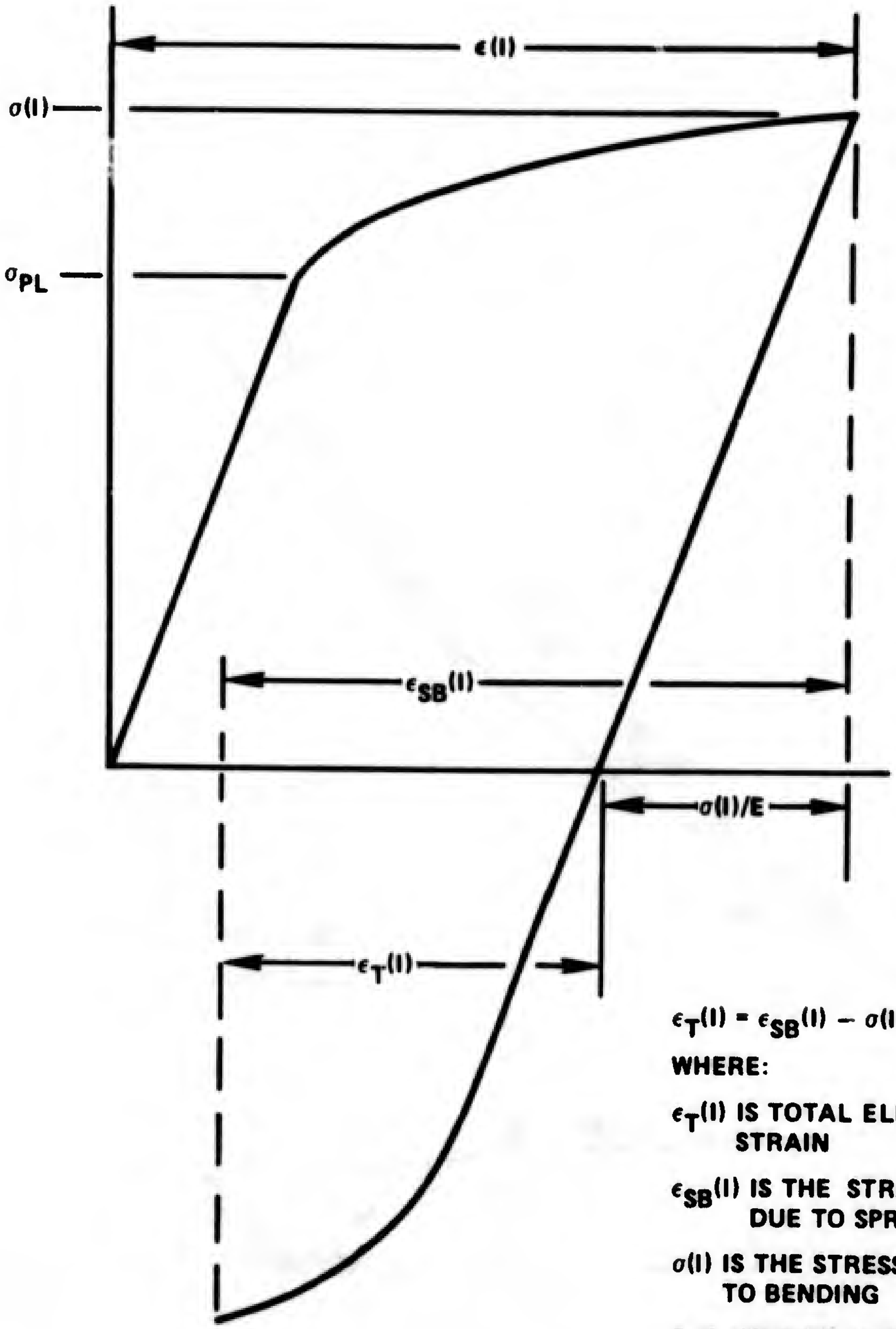


Figure 8 - Effect of Varying Curve Fitting Parameters on the Shape of a Predicted Effective Stress-Strain Curve



$\epsilon_T(I) = \epsilon_{SB}(I) - \sigma(I)/E$

WHERE:

$\epsilon_T(I)$ IS TOTAL ELEMENT STRAIN

$\epsilon_{SB}(I)$ IS THE STRAIN DUE TO SPRINGBACK

$\sigma(I)$ IS THE STRESS DUE TO BENDING

E IS YOUNG'S MODULUS

Figure 9 - Element Strain due to Bending and Springback

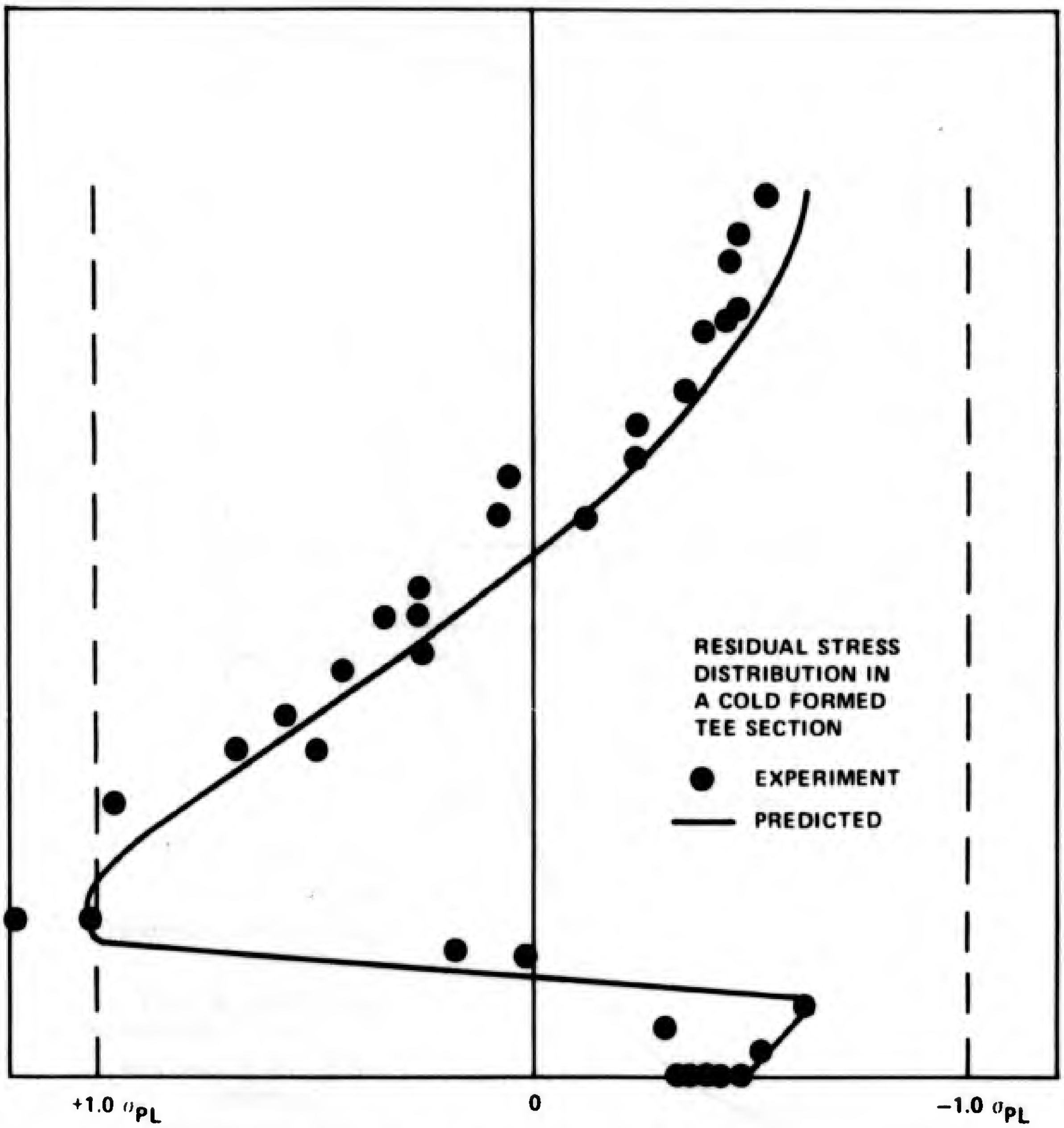
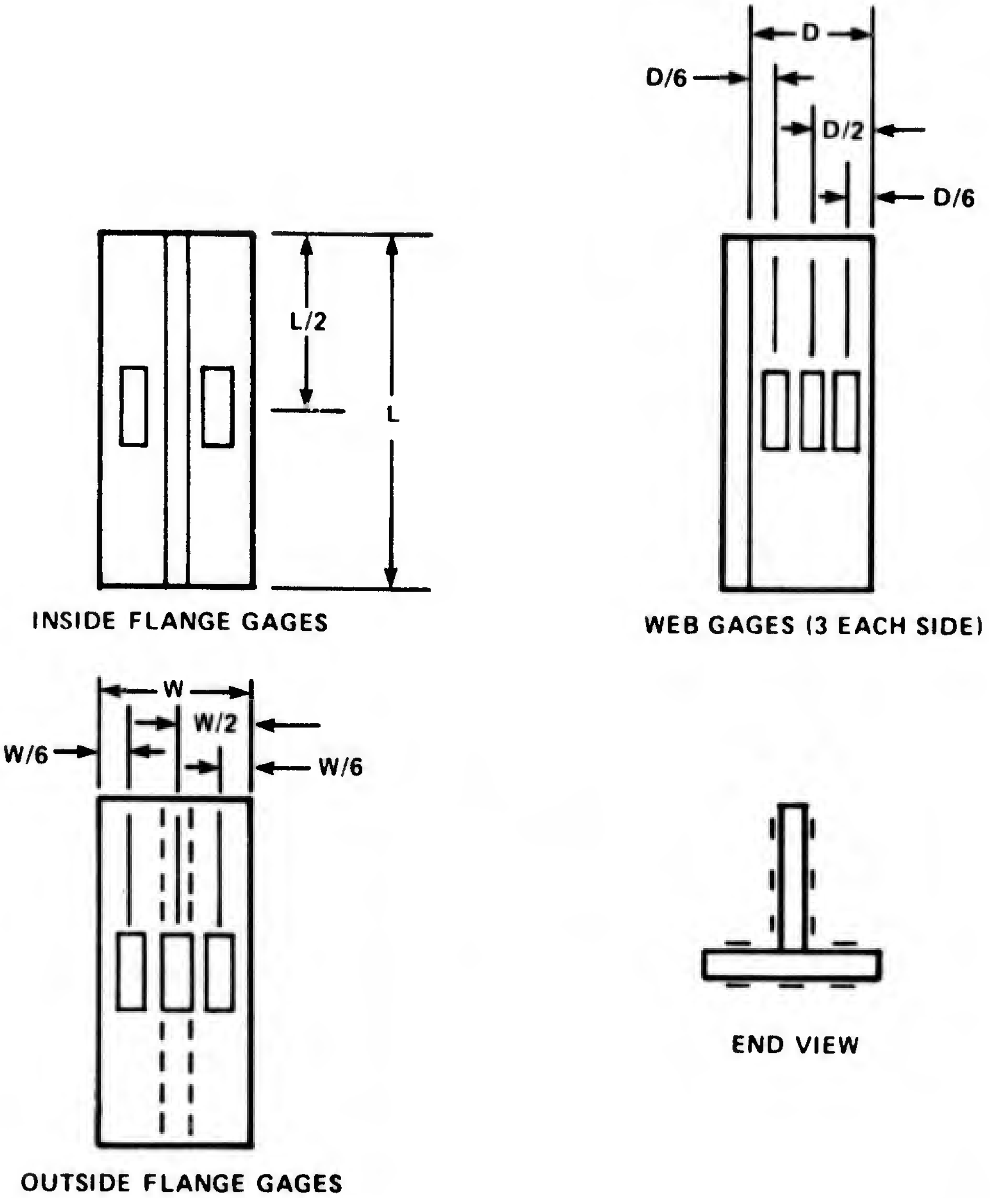


Figure 10 - Residual Stress Distribution in a Cold-Formed Tee Section



INSIDE FLANGE GAGES

WEB GAGES (3 EACH SIDE)

OUTSIDE FLANGE GAGES

END VIEW

NOT TO SCALE

Figure 11 - Strain Gage Locations on Uniaxial Cold-Formed Tee Section Specimens

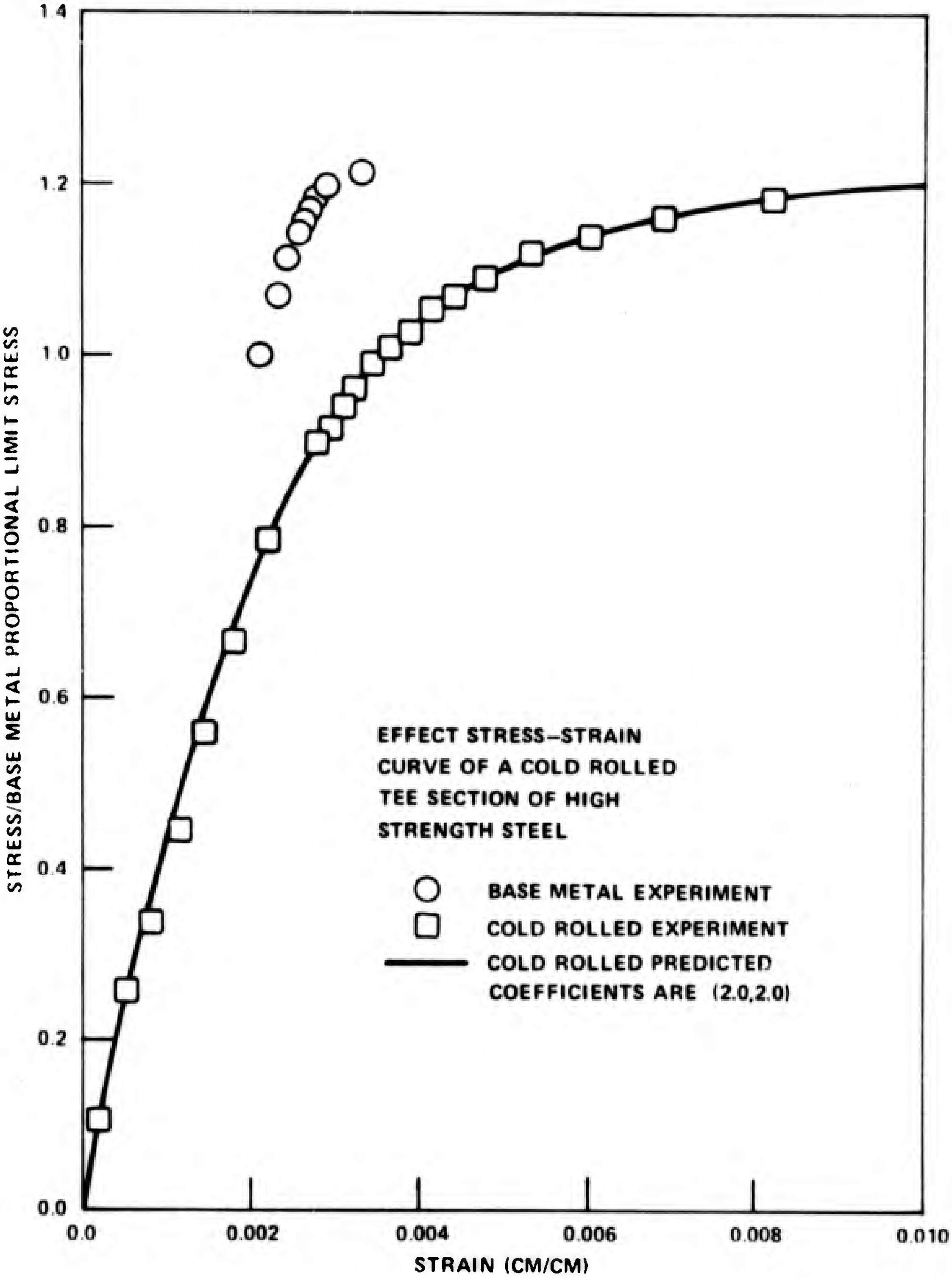


Figure 12 - Effective Stress-Strain Curve of a Cold Rolled Tee Section of Material that has a Plateau Stress-Strain Curve using the Kinematic-Iostropic Hardening Rule

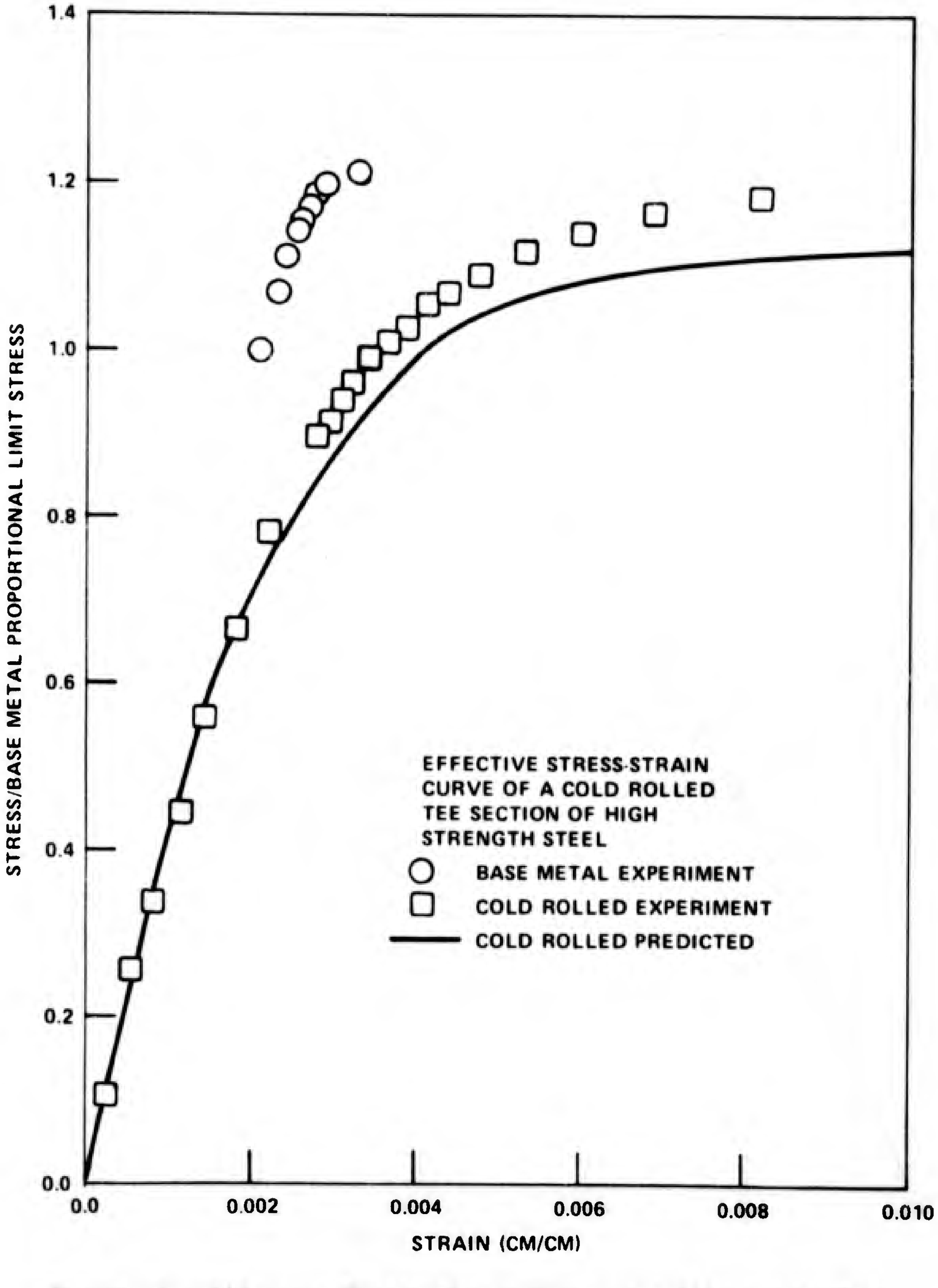


Figure 13 - Effective Stress-Strain Curve of a Cold Rolled Tee Section of Material that has a Plateau Stress-Strain Curve using Experimental Hardening Rule

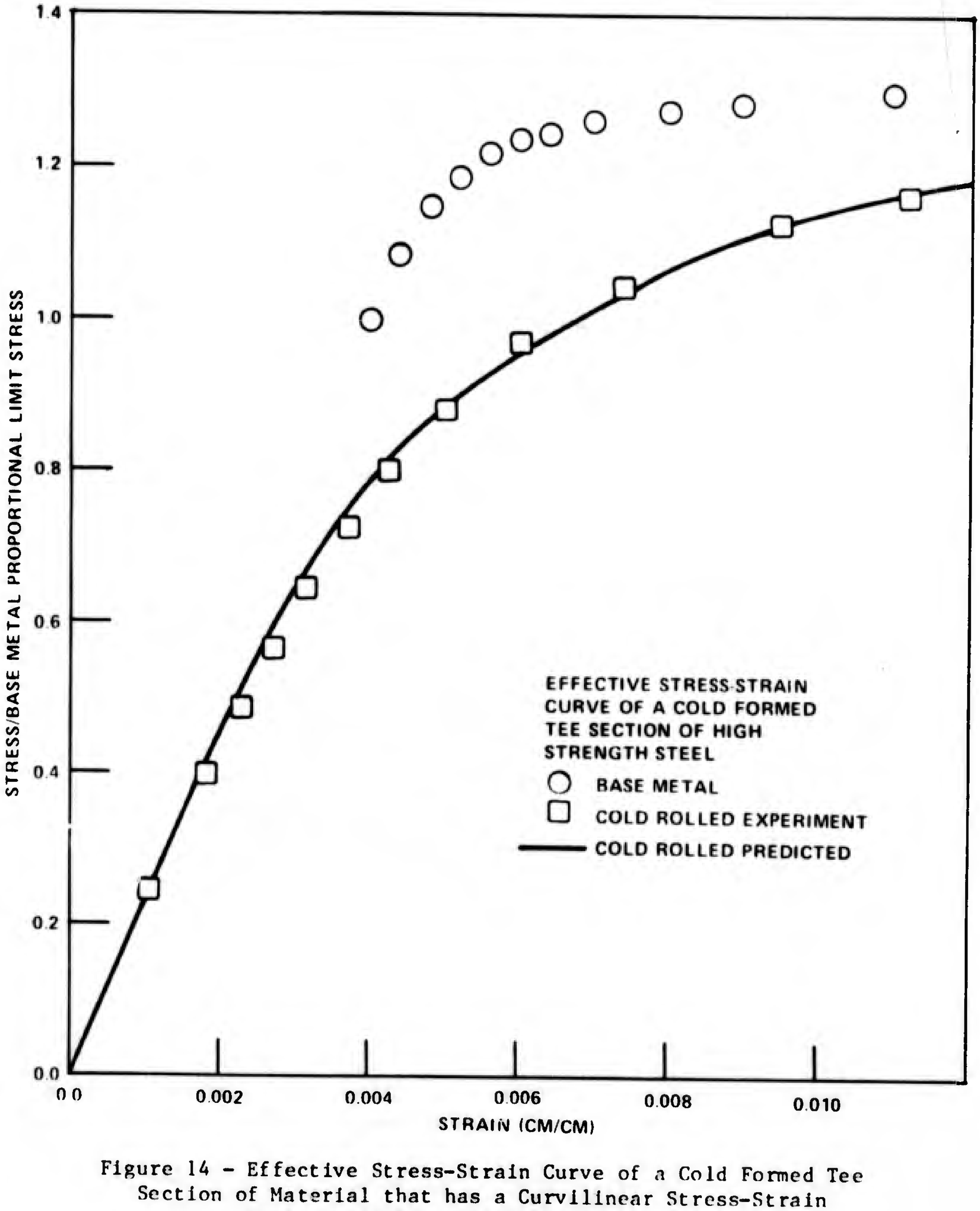


Figure 14 - Effective Stress-Strain Curve of a Cold Formed Tee Section of Material that has a Curvilinear Stress-Strain Curve using Experimental Hardening Rule

APPENDIX A

INPUT DESCRIPTION, SAMPLE PROBLEM AND OUTPUT

Input to the program consists of basic geometry, certain indices and base metal compressive stress-strain curves. The following text gives a complete description of data formats and options. All variables are listed in the order in which they should appear, and the format or field in which they appear is given. If the parameter is an integer value and has to be right justified, the letter "R" will appear in the format or field specification.

CARD SET (NUMBER OF CARDS)	PARAMETER (FIELD) AND DESCRIPTION
A (1)	TITLE (8A10) Title of problem.
B (1)	IBENDS (1-5R) Number of bends used in the analysis. Up to ten bends are allowed.
	NE (6-10R) Number of elements. A maximum of 50 is allowed. This number should be evenly devisable by four for "tee" sections.
	ICRV (11-15R) Number of base metal stress-strain curves to be read in. A maximum of "NE" curves are allowed.
	KBE (16-20R) Equal to 11 - Use kinematic - isotropic hardening rule; Equal to 21 - Use experimental hardening rule for high strength steel with a curvilinear base metal stress - strain curve; Equal to 22 - Use experimental hardening rule for high strength steel with a plateau base metal stress-strain curve.
	IGEOM (21-25R) Equal to 0 for tee section; Equal to 1 for a rectangular section; Equal to 2 for a circular section; Equal to 3 for a section of arbitrary shape.

	INEX (26-30R) Equal to or less than zero for an internal tee stiffener; Greater than zero for an external stiffener.
	MODSQD (31-35R) Equal to 0 - Stress-strain curves for a segmented tee section are not printed; Not equal to 0 - Curves will be printed.
	ITSTR (36-40R) Equal to 0 - No initial stress is to be read; Not equal to 0 - read initial stresses later in input.
	DEBUGR (41-45R) Equal to 0 - No printout of intermediate stress-strain curves; Less than 0 - Print out all intermediate curves; Greater than 0 but less than or equal to "NE" - Print out intermediate curves for the element whose index is equal to DEBUGR.
	ITR (46-50R) Equal to 0 - No printout of iterative quantities; Not equal to zero - Print out iterative quantities.
C (1 or 2)	RADII (I), I = 1, IBENDS (1-80@10) Radii of consecutive bends. The last radius given must be the design radius. All radii are measured to the innermost fiber.
D (1)	WD (1-10) Web depth, shell to flange
IGEOM = 0	WT (11-20) Web thickness
	FW (21-30) Flange width
	FT (31-40) Flange thickness
IGEOM = 1	WD (1-10) Section dimension in radial direction
	WT (11-20) Section dimension perpendicular to radial direction

IGEOM = 2	WD (1-10) Section diameter
IGEOM = 3	Skip this card
E (1)	SRED (1-10) Percentage reduction to be applied to compressive stress-strain curves to obtain tensile curves.
	STRNK (11-20) Strain increment to be used in the calculation of the effective stress-strain curve. The total strain range of this curve will be 49*STRNK.
	FABSTR (21-30) Fabrication stress to be applied to calculated effective stress-strain curves.
	SPLF (31-40) Factor to multiply the calculated kinematic reduction in the proportional limit of each element KBE = 11. Default value is 1.0. Both SPLF and SUF must be zero for default values to be supplied.
	SUF (41-50) Factor to multiply the calculated isotropic increase in the ultimate limit of each element if KBE = 11. Default value is 0.0.
F (ICRV/20)	NPAT(I), I = 1, ICRV (1-80@5R) Number of Points in each of the base metal stress-strain curves to be read in later.
G (NE/40)	NPA(I), I = 1, NE (1-80@2R) Index of stress-strain curve to be used for element "I." The first curve read in has an index of 1. The last curve read has an index of ICRV. Elements are numbered in ascending order from the innermost fiber. Thus NPA (1)

	specifies the stress-strain curve of the innermost element. NPA(NE) specifies the stress-strain curve of the outtermost element. For tee sections one fourth of the total number of elements are located in the flange while the remaining elements are placed in the web.
H (NPAT(I) Cards for the "I" curve)	STRESS(J), STRAIN(J), J = 1, NPAT (I) (1-10, 11-20) The stress and strain values associated with point "J." The first point must be (0.0, 0.0). The second point must be the proportional limit stress and strain. The last point is taken to be the ultimate limit. There is one card per point. All stress-strain curves are read consecutively.
I (NE/8)	SIL(I), I = 1, NE (8F10.3) Values of initial stress. Read only if ITSTR is not equal to zero.
J (NE)	ED(I), EW(I), I = 1, NE (1-10, 11-20) ED(I) is the depth of element "I." EW(I) is the width of element "I." Use only if IGEOM = 3.

SAMPLE PROBLEM

The problem that follows is included to give the user an idea of the output format and of those parameters printed with the standard output. More detailed output is available, but is usually obtained only for debugging purposes. This extra output consists of the stress-strain history of one or all ements and of intermediate values of certain iterative quantities.

The listing of the example problem data is followed by the output produced when that data was analyzed.

```
EXAMPLE OF MULTIBEND ANALYSIS
```

```
    4   20    2   11
```

```
20.0      17.5      16.0      15.0
```

```
1.40      0.30      1.50      0.50
```

```
0.03      0.0005    0.0       2.5
2.0
```

```
    6    7
```

```
 1.1 1 1 1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
```

```
0.0       0.0
87100.0   0.0029
87120.0   0.00356
87132.0   0.00423
87190.0   0.00688
87500.0   0.02145
0.0       0.0
```

```
77000.0   0.00257
```

```
78000.0   0.0027
```

```
79000.0   0.0029
```

```
79500.0   0.0031
```

```
80000.0   0.0046
```

```
81000.0   0.0200
```

```
EXAMPLE OF MULTIBEND ANALYSIS


FRAME IS INTERNAL

KINEMATIC-ISOTROPIC HARDENING USED

DESIGN RADIUS                                     15.000

WEB DEPTH                                          1.400

WEB THICKNESS                                       .300

FLANGE WIDTH                                       1.500

FLANGE THICKNESS                                    .500

NUMBER OF ELEMENTS                                  20

TENSILE STRENGTH REDUCTION                          .030

STRAIN INCREMENT                                   .000500

PROPORTIONAL LIMIT REDUCTION FACTOR               2.500

ULTIMATE LIMIT INCREASE FACTOR                    2.000

FRAME AREA                                         1.170

CENTROID                                            .591

RADII OF CONSECUTIVE BENDS                        20.000
                                                  17.500
                                                  16.000
                                                  15.000
MATERIAL COMPRESSIVE INPUT STRESS-STRAIN CURVE  1
PROPORTIONAL LIMIT STRESS       87100.      0.2 PERCENT YIELD STRESS       87147.

    STRESS            STRAIN               ES                   ET

        0.          0.000000         0.                   .300345E+08
    87100.           .002900          .300345E+08         .244719E+08
    87120.           .003560          .244719E+08         .240602E+05
    87132.           .004230          .205986E+08         .210843E+05
    87190.           .006880          .126730E+08         .213705E+05
    87500.           .021450          .407925E+07         .212766E+05

MATERIAL TENSILE COMPUTED STRESS-STRAIN CURVE  1
PROPORTIONAL LIMIT STRESS       84487.      0.2 PERCENT YIELD STRESS       84532.

    STRESS            STRAIN               ES                   ET

        0.          0.000000         0.                   .300345E+08
    84487.           .002813          .300345E+08         .243325E+08
    84506.           .003473          .243325E+08         .233389E+05
    84518.           .004143          .204004E+08         .204522E+05
    84574.           .006793          .124504E+08         .207298E+05
    84875.           .021363          .397306E+07         .206387E+05
```

```
MATERIAL COMPRESSIVE INPUT STRESS-STRAIN CURVE  2
PROPORTIONAL LIMIT STRESS       77000.       0.2 PERCENT YIELD STRESS       79990.

    STRESS               STRAIN               ES                   ET

        0.             0.000000           0.                   .299611E+08
    77000.              .002570            .299611E+08         .288889E+08
    78000.              .002700            .288889E+08         .606061E+07
    79000.              .002900            .272414E+08         .375000E+07
    79500.              .003100            .256452E+08         .588235E+06
    80000.              .004600            .173913E+08         .887574E+05
    81000.              .020000            .405000E+07         .649351E+05

MATERIAL TENSILE COMPUTED STRESS-STRAIN CURVE  2
PROPORTIONAL LIMIT STRESS       74690.       0.2 PERCENT YIELD STRESS       77591.

    STRESS               STRAIN               ES                   ET

        0.             0.000000           0.                   .299611E+08
    74690.              .002493            .299611E+08         .288570E+08
    75660.              .002622            .288570E+08         .591468E+07
    76630.              .002821            .271651E+08         .365121E+07
    77115.              .003020            .255314E+08         .570925E+06
    77600.              .004520            .171685E+08         .861023E+05
    78570.              .019919            .394450E+07         .629911E+05

ELEMENT GEOMETRY AND INITIAL STRESS

     WIDTH       DEPTH         Y        STRESS


     1.5000      .1000       .0500         0.
     1.5000      .1000       .1500         0.
     1.5000      .1000       .2500         0.
     1.5000      .1000       .3500         0.
     1.5000      .1000       .4500         0.
      .3000      .0933       .5467         0.
      .3000      .0933       .6400         0.
      .3000      .0933       .7333         0.
      .3000      .0933       .8267         0.
      .3000      .0933       .9200         0.
      .3000      .0933      1.0133         0.
      .3000      .0933      1.1067         0.
      .3000      .0933      1.2000         0.
      .3000      .0933      1.2933         0.
      .3000      .0933      1.3867         0.
      .3000      .0933      1.4800         0.
      .3000      .0933      1.5733         0.
      .3000      .0933      1.6667         0.
      .3000      .0933      1.7600         0.
      .3000      .0933      1.8533         0.
```

```
RADIUS AFTER SPRINGBACK FOR BEND 1               20.000

FULLY BENT RADIUS                                18.721

NEUTRAL AXIS AFTER SPRINGBACK                      .624

FULLY BENT NEUTRAL AXIS                            .379

APPLIED MOMENT                                    .371553E+05


STRESS AND STRAIN HISTURY UF SECTIUN DUE TO COLD FORMING FUR BEND  1 OF  4      RADIUS IS  20.000
  I      Y(I)            BENDING                         SPRINGBACK                       FINAL
                   STRAIN         STRESS          STRAIN          STRESS          STRAIN          STRESS

  1      .0500    -.0172061      -87410.        .0022229        66763.        -.0006946        -20861.
  2      .1500    -.0119704      -87298.        .0018358        55136.        -.0010780        -32376.
  3      .2500    -.0067346      -87187.        .0014486        43509.        -.0014614        -43891.
  4      .3500    -.0014988      -45015.        .0010615        31882.        -.0004409        -13243.
  5      .4500     .0037370       84511.        .0006744        20255.         .0034951         78413.
  6      .5467     .0087983       77869.        .0003002         8994.         .0028992         77817.
  7      .6400     .0136850       78177.       -.0000611        -1831.         .0025482         76346.
  8      .7333     .0185717       78485.       -.0004224       -12656.         .0021971         65829.
  9      .8267     .0234585       78491.       -.0007837       -23481.         .0018360         55010.
 10      .9200     .0283452       78491.       -.0011450       -34307.         .0014747         44185.
 11     1.0133     .0332319       78491.       -.0015063       -45132.         .0011134         33360.
 12     1.1067     .0381187       78491.       -.0018677       -55957.         .0007521         22534.
 13     1.2000     .0430054       78491.       -.0022290       -66782.         .0003908         11709.
 14     1.2933     .0478921       78491.       -.0025903       -69801.         .0000295           884.
 15     1.3867     .0527789       78491.       -.0029516       -70709.        -.0003318         -9941.
 16     1.4800     .0576656       78491.       -.0033129       -71169.        -.0006931        -20766.
 17     1.5733     .0625523       78491.       -.0036742       -71629.        -.0010544        -31592.
 18     1.6667     .0674391       78491.       -.0040355       -72089.        -.0014157        -42417.
 19     1.7600     .0723258       78491.       -.0043968       -72537.        -.0017770        -53242.
 20     1.8533     .0772125       78491.       -.0047581       -72903.        -.0021383        -64067.
EQUILIBRIUM CHECK OF RESIDUAL STRESS DISTRIBUTION

UNBALANCED FORCE IN CRUSS SECTION IS       -156.
UNBALANCED MOMENT IN CRUSS SECTION IS       -107.
```

```
RADIUS AFTER SPRINGBACK FOR BEND 2          17.500

FULLY BENT RADIUS                           16.509

NEUTRAL AXIS AFTER SPRINGBACK                 .618

FULLY BENT NEUTRAL AXIS                       .429

APPLIED MOMENT                              .370476E+05


STRESS AND STRAIN HISTORY OF SECTION DUE TO COLD FORMING FOR BEND  2 OF  4      RADIUS IS  17.000
  I       Y(I)            HENDING                      SPRINGBACK                       FINAL
                    STRAIN          STRESS        STRAIN          STRESS         STRAIN          STRESS

  1      .0500    -.0046955        -87357.       .0021848         65620.      -.0007309         -21951.
  2      .1500    -.0040236        -87256.       .0018002         54069.      -.0011121         -33400.
  3      .2500    -.0033518        -87118.       .0014157         42519.      -.0014920         -44812.
  4      .3500    -.0012761        -38328.       .0010311         30969.      -.0002481          -7453.
  5      .4500     .0037152         78413.       .0006465         19418.       .0032637          78413.
  6      .5467     .0041393         77923.       .0002748          8233.       .0028796          77872.
  7      .6400     .0047732         78284.      -.0000842         -2521.       .0025287          75763.
  8      .7333     .0054070         78413.      -.0004431        -13275.       .0021741          65138.
  9      .8267     .0060308         78413.      -.0008020        -24029.       .0018151          54384.
 10      .9200     .0066544         78413.      -.0011610        -34783.       .0014562          43630.
 11     1.0133     .0072780         78413.      -.0015199        -45537.       .0010973          32876.
 12     1.1067     .0079016         78413.      -.0018788        -56291.       .0007383          22122.
 13     1.2000     .0085251         78413.      -.0022377        -67045.       .0003794          11368.
 14     1.2933     .0091487         78413.      -.0025967        -69831.       .0000205            614.
 15     1.3867     .0097723         78413.      -.0029556        -70714.      -.0003385         -10140.
 16     1.4800     .0103959         78413.      -.0033145        -71171.      -.0006974         -20894.
 17     1.5733     .0110195         78413.      -.0036735        -71628.      -.0010563         -31648.
 18     1.6667     .0116430         78413.      -.0040324        -72085.      -.0014152         -42402.
 19     1.7600     .0122666         78413.      -.0043913        -72531.      -.0017742         -53156.
 20     1.8533     .0128902         78413.      -.0047503        -72895.      -.0021331         -63910.
EQUILIBRIUM CHECK OF RESIDUAL STRESS DISTRIBUTION

UNBALANCED FORCE IN CRUSS SECTION IS        145.
UNBALANCED MOMENT IN CRUSS SECTION IS        29.
```

```
RADIUS AFTER SPRINGBACK FOR BEND 3           16.000

FULLY BENT RADIUS                            15.156

NEUTRAL AXIS AFTER SPRINGBACK                  .618

FULLY BENT NEUTRAL AXIS                        .464

APPLIED MOMENT                                 .370410E+05


STRESS AND STRAIN HISTORY OF SECTION DUE TO COLD FORMING FOR BEND  3 OF  4      RADIUS IS  16.000

  I      Y(I)            BENDING                         SPRINGBACK                         FINAL
                    STRAIN          STRESS          STRAIN          STRESS          STRAIN          STRESS


  1      .0500     -.0043819        -87330.        .0021849         65622.       -.0007299         -21922.
  2      .1500     -.0038804        -87232.        .0018003         54072.       -.0011112         -33375.
  3      .2500     -.0033775        -87062.        .0014157         42521.       -.0014901         -44755.
  4      .3500     -.0012509        -37569.        .0010311         30970.       -.0002228          -6692.
  5      .4500      .0031437         78413.        .0006466         19419.        .0032637          78413.
  6      .5467      .0036090         77944.        .0002748          8233.        .0028763          77896.
  7      .6400      .0040860         78294.       -.0000842         -2521.        .0025290          75772.
  8      .7333      .0045553         78335.       -.0004431        -13276.        .0021714          65059.
  9      .8267      .0050203         78413.       -.0008021        -24030.        .0018151          54383.
 10      .9200      .0054853         78413.       -.0011610        -34785.        .0014562          43628.
 11     1.0133      .0059503         78413.       -.0015199        -45539.        .0010972          32874.
 12     1.1067      .0064153         78413.       -.0018789        -56294.        .0007383          22119.
 13     1.2000      .0068803         78413.       -.0022378        -67048.        .0003793          11365.
 14     1.2933      .0073453         78413.       -.0025968        -69831.        .0000204            610.
 15     1.3867      .0078103         78413.       -.0029557        -70715.       -.0003386         -10144.
 16     1.4800      .0082753         78413.       -.0033147        -71172.       -.0006975         -20899.
 17     1.5733      .0087403         78413.       -.0036736        -71629.       -.0010565         -31653.
 18     1.6667      .0092053         78413.       -.0040326        -72086.       -.0014154         -42407.
 19     1.7600      .0096703         78413.       -.0043915        -72532.       -.0017744         -53162.
 20     1.8533      .0101353         78413.       -.0047505        -72895.       -.0021333         -63916.

EQUILIBRIUM CHECK OF RESIDUAL STRESS DISTRIBUTION

UNBALANCED FORCE IN CROSS SECTION IS        273.
UNBALANCED MOMENT IN CROSS SECTION IS        69.
```

```
RADIUS AFTER SPRINGBACK FOR BEND 4              15.000

FULLY BENT RADIUS                               14.268

NEUTRAL AXIS AFTER SPRINGBACK                     .608

FULLY BENT NEUTRAL AXIS                           .464

APPLIED MOMENT                                   .369564E+05


STRESS AND STRAIN HISTORY OF SECTION DUE TO COLD FORMING FOR BEND  4 OF  4      RADIUS IS  15.000
  I      Y(I)            BENDING                     SPRINGBACK                      FINAL
                   STRAIN        STRESS         STRAIN        STRESS         STRAIN         STRESS

  1      .0500    -.0039178      -87293.       .0021308       63997.       -.0007828       -23509.
  2      .1500    -.0035283      -87191.       .0017492       52537.       -.0011609       -34867.
  3      .2500    -.0031364      -86995.       .0013677       41078.       -.0015359       -46131.
  4      .3500    -.0010983      -32988.       .0009861       29618.       -.0001149        -3450.
  5      .4500     .0031590       78413.       .0006046       18159.        .0032218        78413.
  6      .5467     .0035167       77966.       .0002358        7064.        .0028380        77913.
  7      .6400     .0038888       78256.      -.0001203        -3606.        .0024916        74651.
  8      .7333     .0042506       78335.      -.0004765       -14275.        .0021381        64059.
  9      .8267     .0046137       78413.      -.0008326       -24944.        .0017846        53468.
 10      .9200     .0049742       78413.      -.0011887       -35614.        .0014285        42799.
 11     1.0133     .0053347       78413.      -.0015448       -46283.        .0010724        32130.
 12     1.1067     .0056951       78413.      -.0019009       -56953.        .0007463        21460.
 13     1.2000     .0060556       78413.      -.0022570       -67532.        .0003602        10791.
 14     1.2933     .0064160       78413.      -.0026131       -69886.        .0000040          121.
 15     1.3867     .0067765       78413.      -.0029692       -70732.       -.0003521       -10548.
 16     1.4800     .0071370       78413.      -.0033253       -71185.       -.0007082       -21218.
 17     1.5733     .0074974       78413.      -.0036814       -71639.       -.0010643       -31887.
 18     1.6667     .0078579       78413.      -.0040376       -72092.       -.0014204       -42557.
 19     1.7600     .0082184       78413.      -.0043937       -72534.       -.0017765       -53226.
 20     1.8533     .0085788       78413.      -.0047498       -72894.       -.0021326       -63895.
EQUILIBRIUM CHECK OF RESIDUAL STRESS DISTRIBUTION

UNBALANCED FORCE IN CROSS SECTION IS        -118.
UNBALANCED MOMENT IN CROSS SECTION IS        -68.
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```
EFFECTIVE STRESS-STRAIN CURVE INCLUDING
RESIDUAL STRESS AND BAUSCHINGER EFFECT
WITH      0. FABRICATION STRESS

    STRESS            STRAIN              ES                 ET

        0.           0.000000        0.                .295471E+08
    14774.            .000500         .295471E+08      .290566E+08
    29057.            .001000         .290566E+08      .275650E+08
    42339.            .001500         .282257E+08      .236891E+08
    52746.            .002000         .263729E+08      .179604E+08
    60299.            .002500         .241196E+08      .133475E+08
    66093.            .003000         .220311E+08      .997978E+07
    70279.            .003500         .200796E+08      .791140E+07
    74005.            .004000         .185012E+08      .694083E+07
    77220.            .004500         .171599E+08      .588587E+07
    79891.            .005000         .159781E+08      .485917E+07
    82079.            .005500         .149234E+08      .426595E+06
    88209.            .024500         .360037E+07      .322650E+06
```

APPENDIX B

PROGRAM LISTING

A listing of the program is included to facilitate any modifications or additions that the user may make. An alphabetical listing of the program and subprograms with a description of their functions is included. A flow chart was previously provided to show the logic of the program.

Programs and their Functions

Program	Function
BE	Modifies element stress-strain curves to account for the Bauschinger Effect. Basis for modification is the combined kinematic-isotropic theoretical hardening rule.
BEX	Modifies element stress-strain curves to account for the Bauschinger Effect. Basis for modification is experimentally derived hardening rules.
BENDS	This is the executive program which performs iterative procedures, input and output.
FAB	Modifies final effective stress-strain curves to account for fit up stress.
FORCRV	Produces for effective stress-strain curves for the cross section analyzed for use in the revised modified Bryant program.
FRMCRV	Produces overall effective stress-strain curve.
GETPL	Finds the proportional limit stress of a stress-strain curve.
GETSTN	Finds a strain that corresponds to a given stress according to a specified stress-strain curve.
HSSCL	Provides experimental hardening rule for high strength steel with a curvilinear type stress strain curve.
HSSPT	Provides experimental hardening rule for high strength steel with a plateau type stress-strain curve.
PNTOUT	Eliminates unnecessary points in a stress-strain curve before printing.
S	Finds a stress that corresponds to a given strain according to a specified stress-strain curve.
STNHRD	Modifies a given stress-strain curve to account for strain hardening.
YPT	Finds the stress corresponding to a given percentage offset strain. Used to find the 0.2 percent offset yield stress.

```
      PROGRAM BENDS(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)                BENDS       2
C                                                                         BENDS       3
C     A PROGRAM TO COMPUTE THE RESIDUAL STRESS DISTRIBUTION AND           BENDS       4
C     EFFECTIVE STRESS-STRAIN CURVE OF A COLD FORMED FRAME OF             BENDS       5
C     GENERAL CROSS SECTION INCORPORATING INELASTIC INITIAL BEND          BENDS       6
C     AND SPRINGBACK AND THE BAUSCHINGER EFFECT                           BENDS       7
C                                                                         BENDS       8
C     IBENDS  NUMBER OF BENDS IN FORMING PROCESS                          BENDS       9
C     NE  TOTAL NUMBER OF ELEMENTS, ABOUT 1/4 WILL BE IN FLANGE           BENDS      10
C     NPTS  NUMBER OF POINTS ON STRESS-STRAIN CURVE                       BENDS      11
C     KBE  HARDENING RULE SELECTOR                                        BENDS      12
C     IGEOM  =0 TEE  =1 RECTANGULAR  =2 CIRCULAR  =3 ARBITRARY            BENDS      13
C     INEX  BLANK OR NEGATIVE-INTERNAL FRAME, POSITIVE-EXTERNAL           BENDS      14
C     MODSQD  NOT EQUAL ZERO PRODUCES CURVES FOR MOD-MOD BRYANT           BENDS      15
C     ITSTR  NOT EQUAL ZERO INITIAL STRESSES ARE TO BE READ               BENDS      16
C     DEBUGR  ID OF ELEMENT WHOSE STRESS-STRAIN HISTORY IS DESIRED        BENDS      17
C     IF NEGATIVE ALL ELEMENT STRESS-STRAIN HISTORIES ARE PRINTED         BENDS      18
C     ITR  NOT EQUAL ZERO PRINTS OUT BASIC ITERATION VALUES               BENDS      19
C     RADII  ARRAY OF RADII USED IN FORMING PROCESS                       BENDS      20
C     WD  WEB TOE TO FLANGE DISTANCE, SECTION DEPTH OR DIAMETER           BENDS      21
C     WT  WEB THICKNESS OR SECTION WIDTH                                  BENDS      22
C     FW  FLANGE WIDTH                                                    BENDS      23
C     FT  FLANGE THICKNESS                                                BENDS      24
C     SRED  PERCENT REDUCTION FOR PRODUCING TENSILE CURVE                 BENDS      25
C     STRNK  STRAIN INCREMENT USED FOR EFFECTIVE CURVES                   BENDS      26
C     FABSTR  FABRICATION STRESS APPLIED TO MOD-MOD BRYANT CURVES         BENDS      27
C     SPLF  PROPORTIONAL LIMIT REDUCTION FACTOR                           BENDS      28
C     SUF  ULTIMATE LIMIT INCREASE FACTOR                                 BENDS      29
C     STRESS(I),STRAIN(I)  STRESS-STRAIN CURVE                            BENDS      30
C                                                                         BENDS      31
      COMMON /AA/ ESRCRV(50,50,2),ESNCRV(50,50,2)                         BENDS      32
      DIMENSION STRESS(50),STRAIN(50),EW(50),ED(50),Y(50),STR(50)         BENDS      33
      DIMENSION TITLE(8),STRT(50),STNT(50),STRBE(50),STNBE(50),ESTN(50)   BENDS      34
      DIMENSION STRM(50),STNM(50),NPAT(50),TR(50,50,2),TN(50,50,2)        BENDS      35
      DIMENSION                      TSTR(50),TS(50),SBS(50)              BENDS      36
      DIMENSION SBN(50),NPA(50),SIL(50),RADII(10)                         BENDS      37
      INTEGER DEBUGR                                                      BENDS      38
    1 FORMAT(8F10.3)                                                      BENDS      39
    2 FORMAT(16I5)                                                        BENDS      40
    3 FORMAT(2F10.3)                                                      BENDS      41
    4 FORMAT(8A10)                                                        BENDS      42
    5 FORMAT(*0STRESS-STRAIN CURVE FOR ELEMENT *,I3/* INCLUDING B.E. DUE BENDS      43
     1 TO INITIAL BENDING*//5X,*STRESS*,14X,*STRAIN*/)                    BENDS      44
    6 FORMAT(5X,*COMPRESSIVE MOMENT IS *,F10.0,3X,*TENSILE MOMENT IS*,    BENDS      45
     1 F10.0)                                                             BENDS      46
    7 FORMAT(5X,3(F7.4,4X),F8.0)                                          BENDS      47
    8 FORMAT(*0ELEMENT GEOMETRY AND INITIAL STRESS*//6X,*WIDTH*,6X,*DEPT BENDS      48
     1H*,8X,*Y*,6X,*STRESS*//)                                            BENDS      49
    9 FORMAT(*0STRESS AND STRAIN HISTORY OF SECTION DUE TO COLD FORMING  BENDS      50
     AFOR BEND *,I2,* OF *,I2,5X,* RADIUS IS *,F7.3                       BENDS      51
     1//3X,*I*,6X,*Y(I)*,13X,*BENDING*,20X,*SPRINGBACK*,20X,*FINAL*/21X, BENDS      52
     23(*STRAIN*,8X,*STRESS*,8X)//)                                       BENDS      53
   10 FORMAT(1X,I3,4X,F7.4,3(4X,F10.7,4X,F10.0))                          BENDS      54
   11 FORMAT(*1*,//* *,8A10//)                                            BENDS      55
   12 FORMAT(*0CURRENT VALUES OF ITERATIVE QUANTITIES*/5X,*RADIUS = *,F7 BENDS      56
     1.3,5X,*INCREMENT = *,F8.4)                                          BENDS      57
   13 FORMAT(5X,*INITIAL BEND N.A. = *,F7.4,3X,*INCREMENT = *,F8.5,3X,*C BENDS      58
```

```
     1OMP. FORCE IS *,F10.0,3X,*TENSILE FORCE IS *,F10.0)
  14 FORMAT(*0DESIGN RADIUS*,T45,F7.3/*0SECTION DEPTH*,T45,F7.3/*0SECTI
     1ON WIDTH*,T45,F7.3/*0NUMBER OF ELEMENTS*,T48,I3/*0TENSILE STRENGTH
     2 REDUCTION*,T45,F7.3/*0STRAIN INCREMENT*,T45,F8.6)
  15 FORMAT(*0DESIGN RADIUS*,T45,F7.3/*0WEB DEPTH*,T45,F7.3/*0WEB THICK
     1NESS*,T45,F7.3/*0FLANGE WIDTH*,T45,F7.3/*0FLANGE THICKNESS*,T45,
     2F7.3/*0NUMBER OF ELEMENTS*,T48,I3/*0TENSILE STRENGTH REDUCTION*,
     3 T45,F7.3/*0STRAIN INCREMENT*,T45,F8.6)
  16 FORMAT(*0MATERIAL COMPRESSIVE INPUT STRESS-STRAIN CURVE*,I3/* PROP
     1ORTIONAL LIMIT STRESS*,2X,F10.0,5X,* 0.2 PERCENT YIELD STRESS*,2X,
     2F10.0//5X,*STRESS*,14X,*STRAIN*,16X,*ES*,18X,*ET*/)
  17 FORMAT(3X,F10.0,10X,F8.6)
  18 FORMAT(*0DESIGN RADIUS*,T45,F7.3/*0SECTION DIAMETER*,T45,F7.3/
     1*0NUMBER OF ELEMENTS*,T48,I3/*0TENSILE STRENGTH REDUCTION*,T45,
     2 F7.3/*0STRAIN INCREMENT*,T45,F8.6)
  19 FORMAT(*0DESIGN RADIUS*,T45,F7.3/*0NUMBER OF ELEMENTS*,T48,I3/*0TE
     1NSILE STRENGTH REDUCTION*,T45,F7.3/*0STRAIN INCREMENT*,T45,F8.6)
  20 FORMAT(*0FRAME AREA*,T45,F7.3/*0CENTROID*,T45,F7.3)
  21 FORMAT(5X,*SPRINGBACK N.A. = *,F7.4,3X,*INCREMENT = *,F8.5,3X,*COM
     1P. FORCE IS *,F10.0,3X,*TENSILE FORCE IS *,F10.0)
  22 FORMAT(*0EXCESSIVE ITERATIONS*//5X,*NO. RADIAL ITERATIONS *,I3/5X,
     1*NO. INITIAL BEND ITERATIONS *,I3/5X,*NO. SPRINGBACK ITERATIONS *,
     2I3/5X,*COMP. FORCE IS *,F10.0/5X,*TENSILE FORCE IS *,F10.0)
  23 FORMAT(*0FRAME IS INTERNAL*)
  24 FORMAT(*0FRAME IS EXTERNAL*)
  25 FORMAT(*0ELEMENT *,I3,* SUFFERS BAUSCHINGER EFFECT ON FINAL COMPRE
     1SSION*)
  26 FORMAT(*1COMPRESSION PHASE ELEMENT STRESS-STRAIN CURVES LACKING RE
     1SIDUAL STRESS EFFECTS *//)
  27 FORMAT(*1RADIUS AFTER SPRINGBACK FOR BEND*,I2,T45,F7.3/*0FULLY BEN
     1T RADIUS*,T45,F7.3/*0NEUTRAL AXIS AFTER SPRINGBACK*,T45,F7.3/*0FUL
     2LY BENT NEUTRAL AXIS*,T45,F7.3/*0APPLIED MOMENT*,T45,E13.6//)
  28 FORMAT(*0MATERIAL TENSILE COMPUTED STRESS-STRAIN CURVE*,I3/ * PROP
     1ORTIONAL LIMIT STRESS*,2X,F10.0,5X,* 0.2 PERCENT YIELD STRESS*,2X,
     2F10.0//5X,*STRESS*,14X,*STRAIN*,16X,*ES*,18X,*ET*/)
  29 FORMAT(*0EQUILIBRIUM CHECK OF RESIDUAL STRESS DISTRIBUTION*
     1/*0UNBALANCED FORCE IN CROSS SECTION IS *,F10.0,        /* UNBALA
     2NCED MOMENT IN CROSS SECTION IS *,F10.0)
  90 FORMAT(40I2)
  91 FORMAT(*0PROPORTIONAL LIMIT REDUCTION FACTOR*,T45,F6.3/*0ULTIMATE
     1LIMIT INCREASE FACTOR*,T45,F6.3)
  92 FORMAT(*0EXPERIMENTAL DATA USED FOR FORMING EFFECTS (HSSCL)*)
  93 FORMAT(5(5X,F10.0,2X,F8.6))
  94 FORMAT(*0KINEMATIC-ISOTROPIC HARDENING USED*)
  95 FORMAT(*0EXPERIMENTAL DATA USED FOR FORMING EFFECTS (HSSPT)*)
  96 FORMAT(*1ELEMENT STRESS-STRAIN CURVES AFTER THE *,I2,* BEND*//)
  97 FORMAT(*0RADII OF CONSECUTIVE BENDS *,(T45,F7.3))
  98 FORMAT(3X,F10.0,10X,F8.6,10X,E13.6,6X,F13.6)
  99 FORMAT(*1TEMPORARY ELEMENT STRESS-STRAIN ARRAYS WHEN EXCESSIVE ITE
     1RATIONS OCCURRED *//)
C
C      READ AND ECHO INPUT
       READ(5,4)(TITLE(I),I=1,8)
       READ(5,2) IBENDS,NE,ICRV,KBE,IGEOM,INEX,MODSOD,ITSTR,DEBUGR,ITR
       READ(5,1) (RADII(I),I=1,IBENDS)
       IF(IGEOM.NE.3) READ(5,1) WD,WT,FW,FT
       READ(5,1) SRED,STRNK,FABSTR,SPLF,SUF
```

```
      READ(5,2) (NPAT(I),I=1,ICRV)                                      BENDS     116
      READ(5,90) (NPA(I),I=1,NE)                                        BENDS     117
      SRED=1.0-SRED                                                     BENDS     118
      DO 47 I=1,ICRV                                                    BENDS     119
      K=NPAT(I)                                                         BENDS     120
   47 READ(5,3) (TR(I,J,1),TN(I,J,1),J=1,K)                             BENDS     121
      DO 48 I=1,NE                                                      BENDS     122
      L=NPA(I)                                                          BENDS     123
      K=NPAT(L)                                                         BENDS     124
      NPA(I)=K                                                          BENDS     125
      DO 49 J=1,K                                                       BENDS     126
      ESRCRV(I,J,1)=TR(L,J,1)                                           BENDS     127
   49 ESNCRV(I,J,1)=TN(L,J,1)                                           BENDS     128
      E=ESRCRV(I,2,1)/ESNCRV(I,2,1)                                     BENDS     129
C                                                                       BENDS     130
C     PRODUCE TENSILE BASE METAL ELEMENT CURVES                         BENDS     131
      ESRCRV(I,1,2)=ESNCRV(I,1,2)=0.0                                   BENDS     132
      DO 39 J=2,K                                                       BENDS     133
      ESRCRV(I,J,2)=ESRCRV(I,J,1)*SRED                                  BENDS     134
   39 ESNCRV(I,J,2)=ESNCRV(I,J,1)-(ESRCRV(I,J,1)-ESRCRV(I,J,2))/E       BENDS     135
   48 CONTINUE                                                          BENDS     136
      IF(SPLF.EQ.0.0.AND.SUF.EQ.0.0) SPLF=1.0                           BENDS     137
      RF=RADII(IBENDS)                                                  BENDS     138
      SRED=1.0-SRED                                                     BENDS     139
      DO 30 I=1,NE                                                      BENDS     140
   30 SIL(I)=0.0                                                        BENDS     141
      IF(ITSTR.NE.0) READ(5,1) (SIL(I),I=1,NE)                          BENDS     142
      WRITE(6,11) (TITLE(I),I=1,8)                                      BENDS     143
      IF(INEX.LE.0) WRITE(6,23)                                         BENDS     144
      IF(INEX.GT.0) WRITE(6,24)                                         BENDS     145
      IF(KBE.EQ.11) WRITE(6,94)                                         BENDS     146
      IF(KBE.EQ.21) WRITE(6,92)                                         BENDS     147
      IF(KBE.EQ.22) WRITE(6,95)                                         BENDS     148
      IF(IGEOM.EQ.0) WRITE(6,15) RF,WD,WT,FW,FT,NE,SRED,STRNK           BENDS     149
      IF(IGEOM.EQ.1) WRITE(6,14) RF,WD,WT,NE,SRED,STRNK                 BENDS     150
      IF(IGEOM.EQ.2) WRITE(6,18) RF,WD,NE,SRED,STRNK                    BENDS     151
      IF(IGEOM.EQ.3) WRITE(6,19) RF,NE,SRED,STRNK                       BENDS     152
      IF(KBE.EQ.11) WRITE(6,91) SPLF,SUF                                BENDS     153
C                                                                       BENDS     154
C     SET BASIC PARAMETERS                                              BENDS     155
      CF=TF=AN=T=AFRAME=YCG=0.0                                         BENDS     156
      N=0                                                               BENDS     157
      NFE=NE/4                                                          BENDS     158
      NWE=NE-NFE                                                        BENDS     159
C                                                                       BENDS     160
C     GET ELEMENT GEOMETRY                                              BENDS     161
      IGEOM=IGEOM+1                                                     BENDS     162
      GO TO (71,72,73,74), IGEOM                                        BENDS     163
C                                                                       BENDS     164
C     TEE SECTION                                                       BENDS     165
   71 IF(INEX.GT.0) GO TO 32                                            BENDS     166
      DO 31 I=1,NE                                                      BENDS     167
      IF(I.GT.NFE) GO TO 33                                             BENDS     168
      ED(I)=FT/FLOAT(NFE)                                               BENDS     169
      EW(I)=FW                                                          BENDS     170
      GO TO 31                                                          BENDS     171
   33 ED(I)=WD/FLOAT(NWE)                                               BENDS     172
```

```
      EW(I)=WT                                                          BENDS    173
   31 CONTINUE                                                          BENDS    174
      GO TO 36                                                          BENDS    175
   32 DO 34 I=1,NE                                                      BENDS    176
      IF(I.GT.NWE) GO TO 35                                             BENDS    177
      ED(I)=WD/FLOAT(NWE)                                               BENDS    178
      EW(I)=WT                                                          BENDS    179
      GO TO 34                                                          BENDS    180
   35 ED(I)=FT/FLOAT(NFE)                                               BENDS    181
      EW(I)=FW                                                          BENDS    182
   34 CONTINUE                                                          BENDS    183
   36 DO 37 I=1,NE                                                      BENDS    184
      Y(I)=T+ED(I)/2.0                                                  BENDS    185
   37 T=T+ED(I)                                                         BENDS    186
      GO TO 75                                                          BENDS    187
C                                                                       BENDS    188
C     RECTANGULAR SECTION                                               BENDS    189
   72 DO 76 I=1,NE                                                      BENDS    190
      ED(I)=WC/FLOAT(NE)                                                BENDS    191
      EW(I)=WT                                                          BENDS    192
      Y(I)=T+ED(I)/2.0                                                  BENDS    193
   76 T=T+ED(I)                                                         BENDS    194
      GO TO 75                                                          BENDS    195
C                                                                       BENDS    196
C     CIRCULAR SECTION                                                  BENDS    197
   73 DO 77 I=1,NE                                                      BENDS    198
      ED(I)=WC/FLOAT(NE)                                                BENDS    199
      Y(I)=T+ED(I)/2.0                                                  BENDS    200
      T=T+ED(I)                                                         BENDS    201
   77 EW(I)=SQRT(WD*WD/4.0-(WD/2.0-Y(I))**2)*2.0                        BENDS    202
      GO TO 75                                                          BENDS    203
C                                                                       BENDS    204
C     ARBITRARY SECTION                                                 BENDS    205
   74 DO 78 I=1,NE                                                      BENDS    206
      READ(5,3) ED(I),EW(I)                                             BENDS    207
      Y(I)=T+ED(I)/2.0                                                  BENDS    208
   78 T=T+ED(I)                                                         BENDS    209
   75 DO 46 I=1,NE                                                      BENDS    210
      AFRAME=AFRAME+ED(I)*EW(I)                                         BENDS    211
   46 YCG=YCG+ED(I)*EW(I)*Y(I)                                          BENDS    212
      SD=T                                                              BENDS    213
      YCG=YCG/AFRAME                                                    BENDS    214
      Y0=YCG                                                            BENDS    215
      WRITE(6,20) AFRAME,YCG                                            BENDS    216
      WRITE(6,97) (RADII(I),I=1,IBENDS)                                 BENDS    217
      SRED=1.0-SRED                                                     BENDS    218
      DO 53 I=1,ICRV                                                    BENDS    219
      K=NPAT(I)                                                         BENDS    220
      E=TR(I,2,1)/TN(I,2,1)                                             BENDS    221
      DO 57 J=1,K                                                       BENDS    222
      STRESS(J)=TR(I,J,1)                                               BENDS    223
      STRAIN(J)=TN(I,J,1)                                               BENDS    224
      STRT(J)=TR(I,J,1)*SRED                                            BENDS    225
   57 STNT(J)=TN(I,J,1)-(TR(I,J,1)-STRT(J))/E                           BENDS    226
      SPLBMC=GETPL(STRESS,STRAIN,K,1)                                   BENDS    227
      SPLBMT=GETPL(STRT,STNT,K,1)                                       BENDS    228
      SYC=YPT(STRESS,STRAIN,K,0.002)                                    BENDS    229
```

```
      SYT=YPT(STRT,STNT,K,0.002)
      DO 58 J=2,K
      TN(1,J,2)=STRESS(J)/STRAIN(J)
      TN(2,J,2)=STRT(J)/STNT(J)
      IF(J.EQ.K) GO TO 58
      TR(1,J,2)=(STRESS(J+1)-STRESS(J-1))/(STRAIN(J+1)-STRAIN(J-1))
      TR(2,J,2)=(STRT(J+1)-STRT(J-1))/(STNT(J+1)-STNT(J-1))
   58 CONTINUE
      TN(1,1,2)=TN(2,1,2)=0.0
      TR(1,1,2)=STRESS(2)/STRAIN(2)
      TR(2,1,2)=STRT(2)/STNT(2)
      TR(1,K,2)=(STRESS(K)-STRESS(K-1))/(STRAIN(K)-STRAIN(K-1))
      TR(2,K,2)=(STRT(K)-STRT(K-1))/(STNT(K)-STNT(K-1))
      WRITE(6,16) I,SPLBMC,SYC
      DO 38 J=1,K
   38 WRITE(6,98) STRESS(J),STRAIN(J),TN(1,J,2),TR(1,J,2)
      WRITE(6,28) I,SPLBMT,SYT
      DO 40 J=1,K
   40 WRITE(6,98) STRT(J),STNT(J),TN(2,J,2),TR(2,J,2)
   53 CONTINUE
      WRITE(6,8)
      DO 44 I=1,NE
   44 WRITE(6,7) EM(I),ED(I),Y(I),SIL(I)
      IF(ITSTR.EQ.0) GO TO 80
      DO 79 I=1,NE
      K=NPA(I)
      DO 59 J=1,K
      STRESS(J)=ESRCRV(I,J,1)
      STRAIN(J)=ESNCRV(I,J,1)
      STRT(J)=ESRCRV(I,J,2)
   59 STNT(J)=ESNCRV(I,J,2)
      IF(SIL(I).LT.0.0) SIL(I)=GETSTN(STRESS,STRAIN,NPTS,SIL(I))
      IF(SIL(I).GT.0.0) SIL(I)=GETSTN(STRT,STNT,NPTS,SIL(I))
   79 CONTINUE
   80 CONTINUE
C
C     BEGIN CURVATURE ITERATION
      DO 100 NEXT=1,IBENDS
      RF=R=RADII(NEXT)
      MEXT=NEXT
      N=0
      F=0.5*R
   42 R=R-F
      N=N+1
      NY=NS=0
      IF(ITR.NE.0.AND.N.LE.15) WRITE(6,12) R,F
      IF(N.GT.15) GO TO 62
      FY0=0.5*YCG
      Y0=YCG
      AM=CF=TF=0.0
C
C     CALCULATE STRAIN,STRESS AND MOMENT
   52 Y0=Y0-FY0
      NY=NY+1
      IF(NEXT.EQ.1) C=1.0/(R+Y0)
      IF(NEXT.NE.1) C=1.0/(R+Y0)-1.0/(RADII(NEXT-1)+YCG)
      DO 51 I=1,NE
```

```
      IPTS=NPA(I)
      Q=Y(I)-Y0
      ESTN(I)=C*Q
      ESTN(I)=ESTN(I)+SIL(I)
      M=1
      IF(ESTN(I).GT.0.0) M=2
      DO 43 J=1,IPTS
      STRM(J)=ESRCRV(I,J,M)
   43 STNM(J)=ESNCRV(I,J,M)
      STR(I)=S(STRM,STNM,IPTS,ESTN(I))
      T=STR(I)*EM(I)*ED(I)
      IF(T.LE.0.0) CF=CF+T
      IF(T.GT.0.0) TF=TF+T
      AM=AM+T*Q
   51 CONTINUE
C
C     CHECK EQUILIBRIUM OF FORCES
      CF=ABS(CF)
      TF=ABS(TF)
      U=ABS(CF-TF)
      V=ABS(CF+TF)/2.0
      YSB=Y0
      IF(ITR.NE.0.AND.NY.LE.10) WRITE(6,13) Y0,FY0,CF,TF
      IF(NY.GT.10) GO TO 62
      IF((U/V).LT.0.02) GO TO 69
      IF(CF.LT.TF) Y0=Y0+FY0
      FY0=FY0/2.0
      AM=CF=TF=0.0
      GO TO 52
C
C     CALCULATE NEUTRAL AXIS AFTER SPRINGBACK
   69 CF=TF=TEST=0.0
      NS=0
      FSB=YCG-Y0
   61 YSB=YSB+FSB
      NS=NS+1
      CSB=1.0/(R+Y0)-1.0/(RF+YSB)
      DO 68 I=1,NE
      IF(KBE.GT.19) GO TO 45
      CALL BE(STR(I),NPA(I),I,STRBE,STNBE,STRM,STNM,SPLF,SUF)
      GO TO 83
   45 CALL BEX(I,STRBE,STNBE,STRM,STNM,NPA(I),IPTS,STR(I),KBE)
   83 DO 82 J=1,IPTS
      TR(I,J,1)=STRBE(J)
      TN(I,J,1)=STNBE(J)
      TR(I,J,2)=STRM(J)
   82 TN(I,J,2)=STNM(J)
      NPAT(I)=IPTS
      Q=YSB-Y(I)
      SBN(I)=CSB*Q
      IF(SBN(I).GT.0.0) SBS(I)=S(STRM,STNM,IPTS,SBN(I))
      IF(SBN(I).LE.0.0) SBS(I)=S(STRBE,STNBE,IPTS,SBN(I))
      STN=STR(I)/E
C
C     ADD ELASTIC STRAIN NEEDED TO RECOVER FROM INITIAL BEND TO STRAIN
C     DUE TO SPRINGBACK AND USE SUM TO GET FINAL STRESS
      TS(I)=STN+SBN(I)
```

```
      IF(TS(I).GT.0.0) TSTR(I)=S(STRM,STNM,IPTS,TS(I))
      IF(TS(I).LE.0.0) TSTR(I)=S(STRBF,STNBE,IPTS,TS(I))
      IF(TSTR(I).LT.0.0) CF=CF+TSTR(I)*EW(I)*ED(I)
      IF(TSTR(I).GT.0.0) TF=TF+TSTR(I)*EW(I)*ED(I)
   64 CONTINUE
C
C     CHECK SUM OF FORCES
      CF=ABS(CF)
      TF=ABS(TF)
      U=ABS(CF-TF)
      V=ABS(CF+TF)/2.0
      IF(ITR.NE.0.AND.NS.LE.10) WRITE(6,21) YSB,FSB,CF,TF
      IF(NS.GT.10) GO TO 62
      IF((U/V).LT.0.02) GO TO 54
      IF(CF.LT.TF) YSB=YSB-FSB
      IF(CF.LT.TF.AND.YSB.GT.YCG) TEST=1.0
      IF(TEST.EQ.0.0.AND.YSB.GT.YCG) FSB=FSB*2.0
      FSB=FSB/2.0
      CF=TF=0.0
      GO TO 61
C
C     CHECK SUM OF MOMENTS
   54 CM=TM=0.0
      DO 56 J=1,NE
      XM=TSTR(J)*EW(J)*ED(J)*(Y(J)-YSB)
      IF(XM.LT.0.0) CM=CM+XM
      IF(XM.GT.0.0) TM=TM+XM
   56 CONTINUE
      CM=ABS(CM)
      TM=ABS(TM)
      U=ABS(CM-TM)
      V=ABS(CM+TM)/2.0
      IF(ITR.NE.0.AND.NS.LE.10) WRITE(6,6) CM,TM
      IF((U/V).LT.0.02) GO TO 41
      IF(CM.GT.TM) R=R+F
      F=F/2.0
      GO TO 42
C
C     END OF CURRENT RADIUS ITERATION
   41 DO 84 I=1,NE
      J=NPA(I)=NPAT(I)
      SIL(I)=TS(I)
      DO 84 K=1,J
      ESRCRV(I,K,1)=TR(I,K,1)
      ESNCRV(I,K,1)=TN(I,K,1)
      ESRCRV(I,K,2)=TR(I,K,2)
   84 ESNCRV(I,K,2)=TN(I,K,2)
      YCG=YSB
      IF(DEBUGR.GE.0) GO TO 65
      WRITE(6,96) MEXT
      DO 50 M=1,2
      DO 50 I=1,NE
      IPTS=NFA(I)
   50 WRITE(6,93) (ESRCRV(I,J,M),ESNCRV(I,J,M),J=1,IPTS)
   65 WRITE(6,27) MEXT,RADII(MEXT),R,YSB,YO,AM
      WRITE(6,9) MEXT,IBENDS,RF
      DO 102 L=1,NE
```

```
  102 WRITE(6,10) L,Y(L),ESTN(L),STR(L),SBN(L),SBS(L),TS(L),TSTR(L)
C
C     CHECK EQUILIBRIUM OF FINAL RESIDUAL STRESS DISTRIBUTION
      W=X=0.0
      DO 55 I=1,NE
      W=W+TSTR(I)*EW(I)*ED(I)
   55 X=X+TSTR(I)*EW(I)*ED(I)*Y(I)
      WRITE(6,29) W,X
  100 CONTINUE
C
C     COMPUTE EFFECTIVE STRESS-STRAIN CURVES FOR ENTIRE FRAME
      CALL FRMCRV(TSTR,NPA,E,EW,ED,AFRAME,DEBUGR,NE,STRNK,FABSTR)
      IF(MODSQD.NE.0) CALL FORCRV (FABSTR,STRNK,INEX,NFE,NWE)
      STOP
   62 WRITE(6,22) N,NY,NS,CF,TF
      WRITE(6,9) NEXT,IBENDS,RF
      DO 70 I=1,NE
   70 WRITE(6,10) I,Y(I),ESTN(I),STR(I),SBN(I),SBS(I),TS(I),TSTR(I)
      IF(DEBUGR.EQ.0) STOP
      WRITE(6,99)
      DO 89 M=1,2
      DO 89 I=1,NE
      IPTS=NFAT(I)
   89 WRITE(6,93) (TR(I,J,M),TN(I,J,M),J=1,IPTS)
      STOP
      END
```

```
      SUBROUTINE BE (A,NPTS,L,STRC,STNC,STRT,STNT,SPLF,SUF)
C
C     PROGRAM TO COMPUTE BAUSCHINGER EFFECT AS A COMBINATION OF
C     KINEMATIC AND ISOTROPIC HARDENING RULES. DEFAULT VALUES
C     OF FACTORS PRODUCE FULL KINEMATIC REDUCTION IN THE PROPORTIONAL
C     LIMIT WITH NO CHANGE IN THE ULTIMATE LIMIT
C
      COMMON /AA/ ESRCRV(50,50,2),ESNCRV(50,50,2)
      DIMENSION STRC(50),STNC(50),STRT(50),STNT(50),STRESS(50)
      DIMENSION STRAIN(50)
      M=1
      IF(A.GT.0.0) M=2
      DO 1 I=1,NPTS
      STRESS(I)=ESRCRV(L,I,M)
    1 STRAIN(I)=ESNCRV(L,I,M)
      STN=GETSTN(STRESS,STRAIN,NPTS,A)
      B=GETPL(STRESS,STRAIN,NPTS,L)
      PLSN=GETSTN(STRESS,STRAIN,NPTS,B)
      PSTN=ABS(STN)
      STRC(1)=STNC(1)=STRT(1)=STNT(1)=0.0
      DO 11 I=2,NPTS
      STRC(I)=ESRCRV(L,I,1)
      STNC(I)=ESNCRV(L,I,1)
      STRT(I)=ESRCRV(L,I,2)
   11 STNT(I)=ESNCRV(L,I,2)
      IF(PSTN.LE.PLSN) RETURN
      E=B/PLSN
      SNRMAX=(ABS(A)-B)/E
      IF(A.GT.0.0) GO TO 30
C
C     PRESTRAIN IS COMPRESSIVE
      F=GETPL(STRT,STNT,NPTS,L)
      G=GETSTN(STRT,STNT,NPTS,F)
      E=F/G
      D=STNT(NPTS)-G
      DO 20 I=2,NPTS
      SNU=SNRMAX*(STNT(I)-G)/D*SUF
      SRU=SNU*E
      SNP=SNRMAX*(STNT(NPTS)-STNT(I))/D*SPLF
      SRP=SNP*E
      STRT(I)=STRT(I)-SRP+SRU
   20 STNT(I)=STNT(I)-SNP+SNU
      CALL STNHRD(A,STRC,STNC,NPTS,PSTN)
      RETURN
C
C     PRESTRAIN IS TENSILE
   30 F=GETPL(STRC,STNC,NPTS,L)
      G=GETSTN(STRC,STNC,NPTS,F)
      E=F/G
      D=STNC(NPTS)-G
      DO 31 I=2,NPTS
      SNU=SNRMAX*(STNC(I)-G)/D*SUF
      SRU=SNU*F
      SNP=SNRMAX*(STNC(NPTS)-STNC(I))/D*SPLF
      SRP=SNP*E
      STRC(I)=STRC(I)-SRP+SRU
   31 STNC(I)=STNC(I)-SNP+SNU
```

```
 SUBROUTINE BE          74/74   OPT=0 ROUND=*/ TRACE          FTN 4.5+414        09/29/76  11.04.43

                  CALL STRHRD(A,STRT,STNT,NPTS,PSTN)                                BE          59
                  RETURN                                                            BE          60
60                END                                                               BE          61
```

```
      SUBROUTINE BEX(L,STRBE,STNBE,STRM,STNM,NPTS,IPTS,A,KBE)
C
C     PROGRAM TO PRODUCE A BAUSCHINGER EFFECT ELEMENTAL STRESS-STRAIN
C     CURVE FROM NONDIMENSIONALIZED EXPERIMENTAL DATA
C
      COMMON /AA/ ESRCRV(50,50,2),ESNCRV(50,50,2)
      COMMON /MATDAT/ CCA,TCA,CCI,TCI,NPTAC,NPTAT,CNA,TNA,NC,NT
      DIMENSION STRBE(50),STNBE(50),STRM(50),STNM(50),STRESS(50)
      DIMENSION STRAIN(50),CCA(50,5),TCA(50,5),CNA(50,5),TNA(50,5)
      DIMENSION CCI(5),TCI(5),NPTAC(5),NPTAT(5)
      DIMENSION SRC(50),SNC(50),SRT(50),SNT(50)
C
C     GET PRESTRAIN
      M=1
      IF(A.GT.0.0) M=2
      DO 30 I=1,NPTS
      STRESS(I)=ESRCRV(L,I,M)
   30 STRAIN(I)=ESNCRV(L,I,M)
C
C     DEFINE ELEMENTAL BAUSCHINGER EFFECT CURVES
      DO 12 I=1,NPTS
      SRC(I)=ESRCRV(L,I,1)
      SNC(I)=ESNCRV(L,I,1)
      SRT(I)=ESRCRV(L,I,2)
   12 SNT(I)=ESNCRV(L,I,2)
      IF(KBE.EQ.21) CALL HSSCL(SRC,SNC,SRT,SNT,NPTS,0)
      IF(KBE.EQ.22) CALL HSSPT(SRC,SNC,SRT,SNT,NPTS,0)
      STN=GETSTN(STRESS,STRAIN,NPTS,A)
      B=GETPL(STRESS,STRAIN,NPTS.L)
      PLSN=GETSTN(STRESS,STRAIN,NPTS,B)
      PSTN=ABS(STN)
      RATIO=STRBE(1)=STNBE(1)=STRM(1)=STNM(1)=0.0
      IF(PSTN.GT.PLSN) GO TO 10
C
C     PRESTRAIN IS LESS THAN THE PROPORTIONAL LIMIT
      IPTS=NPTS
      DO 11 I=2,IPTS
      STRBE(I)=ESRCRV(L,I,1)
      STNBE(I)=ESNCRV(L,I,1)
      STRM(I)=ESRCRV(L,I,2)
   11 STNM(I)=ESNCRV(L,I,2)
      RETURN
   10 IF(STN.GT.0.0) GO TO 30
C
C     PRESTRAIN IS COMPRESSIVE
      DO 21 I=2,NT
      IF(PSTN.GE.TCI(I)) GO TO 21
      RATIO=(PSTN-TCI(I-1))/(TCI(I)-TCI(I-1))
      K=I
      GO TO 22
   21 CONTINUE
      IF(RATIO.EQ.0.0) GO TO 24
   22 IPTS=NPTAT(K)
      DS=(STRAIN(NPTS)-STRAIN(2))/(FLOAT(IPTS)-2.0)
      STRBE(2)=STRESS(2)
      STNBE(2)=STRAIN(2)
      DO 26 I=3,IPTS
```

```
      STNBE(I)=STNBE(I-1)+DS
   26 STRBE(I)=S(STRESS,STRAIN,NPTS,STNBE(I))
      DO 23 I=2,IPTS
      STRM(I)=TCA(I,K-1)+RATIO*(TCA(I,K)-TCA(I,K-1))
   23 STNM(I)=TNA(I,K-1)+RATIO*(TNA(I,K)-TNA(I,K-1))
      CALL STNHRD(A,STRBE,STNBE,IPTS,PSTN)
      RETURN
C
C     PRESTRAIN IS GREATER THAN HIGHEST AVAILABLE EXPERIMENTAL DATA
   24 IPTS=NPTAT(NT)
      DS=(STRAIN(NPTS)-STRAIN(2))/(FLOAT(IPTS)-2.0)
      STRBE(2)=STRESS(2)
      STNBE(2)=STRAIN(2)
      DO 27 I=3,IPTS
      STNBE(I)=STNBE(I-1)+DS
   27 STRBE(I)=S(STRESS,STRAIN,NPTS,STNBE(I))
      DO 25 I=2,IPTS
      STRM(I)=TCA(I,NT)
   25 STNM(I)=TNA(I,NT)
      CALL STNHRD(A,STRBE,STNBE,IPTS,PSTN)
      RETURN
C
C     PRESTRAIN IS TENSILE
   30 DO 31 I=2,NC
      IF(PSTN.GE.CCI(I)) GO TO 31
      RATIO=(PSTN-CCI(I-1))/(CCI(I)-CCI(I-1))
      K=I
      GO TO 32
   31 CONTINUE
      IF(RATIO.EQ.0.0) GO TO 34
   32 IPTS=NPTAC(K)
      DS=(STRAIN(NPTS)-STRAIN(2))/(FLOAT(IPTS)-2.0)
      STRM(2)=STRESS(2)
      STNM(2)=STRAIN(2)
      DO 36 I=3,IPTS
      STNM(I)=STNM(I-1)+DS
   36 STRM(I)=S(STRESS,STRAIN,NPTS,STNM(I))
      DO 33 I=2,IPTS
      STRBE(I)=CCA(I,K-1)+RATIO*(CCA(I,K)-CCA(I,K-1))
   33 STNBE(I)=CNA(I,K-1)+RATIO*(CNA(I,K)-CNA(I,K-1))
      CALL STNHRD(A,STRM,STNM,IPTS,PSTN)
      RETURN
C
C     PRESTRAIN IS GREATER THAN HIGHEST AVAILABLE EXPERIMENTAL DATA
   34 IPTS=NPTAC(NC)
      DS=(STRAIN(NPTS)-STRAIN(2))/(FLOAT(IPTS)-2.0)
      STRM(2)=STRESS(2)
      STNM(2)=STRAIN(2)
      DO 37 I=3,IPTS
      STNM(I)=STNM(I-1)+DS
   37 STRM(I)=S(STRESS,STRAIN,NPTS,STNM(I))
      DO 35 I=2,IPTS
      STRBE(I)=CCA(I,NC)
   35 STNBE(I)=CNA(I,NC)
      CALL STNHRD(A,STRM,STNM,IPTS,PSTN)
      RETURN
      END
```

```
      SUBROUTINE FRMCRV(RES,NPA,E,EM,ED,AFRAME,DEBUGR,NE,STRNK,FABSTR)  FRMCRV   2
C                                                                       FRMCRV   3
C     PROGRAM TO ADD EFFECTS OF RESIDUAL STRESS TO ELEMENT CURVES       FRMCRV   4
C     AND PRODUCE AVERAGE FRAME STRESS-STRAIN CURVE                     FRMCRV   5
C                                                                       FRMCRV   6
      COMMON /AA/ ESRCRV(50,50,2),ESNCRV(50,50,2)                       FRMCRV   7
      DIMENSION RES(50),STRS(50),STRN(50),STR(50),STN(50),EM(50)        FRMCRV   8
      DIMENSION ED(50),NPA(50)                                          FRMCRV   9
      INTEGER DEBUGR                                                    FRMCRV  10
   21 FORMAT(3X,F10.0,10X,F8.6,10X,E13.6,6X,E13.6)                      FRMCRV  11
   22 FORMAT(*1EFFECTIVE STRESS-STRAIN CURVE INCLUDING*/* RESIDUAL STRES FRMCRV  12
     1S AND BAUSCHINGER EFFECT*/* WITH *,F7.0,* FABRICATION STRESS*//5X, FRMCRV  13
     2*STRESS*,14X,*STRAIN*,16X,*ES*,18X,*ET*/)                         FRMCRV  14
   23 FORMAT(*1STRESS-STRAIN CURVE BEFORE RESIDUAL STRESS EFFECT FOR ELE FRMCRV  15
     1MENT*,I3//6X,*STRESS*,14X,*STRAIN*/)                              FRMCRV  16
   24 FORMAT(*0RESIDUAL STRESS IS*,F10.0,4X,*CORRESPONDING STRAIN IS *, FRMCRV  17
     1F7.4)                                                             FRMCRV  18
   25 FORMAT(*0STRESS-STRAIN CURVE ACCOUNTING FOR R.S. AND B.E. FOR ELEM FRMCRV  19
     1ENT *,I3//6X,*STRESS*,14X,*STRAIN*/)                              FRMCRV  20
   26 FORMAT(*0STRESS-STRAIN CURVE USED TO COMPUTE EFFECTIVE FRAME CURVE FRMCRV  21
     1 FOR ELEMENT *,I3//6X,*STRESS*,14X,*STRAIN*/)                     FRMCRV  22
   27 FORMAT(5(5X,F10.0,2X,F8.6))                                       FRMCRV  23
   28 FORMAT(*1ELEMENT STRESS-STRAIN CURVES INCORPORATING B.E. AND R.S.* FRMCRV  24
     1//)                                                               FRMCRV  25
      STRS(1)=STRN(1)=STR(1)=STN(1)=0.0                                 FRMCRV  26
      DO 1 I=1,NE                                                       FRMCRV  27
      A=RES(I)                                                          FRMCRV  28
      C=0.0                                                             FRMCRV  29
      NPTS=NPA(I)                                                       FRMCRV  30
      DO 2 J=2,NPTS                                                     FRMCRV  31
      STR(J)=ESRCRV(I,J,1)                                              FRMCRV  32
    2 STN(J)=ESNCRV(I,J,1)                                              FRMCRV  33
      IF(I.NE.DEBUGR) GO TO 12                                          FRMCRV  34
      WRITE(6,23) I                                                     FRMCRV  35
      DO 14 K=1,NPTS                                                    FRMCRV  36
   14 WRITE(6,21) STR(K),STN(K)                                         FRMCRV  37
   12 IF(A.GT.0.0) GO TO 3                                              FRMCRV  38
C                                                                       FRMCRV  39
C     COMPRESSIVE RESIDUAL STRESS                                       FRMCRV  40
      B=GETSTN(STR,STN,NPTS,A)                                          FRMCRV  41
      DO 11 J=2,50                                                      FRMCRV  42
      STRN(J)=C=C+STRNK                                                 FRMCRV  43
      D=ABS(B)+C                                                        FRMCRV  44
   11 STRS(J)=S(STR,STN,NPTS,D)+A                                       FRMCRV  45
      GO TO 4                                                           FRMCRV  46
C                                                                       FRMCRV  47
C     TENSILE RESIDUAL STRESS UNLOADS ELASTICALLY UNTIL ELEMENT GOES    FRMCRV  48
C     INTO COMPRESSION                                                  FRMCRV  49
    3 B=A/E                                                             FRMCRV  50
      DO 5 J=2,50                                                       FRMCRV  51
      STRN(J)=C=C+STRNK                                                 FRMCRV  52
      IF(C.LE.B) STRS(J)=E*C                                            FRMCRV  53
      D=C-B                                                             FRMCRV  54
      IF(C.GT.B) STRS(J)=S(STR,STN,NPTS,D)+A                            FRMCRV  55
    5 CONTINUE                                                          FRMCRV  56
    4 DO 6 J=1,50                                                       FRMCRV  57
      ESRCRV(I,J,1)=STRS(J)                                             FRMCRV  58
```

```
    6 ESNCRV(I,J,1)=STRN(J)
      IF(I.NE.DEBUGR) GO TO 1
      WRITE(6,24) A,B
      WRITE(6,25) I
      DO 16 J=1,50
   16 WRITE(6,21) STRS(J),STRN(J)
    1 CONTINUE
C
C     INDIVIDUAL ELEMENT CURVES NOW INCORPORATE B.E. AND R.S.
      IF(DEBUGR.GE.0) GO TO 19
      WRITE(6,28)
      DO 20 I=1,NE
   20 WRITE(6,27) (ESRCRV(I,J,1),ESNCRV(I,J,1),J=1,50)
   19 CONTINUE
      STRS(1)=STRN(1)=0.0
      C=0.0
      I=1
    7 I=I+1
      B=0.0
      STRN(I)=C=C+STRNK
      J=0
    8 J=J+1
      DO 9 K=1,50
      STR(K)=ESRCRV(J,K,1)
    9 STN(K)=ESNCRV(J,K,1)
      IF(DEBUGR.LE.0) GO TO 17
      IF(J.NE.DEBUGR.OR.I.NE.2) GO TO 17
      WRITE(6,26) J
      DO 18 K=1,50
   18 WRITE(6,21) STR(K),STN(K)
   17 CONTINUE
C
C     SUM AREA WEIGHTED STRESSES TO GET AVERAGE STRESS
      A=S(STR,STN,50,C)*EW(J)*ED(J)/AFRAME
      B=B+A
      IF(J.LT.NE) GO TO 8
      STRS(I)=B
      IF(I.LT.50) GO TO 7
      WRITE(6,22) FABSTR
      L=50
      IF(FABSTR.NE.0.0) CALL FAB(STRS,STRN,FABSTR,L)
      CALL PNTOUT(STRS,STRN,L)
      DO 15 I=2,L
      STN(I)=STRS(I)/STRN(I)
      IF(I.EQ.L) GO TO 15
      STR(I)=(STRS(I+1)-STRS(I-1))/(STRN(I+1)-STRN(I-1))
   15 CONTINUE
      STN(1)=0.0
      STR(1)=STRS(2)/STRN(2)
      STR(L)=(STRS(L)-STRS(L-1))/(STRN(L)-STRN(L-1))
      DO 10 I=1,L
   10 WRITE(6,21) STRS(I),STRN(I),STN(I),STR(I)
      RETURN
      END
```

```
      SUBROUTINE FORCRV (FABSTR,STRNK,INEX,NFE,NWE)
C
C     PROGRAM TO PRODUCE STRESS-STRAIN CURVES FOR MOD-MOD BRYANT
C
      COMMON /AA/ ESRCRV(50,50,2),ESNCRV(50,50,2)
      DIMENSICN STRN(50,4),AVG(50,4),NP(4)
      DIMENSION STR(50),STN(50)
   11 FORMAT(*1STRESS-STRAIN CURVES FOR MOD-MOD BRYANT*/* WITH A FABRICA
     1TION STRESS OF *,F10.0///10X,*SEG. 1*,
     216X,*SEG. 2*,16X,*SEG. 3*,16X,*FLANGE*//4X,*STRESS*,4X,*STRAIN*,
     36X,*STRESS*,4X,*STRAIN*,6X,*STRESS*,4X,*STRAIN*,6X,*STRESS*,4X,
     4*STRAIN*/)
   12 FORMAT(1H )
   13 FORMAT(*0NUMBER OF ELEMENTS MUST BE A MULTIPLE OF FOUR TO */* OBTA
     1IN CURVES FOR THE REVISED MODIFIED BRYANT PROGRAM *)
   14 FORMAT(1H+,3X,F8.0,2X,F8.6)
   15 FORMAT(1H+,25X,F8.0,2X,F8.6)
   16 FORMAT(1H+,47X,F8.0,2X,F8.6)
   17 FORMAT(1H+,69X,F8.0,2X,F8.6)
      NUM=NFE+NWE
      K=NUM/4*4
      IF(K.EQ.NUM) GO TO 21
      WRITE(6,13)
      RETURN
   21 DO 22 I=1,50
      IFIN=0
      DO 23 J=1,4
      TOTAL=0.0
      ISTART=IFIN+1
      L=NWE/3
      IF(INEX.LE.0.AND.J.EQ.1) L=NFE
      IF(INEX.GT.0.AND.J.EQ.4) L=NFE
      IFIN=IFIN+L
      DO 24 K=ISTART,IFIN
   24 TOTAL=TOTAL+ESRCRV(K,I,1)
   23 AVG(I,J)=TOTAL/FLOAT(L)
   22 CONTINUE
      XKONT=-STRNK
      DO 25 I=1,50
      XKONT=XKONT+STRNK
      DO 25 J=1,4
   25 STRN(I,J)=XKONT
      DO 2 I=1,4
      DO 3 J=1,50
      STR(J)=AVG(J,I)
    3 STN(J)=STRN(J,I)
      IF(FABSTR.NE.0.0) CALL FAB(STR,STN,FABSTR,50)
      M=50
      CALL PNTOUT (STR,STN,M)
      NP(I)=M
      DO 4 J=1,M
      AVG(J,I)=STR(J)
    4 STRN(J,I)=STN(J)
    2 CONTINUE
    1 WRITE(6,11) FABSTR
      N=MAX0(NP(1),NP(2),NP(3),NP(4))
      DO 5 I=1,N
```

```
SUBROUTINE FORCRV      74/74    OPT=0 ROUND=*/ TRACE            FTN 4.5+414        09/29/76  11.04.43

            WRITE(6,12)
            IF(INEX.LE.0) GO TO 6
            IF(I.LE.NP(1)) WRITE(6,14) AVG(I,1),STRN(I,1)
            IF(I.LE.NP(2)) WRITE(6,15) AVG(I,2),STRN(I,2)
            IF(I.LE.NP(3)) WRITE(6,16) AVG(I,3),STRN(I,3)
            IF(I.LE.NP(4)) WRITE(6,17) AVG(I,4),STRN(I,4)
            GO TO 5
          6 IF(I.LE.NP(4)) WRITE(6,14) AVG(I,4),STRN(I,4)
            IF(I.LE.NP(3)) WRITE(6,15) AVG(I,3),STRN(I,3)
            IF(I.LE.NP(2)) WRITE(6,16) AVG(I,2),STRN(I,2)
            IF(I.LE.NP(1)) WRITE(6,17) AVG(I,1),STRN(I,1)
          5 CONTINUE
            RETURN
            END
```

```
SUBROUTINE FAB        74/74    OPT=0 ROUND=*/ TRACE              FTN 4.5+414        09/29/76  11.04.43

                  SUBROUTINE FAB(STR,STN,FABSTR,L)
            C
            C     PROGRAM TO ACCOUNT FOR FIT-UP STRESS
            C
                  DIMENSION STR(50),STN(50)
                  Q=SIGN(1.0,FABSTR)
                  STR(1)=STN(1)=0.0
                  M=L
                  DO 101 J=2,M
                  IF(ABS(FABSTR).GT.STR(J)) GO TO 101
                  R=(ABS(FABSTR)-STR(J-1))/(STR(J)-STR(J-1))
                  FABSTN=R*(STN(J)-STN(J-1))+STN(J-1)
                  L=L-J+2
                  N=J-1
                  DO 102 K=2,L
                  N=N+1
                  STR(K)=STR(N)+FABSTR
              102 STN(K)=STN(N)+Q*FABSTN
                  GO TO 100
              101 CONTINUE
              100 RETURN
                  END
```

```
FUNCTION GETSTN      74/74    OPT=0 ROUND=*/ TRACE            FTN 4.5+414        09/29/76  11.04.43

              FUNCTION GETSTN(STRESS,STRAIN,NPTS,STR)
        C
        C     PROGRAM TO CALCULATE STRAIN GIVEN A STRESS
        C
              DIMENSION STRESS(50),STRAIN(50)
              DO 2 I=2,NPTS
              IF(ABS(STR).GT.STRESS(I)) GO TO 2
              RATIO=1.0-(STRESS(I)-ABS(STR))/(STRESS(I)-STRESS(I-1))
              F=SIGN(1.0,STR)
              GETSTN=F*(STRAIN(I-1)+RATIO*(STRAIN(I)-STRAIN(I-1)))
              RETURN
            2 CONTINUE
              GETSTN=STRAIN(NPTS)
              RETURN
              END
```

```
FUNCTION S          74/74   OPT=0 ROUND=*/ TRACE            FTN 4.5+414        09/29/76  11.04.43

                  FUNCTION S(STRESS,STRAIN,NPTS,ES)
C
C                 PROGRAM TO GET STRESS FROM STRESS-STRAIN CURVE GIVEN ELASTIC STRAI
C
                  DIMENSION STRESS(50),STRAIN(50)
                  SIGU=STRESS(NPTS)*0.999
                  F=SIGN(1.0,ES)
                  STN=ABS(ES)
                  IF(STN.LT.STRAIN(NPTS)) GO TO 1
                  S=SIGU*F
                  RETURN
                1 DO 2 I=2,NPTS
                  IF(STRAIN(I).GT.STN) GO TO 3
                2 CONTINUE
                3 RATIO=1.0-(STRAIN(I)-STN)/(STRAIN(I)-STRAIN(I-1))
                  S=F*(STRESS(I-1)+RATIO*(STRESS(I)-STRESS(I-1)))
                  IF(ABS(S).GE.SIGU) S=F*SIGU
                  RETURN
                  END
```

```
FUNCTION GETPL       74/74    OPT=0 ROUND=*/ TRACE            FTN 4.5+414        09/29/76  11.04.43

            FUNCTION GETPL(STR,STN,NPTS,ID)                                      GETPL        2
      C                                                                          GETPL        3
      C     PROGRAM TO FIND PROPORTIONAL LIMIT STRESS                            GETPL        4
      C                                                                          GETPL        5
            DIMENSION STR(50),STN(50)                                            GETPL        6
         11 FORMAT(*0PROPORTIONAL LIMIT NOT FOUND FOR ELEMENT *,I2//5X,*STRESS   GETPL        7
           1*,14X,*STRAIN*/)                                                     GETPL        8
         12 FORMAT(3X,F10.0,10X,F8.6)                                            GETPL        9
            E=STR(2)/STN(2)                                                      GETPL       10
            DO 1 I=3,NPTS                                                        GETPL       11
            A=STR(I)/STN(I)                                                      GETPL       12
            B=ABS(E-A)/E                                                         GETPL       13
            J=I                                                                  GETPL       14
            IF(B.GT.0.005) GO TO 2                                               GETPL       15
          1 CONTINUE                                                             GETPL       16
            GO TO 3                                                              GETPL       17
          2 GETPL=STR(J-1)                                                       GETPL       18
            RETURN                                                               GETPL       19
          3 WRITE(6,11) ID                                                       GETPL       20
            DO 4 I=1,NPTS                                                        GETPL       21
          4 WRITE(6,12) STR(I),STN(I)                                            GETPL       22
            STOP                                                                 GETPL       23
            END                                                                  GETPL       24
```

```
FUNCTION YPT          74/74    OPT=0 ROUND=*/ TRACE              FTN 4.5+414          09/29/76  11.04.43

                 FUNCTION YPT(STRESS,STRAIN,NPTS,XSTN)                                  YPT        2
          C                                                                             YPT        3
          C      CALCULATION OF A GIVEN PERCENT OFFSET STRESS                           YPT        4
          C                                                                             YPT        5
                 DIMENSION STRESS(50),STRAIN(50)                                        YPT        6
                 STR=GETPL(STRESS,STRAIN,NPTS,1)                                        YPT        7
                 STN=GETSTN(STRESS,STRAIN,NPTS,STR)+0.002                               YPT        8
                 YPT=S(STRESS,STRAIN,NPTS,STN)                                          YPT        9
                 RETURN                                                                 YPT       10
                 END                                                                    YPT       11
```

```
SUBROUTINE STNHRD      74/74    OPT=0 ROUND=*/ TRACE              FTN 4.5+414         09/29/76  11.04.43

                     SUBROUTINE STNHRD (STR,STRBE,STNBE,IPTS,PSTN)
               C
               C     PROGRAM TO PRODUCE STRAIN HARDENED CURVE
               C
                     DIMENSION STRBE(50),STNBE(50),SR(50),SN(50)
                     STRBE(1)=STNBE(1)=SR(1)=SN(1)=0.0
                     E=STRBE(2)/STNBE(2)
                     DO 1 J=1,IPTS
                     SR(J)=STRBE(J)
                   1 SN(J)=STNBE(J)
                     STRBE(2)=ABS(STR)*0.999
                     STNBE(2)=STRBE(2)/E
                     STNINC=(SN(IPTS)-SN(2))/(FLOAT(IPTS)-2.0)
                     H=PSTN
                     DO 2 J=3,IPTS
                     STNBE(J)=STNBE(J-1)+STNINC
                     H=H+STNINC
                   2 STRBE(J)=S(SR,SN,IPTS,H)
                     RETURN
                     END
```

```
SUBROUTINE PNTOUT      74/74    OPT=0 ROUND=*/ TRACE            FTN 4.5+414        09/29/76  11.04.43

                 SUBROUTINE PNTOUT (STRS,STRN,NPTS)
           C
           C     PROGRAM TO REMOVE UNNECESSARY POINTS FROM STRESS-STRAIN CURVES
           C
                 DIMENSION STRS(50),STRN(50)
                 E=STRS(2)/STRN(2)
                 M=NPTS
                 I=0
               1 I=I+1
               2 IF(I.EQ.(NPTS-1)) RETURN
                 ET1=(STRS(I+1)-STRS(I))/(STRN(I+1)-STRN(I))
                 IF(ET1.GT.(E*0.05)) GO TO 4
                 STRS(I+1)=STRS(M)
                 STRN(I+1)=STRN(M)
                 NPTS=I+1
                 RETURN
               4 P=0.20
                 IF(ET1.GT.(E*0.1)) P=0.10
                 IF(ET1.GT.(E*0.3)) P=0.02
                 ET2=(STRS(I+2)-STRS(I+1))/(STRN(I+2)-STRN(I+1))
                 Q=(ET1-ET2)/ET1
                 IF(Q.GT.P) GO TO 1
                 L=NPTS-1
                 K=I+1
                 DO 3 J=K,L
                 STRS(J)=STRS(J+1)
               3 STRN(J)=STRN(J+1)
                 NPTS=NPTS-1
                 GO TO 2
                 END
```

```
      SUBROUTINE HSSCL (STRESS,STRAIN,STRT,STNT,NPTS,DEBUGR)
C
C     DEFINITION OF MATERIAL PROPERTIES OF HIGH STRENGTH
C     STEEL WITH A CURVILINEAR TYPE OF STRESS-STRAIN CURVE
C
      COMMON /MATDAT/ CCA,TCA,CCI,TCI,NPTAC,NPTAT,CNA,TNA,NC,NT
      DIMENSION CCA(50,5),TCA(50,5),CCI(5),TCI(5),NPTAC(5),NPTAT(5)
      DIMENSICN STRESS(50),STRAIN(50),STRT(50),STNT(50)
      DIMENSION CNA(50,5),TNA(50,5)
      INTEGER DEBUGR
   11 FORMAT(*0COMPRESSIVE STRESS-STRAIN CURVES AFFECTED BY PRESTRAIN *
     1  //4X,4(*PRESTRAIN=*,F7.4,6X)/3X,4(*STRESS*,5X,*STRAIN*,6X)/)
   12 FORMAT(1X,4(F10.0,2X,F7.4,4X))
   13 FORMAT(*0TENSILE STRESS-STRAIN CURVES AFFECTED BY PRESTRAIN *
     1//4X,4(*PRESTRAIN=*,F7.4,6X)/3X,4(*STRESS*,5X,*STRAIN*,6X)/)
      NC=NT=4
      NPTAC(1)=NPTAC(2)=NPTAC(3)=NPTAC(4)=24
      CCI(1)=0.0000$CCI(2)=0.0100$CCI(3)=0.0200$CCI(4)=0.0350
      CNA(01)=0.00$CNA(02)=1.00$CNA(03)=2.00$CNA(04)=3.00$CNA(05)=4.00
      CNA(06)=4.40$CNA(07)=4.60$CNA(08)=4.80$CNA(09)=5.00$CNA(10)=5.20
      CNA(11)=5.40$CNA(12)=5.60$CNA(13)=5.80$CNA(14)=6.00$CNA(15)=7.00
      CNA(16)=8.00$CNA(17)=9.00$CNA(18)=10.0$CNA(19)=12.0$CNA(20)=14.0
      CNA(21)=16.0$CNA(22)=18.0$CNA(23)=20.0$CNA(24)=40.0
      CCA(01,2)=1.000$CCA(02,2)=0.900$CCA(03,2)=0.815$CCA(04,2)=0.749
      CCA(05,2)=0.693$CCA(06,2)=0.663$CCA(07,2)=0.662$CCA(08,2)=0.661
      CCA(09,2)=0.666$CCA(10,2)=0.670$CCA(11,2)=0.677$CCA(12,2)=0.686
      CCA(13,2)=0.702$CCA(14,2)=0.709$CCA(15,2)=0.756$CCA(16,2)=0.801
      CCA(17,2)=0.837$CCA(18,2)=0.875$CCA(19,2)=0.929$CCA(20,2)=0.956
      CCA(21,2)=0.970$CCA(22,2)=0.979$CCA(23,2)=0.993$CCA(24,2)=1.024
      CCA(01,3)=1.000$CCA(02,3)=0.867$CCA(03,3)=0.748$CCA(04,3)=0.677
      CCA(05,3)=0.612$CCA(06,3)=0.582$CCA(07,3)=0.582$CCA(08,3)=0.580
      CCA(09,3)=0.579$CCA(10,3)=0.565$CCA(11,3)=0.588$CCA(12,3)=0.591
      CCA(13,3)=0.600$CCA(14,3)=0.608$CCA(15,3)=0.638$CCA(16,3)=0.675
      CCA(17,3)=0.706$CCA(18,3)=0.736$CCA(19,3)=0.785$CCA(20,3)=0.824
      CCA(21,3)=0.860$CCA(22,3)=0.890$CCA(23,3)=0.910$CCA(24,3)=0.992
      CCA(01,4)=1.000$CCA(02,4)=0.867$CCA(03,4)=0.733$CCA(04,4)=0.671
      CCA(05,4)=0.603$CCA(06,4)=0.573$CCA(07,4)=0.571$CCA(08,4)=0.573
      CCA(09,4)=0.572$CCA(10,4)=0.572$CCA(11,4)=0.579$CCA(12,4)=0.581
      CCA(13,4)=0.590$CCA(14,4)=0.596$CCA(15,4)=0.629$CCA(16,4)=0.656
      CCA(17,4)=0.681$CCA(18,4)=0.706$CCA(19,4)=0.751$CCA(20,4)=0.784
      CCA(21,4)=0.811$CCA(22,4)=0.836$CCA(23,4)=0.849$CCA(24,4)=0.917
      DO 1 I=1,4
      NPTAT(I)=NPTAC(I)
    1 TCI(I)=CCI(I)
      DO 3 I=1,24
      CNA(I,1)=TNA(I,1)=CNA(I,1)*0.001
      CCA(I,1)=S(STRESS,STRAIN,NPTS,CNA(I,1))
    3 TCA(I,1)=S(STRT,STNT,NPTS,TNA(I,1))
      DO 2 I=1,24
      DO 2 J=2,4
      TNA(I,J)=TNA(I,1)
      CNA(I,J)=CNA(I,1)
      TCA(I,J)=CCA(I,J)*TCA(I,1)
    2 CCA(I,J)=CCA(I,J)*CCA(I,1)
      IF(DEBUGR.GE.0) RETURN
      WRITE(6,11) (CCI(I),I=1,4)
      WRITE(6,12) ((CCA(I,J),CNA(I,J),J=1,4),I=1,24)
```

```
SUBROUTINE HSSCL       74/74    OPT=0 ROUND=*/ TRACE              FTN 4.5+414          09/29/76  11.04.43

                    WRITE(6,13) (TCI(I),I=1,4)                                          HSSCL      59
                    WRITE(6,12) ((TCA(I,J),TNA(I,J),J=1,4),I=1,24)                      HSSCL      60
 60                 RETURN                                                              HSSCL      61
                    END                                                                 HSSCL      62
```

```
            SUBROUTINE HSSPT (STRESS,STRAIN,STRT,STNT,NPTS,DEBUGR)
      C
      C     DEFINITION OF MATERIAL PROPERTIES OF HIGH STRENGTH
      C     STEEL WITH A PLATEAU TYPE STRESS-STRAIN CURVE
      C
            COMMON /MATDAT/ CCA,TCA,CCI,TCI,NPTAC,NPTAT,CNA,TNA,NC,NT
            DIMENSION CCA(50,5),TCA(50,5),CCI(5),TCI(5),NPTAC(5),NPTAT(5)
            DIMENSION STRESS(50),STRAIN(50),STRT(50),STNT(50)
            DIMENSION CNA(50,5),TNA(50,5)
            INTEGER DEBUGR
         11 FORMAT(*0COMPRESSIVE STRESS-STRAIN CURVES AFFECTED BY PRESTRAIN *
          1  //4X,5(*PRESTRAIN=*,F7.4,6X)/3X,5(*STRESS*,5X,*STRAIN*,6X)/)
         12 FORMAT(1X,5(F10.0,2X,F7.4,4X))
         13 FORMAT(*0TENSILE STRESS-STRAIN CURVES AFFECTED BY PRESTRAIN *
          1//4X,5(*PRESTRAIN=*,F7.4,6X)/3X,5(*STRESS*,5X,*STRAIN*,6X)/)
            NC=NT=5
            NPTAC(1)=NPTAC(2)=NPTAC(3)=NPTAC(4)=NPTAC(5)=22
            CCI(1)=0.0$CCI(2)=0.0034$CCI(3)=0.0052$CCI(4)=0.0086$CCI(5)=0.016
            CNA(01)=0.00$CNA(02)=0.50$CNA(03)=1.00$CNA(04)=1.50$CNA(05)=2.00
            CNA(06)=2.50$CNA(07)=3.00$CNA(08)=3.50$CNA(09)=4.00$CNA(10)=4.50
            CNA(11)=5.00$CNA(12)=5.50$CNA(13)=6.00$CNA(14)=7.00$CNA(15)=8.00
            CNA(16)=9.00$CNA(17)=10.0$CNA(18)=11.0$CNA(19)=12.0$CNA(20)=15.0
            CNA(21)=20.0$CNA(22)=40.0
            CCA(01,2)=1.000$CCA(02,2)=0.902$CCA(03,2)=0.902$CCA(04,2)=0.902
            CCA(05,2)=0.902$CCA(06,2)=0.896$CCA(07,2)=0.892$CCA(08,2)=0.949
            CCA(09,2)=1.000$CCA(10,2)=1.017$CCA(11,2)=1.026$CCA(12,2)=1.029
            CCA(13,2)=1.029$CCA(14,2)=1.030$CCA(15,2)=1.030$CCA(16,2)=1.030
            CCA(17,2)=1.030$CCA(18,2)=1.030$CCA(19,2)=1.031$CCA(20,2)=1.031
            CCA(21,2)=1.031$CCA(22,2)=1.031
            CCA(01,3)=1.000$CCA(02,3)=0.914$CCA(03,3)=0.805$CCA(04,3)=0.745
            CCA(05,3)=0.699$CCA(06,3)=0.594$CCA(07,3)=0.637$CCA(08,3)=0.670
            CCA(09,3)=0.733$CCA(10,3)=0.783$CCA(11,3)=0.831$CCA(12,3)=0.868
            CCA(13,3)=0.898$CCA(14,3)=0.938$CCA(15,3)=0.938$CCA(16,3)=0.938
            CCA(17,3)=0.938$CCA(18,3)=0.938$CCA(19,3)=0.938$CCA(20,3)=0.938
            CCA(21,3)=0.938$CCA(22,3)=0.938
            CCA(01,4)=1.000$CCA(02,4)=0.719$CCA(03,4)=0.680$CCA(04,4)=0.626
            CCA(05,4)=0.587$CCA(06,4)=0.550$CCA(07,4)=0.516$CCA(08,4)=0.534
            CCA(09,4)=0.575$CCA(10,4)=0.610$CCA(11,4)=0.644$CCA(12,4)=0.676
            CCA(13,4)=0.705$CCA(14,4)=0.759$CCA(15,4)=0.804$CCA(16,4)=0.844
            CCA(17,4)=0.879$CCA(18,4)=0.880$CCA(19,4)=0.881$CCA(20,4)=0.883
            CCA(21,4)=0.884$CCA(22,4)=0.885
            CCA(01,5)=1.000$CCA(02,5)=0.653$CCA(03,5)=0.632$CCA(04,5)=0.582
            CCA(05,5)=0.545$CCA(06,5)=0.510$CCA(07,5)=0.478$CCA(08,5)=0.490
            CCA(09,5)=0.532$CCA(10,5)=0.559$CCA(11,5)=0.586$CCA(12,5)=0.614
            CCA(13,5)=0.639$CCA(14,5)=0.683$CCA(15,5)=0.719$CCA(16,5)=0.747
            CCA(17,5)=0.769$CCA(18,5)=0.797$CCA(19,5)=0.835$CCA(20,5)=0.838
            CCA(21,5)=0.841$CCA(22,5)=0.844
            DO 1 I=1,5
            NPTAT(I)=NPTAC(I)
          1 TCI(I)=CCI(I)
            DO 3 I=1,22
            CNA(I,1)=CNA(I,1)*0.001
            TNA(I,1)=CNA(I,1)
            CCA(I,1)=S(STRESS,STRAIN,NPTS,CNA(I,1))
          3 TCA(I,1)=S(STRT,STNT,NPTS,TNA(I,1))
            DO 2 I=1,22
            DO 2 J=2,5
```

```
      TNA(I,J)=TNA(I,1)                                                 HSSPT      59
      CNA(I,J)=CNA(I,1)                                                 HSSPT      60
      TCA(I,J)=CCA(I,J)*TCA(I,1)                                        HSSPT      61
    2 CCA(I,J)=CCA(I,J)*CCA(I,1)                                        HSSPT      62
      IF(DEBUGR.GE.0) RETURN                                            HSSPT      63
      WRITE(6,11) (CCI(I),I=1,5)                                        HSSPT      64
      WRITE(6,12) ((CCA(I,J),CNA(I,J),J=1,5),I=1,22)                    HSSPT      65
      WRITE(6,13) (TCI(I),I=1,5)                                        HSSPT      66
      WRITE(6,12) ((TCA(I,J),TNA(I,J),J=1,5),I=1,22)                    HSSPT      67
      RETURN                                                            HSSPT      68
      END                                                               HSSPT      69
```

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