The effect of residual stress distribution on the ultimate strength of tubular beam-columns

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Title: The Effect of Residual Stress Distribution on the Ultimate Strength of Tubular Beam-Columns.

APPROVED BY MEMBERS OF THE THESIS COMMITTEE:

Wendelin H. Mueller, III, Chairman
Hacik Erzurumlu
Ansel Johnson
Arnold Wagner

Using data for the longitudinal residual stress distribution in welded steel tubes, curves describing these distributions are selected for study. Each of these curves are checked for static balance across the tube cross section. The curves that exhibit an imbalance are adjusted by a combination of a simplified model for each
and the use of a computer program that is developed to calculate the resulting forces and moments on the cross section. The residual stress in the area of the tube wall opposite the longitudinal weld is found to be the most important in the adjustment to obtain exact equilibrium. The method of adjustment is rational and based on maintaining a smooth curve shape that matches the raw data the closest and producing a curve that is balanced within the accuracy limits required.

The balanced longitudinal residual stress distributions are used to determine M-P-\(\phi\) relationships, where M equals moment, P equals axial load, and \(\phi\) equals curvature. A computer program developed by Wagner (13) is modified to determine these relationships. The program was originally developed for a bending axis through the weld and the results are found to be inaccurate for other orientations. The problem is identified as the creation of a moment on the cross section from an uneven distribution of axial stress caused during the iteration to determine axial strain from an applied axial force. The problem is solved by adding another iteration to the program to redistribute the axial strains and eliminate the moment.

The M-P-\(\phi\) relationships obtained from this computer program for three longitudinal residual stress distributions with five different bending axis orientations are compared and one residual stress distribution curve is selected
to compare with Wagner's (13) distribution. The beam column failure load computer program (13) is used with the M-P-Ø relationships generated and the results are compared with test data.

The conclusion is reached that residual stresses have a large influence on the behavior of welded steel tube beam columns. The difference in effect of each residual stress distribution is not large. This could be because all of the curves have the same general shape with very large stresses close to the weld and rapidly decreasing away from it. With the effect of residual stresses included, the beam column failure load program still overestimates actual member strength. Therefore, other conditions effecting member strength when used as beam columns require further study and the residual stress distribution labeled curve number three which is Chen and Ross's (3,4) curve forced to two maximums from x/d = 1.0 to x/d = n is recommended for use in further research.
THE EFFECT OF RESIDUAL STRESS DISTRIBUTION ON THE ULTIMATE STRENGTH OF TUBULAR BEAM-COLUMNS

by

STEVEN L. BARRETT

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CHAPTER I

INTRODUCTION

The idealized model that is used to exhibit the behavior of steel in most mechanics of materials texts has well defined characteristics. The idealized material is stress-strain free prior to application of any load, there are no thermal strains, the material is homogenous and it has a bilinear stress strain relationship with constant slope to yield and a constant value beyond. If this material is used in an idealized member it is possible to theoretically predict the member's exact behavior under load. For different cross section shapes it is possible to determine the effect of slenderness on the member's behavior if it is used as a compression member, a beam, or a beam-column.

For a real structural member the prediction of actual behavior is much more difficult. Actual materials are not entirely homogenous and do not have bilinear stress strain curves. A real structural member is not stress free prior to loading, may have a complex cross section shape which has no simple closed form solution for critical buckling load, may have accidental eccentricity of load, initial crookedness and any number of stresses
induced during erection. Each of these conditions that can be accurately measured in the laboratory should be investigated to determine its individual effect on the strength of the member. Once the relative magnitude of the individual effect is known, a decision can be made whether or not to include that effect in every member analysis. To that end, there has been considerable research done on certain structural shapes in various materials. The largest volume of research has been done on rolled steel wide flange shapes due to their widespread application for structures of all types. (1,2,5,8,10)

Because the information available for the steel wide flange shape is extensive, there has been a tendency to apply it to other cross section shapes where data has not yet been developed. For any particular case this practice may or may not be conservative. It is not possible to completely discount any of the previously mentioned effects on a cross section shape other than a wide flange based on the argument that such an effect did not alter the behavior of the wide flange as idealized. Nor is it possible to make a direct comparison without some data being developed for the particular cross section.

The complete description of the effect of all possible initial conditions on a welded steel tube cross section for all types of loading is too broad in scope for this study. Therefore the single consideration of the effect of residual
stress was selected to study. Residual stresses are those stresses which are present in a member after it is fabricated to its finished form. Usually these residual stresses cause a reduction in strength in fatigue, fracture and stability although for some distributions a strengthening at certain load levels will be exhibited. These stresses may result from uneven cooling after hot rolling as for structural shapes and plates, from cold bending during fabrication, from welding or from cutting, drilling and punching during fabrication. Usually residual stresses with the largest magnitude result from cooling and welding. In many cases, residual stresses in the region of a weld will be greater than the yield stress. It therefore becomes important to determine the distribution and magnitude of residual stress in a member that has extensive welding during fabrication. Recent research has suggested some possible distributions of both longitudinal and circumferential residual stresses in welded steel tubes. (3,7,11,12,13)

The primary goal of this project was to analyze and select one longitudinal residual stress distribution in welded steel tubes from the literature and test data available and then determine the effect of this distribution on the ultimate beam-column failure load of the tube. The circumferential residual stress was not included since the project was simplified excluding the effects of
local buckling or ovaling from consideration. After determination of the residual stress distribution, moment-curvature-axial load curves could be generated by computer. These describe the performance of the cross section of the tube. Then, using these curves, an iterative open form computer solution calculates the beam column failure load. The solution obtained is compared to the ideal case of no residual stress and with the results of previous research using different distributions. From this comparison it is possible to determine the relative effect of residual stresses in determining failure load and the effect of changing the distribution.
CHAPTER II

REVIEW OF LITERATURE

The distribution of longitudinal residual stress described by a linear variation between three peak values was used by Wagner (12,13) in the absence of actual test data. This distribution gave a starting point for the computation of M-P-Ø curves, where M equals moment, P equals axial load and Ø equals curvature with the effect of some residual stress added. A computer program was developed using the assumed general shape that could adjust the value of residual stress on each element of the tube such that force and rotational equilibrium would be satisfied.

While there is a large volume of information on the magnitude and distribution of residual stresses in wide flange sections (4,8), there is a scarcity of information about the distribution and magnitude in welded steel tubes or its effect on the beam column failure load. Some investigators have suggested possible theoretical distributions (7) while others (4) have attempted to use more realistic patterns in correlating experimental results. They, however, discounted the necessity of static equilibrium across the cross section considering the imbalance of
internal forces to be of little consequence. Further, no consideration of the uniformity of the stress field through the tube wall thickness was made.

Recently however Tran (11) developed test data that first confirmed a uniform field of longitudinal stress through the wall of a tube and showed a very close approximation to static equilibrium across the section.
CHAPTER III

COMPUTER PROGRAM FOR CURVE ADJUSTMENT

In order to determine the best curve to describe the longitudinal residual stress distribution in the welded tube it was necessary to generate a method of rapidly checking the balance of forces and moments that each distribution curve implied. If the residual stress distribution through the thickness of the tube wall was not uniform, it would be necessary to check the balance for several layers and use that information in the generation of moment-curvature axial load curves. However, Tran (11) has shown that the distribution through the tube wall is uniform. Therefore, it is only necessary to consider one layer equal to the tube wall thickness. To check the balance of forces and moments accurately and quickly, it was decided to write a computer program that could handle any general curve describing the residual stress pattern.

Consider the general longitudinal residual stress distribution shown in Figure 1. The ordinates of the residual stresses are measured along the X axis with the weld located on the Y axis. To make the curve easier to represent, it is convenient to straighten the circumference
of the tube, in effect unrolling the tube so it is flat (Fig. 2). Now the area under any portion of this curve will represent a force, since the distance along the circumference multiplied by the wall thickness is area. Area multiplied by stress, which is force per unit area, is force. This force will be located at the center of gravity of the area under the stress curve. The distance from any single point on the tube circumference to the force, multiplied by the force will equal moment. Since the tube is under no external loading and therefore must be in static equilibrium for internal stresses, the summation of forces and the summation of moments over the entire cross section of the tube must be equal to zero.

In general the problem is to find the area (force), center of gravity and first moment of area (moment) about some point for segments under a general curve that the mathematical description for is not known. The method used will be a linear approximation of segments of the curve, in other words, short straight lines between points on the curve. Sign convention used for this development were: Tensile stresses positive, plotted above the X axis (Fig. 2); compressive stresses negative, plotted below the X axis; positive moment about any singular point, clockwise; negative moment counter clockwise.

There are several possible conditions that must be accounted for if the program is to handle all possible
Figure 1. Longitudinal residual stress in a welded steel tube

Figure 2. Longitudinal residual stress

Circumference of tube unrolled
Refering to Figure 3:

Let \( Y_1 \) = First ordinate on curve
\( Y_2 \) = Second ordinate on curve
\( X_1 \) = First abscissa on curve
\( X_2 \) = Second abscissa on curve

C.G.\(_1\) = Distance from Y axis to center of gravity of area\(_1\)
C.G.\(_2\) = Distance from Y axis to center of gravity of area\(_2\)

Area\(_1\) = \((X_2 - X_1) \cdot (Y_1)\)
C.G.\(_1\) = \(\frac{(X_2 - X_1)}{2} \cdot \frac{X_1}{2} + \frac{X_2}{2} = \frac{X_1 + X_2}{2}\)

Area\(_2\) = \((X_2 - X_1) \cdot (Y_2 - Y_1)\)
C.G.\(_2\) = \(\frac{2}{3} (X_2 - X_1) + \frac{X_1}{3} = \frac{2X_2 + X_1}{3}\)

Now since this is for a tube the X distances can be thought of as arc lengths. (Fig. 4)

C.G.\(_X\) = Arc Length
\(\frac{1}{2}\) circumference = \(\frac{2\pi r}{2}\)
\(\theta\) (radians) = \(\frac{(C.G.\(_X\)) \cdot (2\pi)}{C.G.\(_X\)} = \frac{C.G.\(_X\)}{r}\)

Lever arm = \(L = r - \cos(\theta) r = (1 - \cos(\theta)) r\)

Moment = (Force) \(\times\) (Lever Arm)

\(M = (F_1 \cdot L_1) + (F_2 \cdot L_2)\)
\(M = (\text{Area}_1 \cdot r - \cos \frac{\text{C.G.}_1}{r}) + (\text{Area}_2 \cdot r - \cos \frac{\text{C.G.}_2}{r})\)

\(M = \left[ (X_2 - X_1) \cdot (Y_1) \right] \left[ 1 - \cos \left( \frac{X_1 + X_2}{2r} \right) \right] (r) + \left[ \frac{2X_2 + X_1}{3} \right] \left( Y_2 - Y_1 \right) \left[ 1 - \cos \left( \frac{2X_2 + X_1}{r} \right) \right] (r)\)
Figure 3. Area under curve

Figure 4. Arc length - Lever arm
cases of slope of the curve and axis interception (Fig. 5 & 6). Taking each of these one at a time, we can express each area and center of gravity in the same terms used previously (Fig. 6). The location of the center of gravity for case 5 and 2 are equivalent (for the X direction) as are case 6 and 1 as well as case 3 and 4. Thinking of this in flow chart form, we have the central part of the force-moment program complete (Fig. 7). Starting with the coordinates of a known curve, it is possible to sum the forces and moments for all the segments of the curve and arrive at a total that will indicate whether or not the section is in static equilibrium. The method could be used for random lengths of curve segments or for a constant increment. The program used for this project used a constant increment for the abscissa simplifying the input required since the ordinates become the only required input. These ordinates were scaled from each curve selected for analysis. Since the summations should be zero about any point, the crown of tube was selected for convenience.

Assuming that an imbalance of force is discovered, it is possible to select the largest ordinate, divide by 10.0 and use this value to modify all ordinates until a change of sign of the summation of forces is detected. Reducing the increment applied to the ordinates, it is possible to continue the iteration until a force balance
Figure 5. Areas under curve
\[ A_1 = \frac{(x_2 - x_1)(y_2)}{2} \]
\[ CG = \frac{2(x_2 - x_1)}{3} + x_1 = \frac{2x_2 + x_1}{3} \]
\[ A_2 = \frac{(x_2 - x_1)(y_1)}{2} \]
\[ CG_2 = \frac{2[(x_2 - x_1) - x_0] + (x_1 + x_0)}{3} \]
\[ = \frac{2x_2 - 2x_1 - 2x_0 + 3x_1 + 3x_0}{3} \]
\[ = \frac{2x_2 + x_1 + x_0}{3} \]

**Figure 6. Areas under curve**
Figure 7. Flow chart - Moment, force summation
of zero is obtained. The result of this procedure is a shift of the X-Axis of the curve. Re-entering the balancing program, the balance of moment for the new ordinates can be found. Now if the moment is not balanced, the program becomes how to select the location and amount of change required to preserve force balance, the general curve shape and bring about moment equilibrium.

In order to maintain a smooth curve, the changes made to balance the moment should vary from ordinate to ordinate. With a large number of ordinates the changes possible become large and the number of possible solutions increases. Because the balanced curve should be the same general shape as the curve started with, each possible solution would have to be compared with it and measured against some criteria to find the best solution. Rather than design a program to do that it was decided to first find a solution by simplifying each curve, approximating the areas, and doing the balancing calculations by hand. This way possible curve shapes could be evaluated by determining the balanced curve ordinates and comparing them with reasonable stress values at each element, thereby eliminating curves with impossible or unlikely distributions.

Then using the more exact summation program previously described on each selected curve, the imbalance for moment and force could be determined. Using this information, changes could be made to the curve and the summation pro-
gram run again. This method eliminates some cases and within four to six runs through the summation program it is possible to find a solution that satisfies the accuracy limit required by Wagner's (13) M-P-D Program.

As one example, the curve suggested by Tran (11) as shown in Figure 8 might be approximated as shown in Figure 9. The summation of forces and moments about the weld can be done as follows:

\[ d = \text{Diameter} \quad \alpha = \text{Angle from weld to center of gravity} \]
\[ x = \text{Arc length to C.G.} \quad \text{L.A.} = \text{Lever arm to center of gravity} \]
\[ r = \text{Radius to center line of element layer} = 0.9635 \text{ in.} \]

\[
\begin{align*}
\frac{x}{d} &= 0.1 \quad \alpha = 0.1 \text{ radians} \quad \text{L.A.} = (1 - \cos \alpha)r = 0.005 \text{ in.} \\
\frac{x}{d} &= 0.3 + 0.35 = 0.65 \quad \alpha = 0.65 \text{ radians} \quad \text{L.A.} = 0.184 \text{ in.} \\
\frac{x}{d} &= 1.00 + 2.14/2 = 2.071 \quad \alpha = 2.071 \text{ radians} \quad \text{L.A.} = 1.337 \\
\Sigma F &= \left(\frac{1}{2}\right)(0.30)(4.7) - (0.7)(4.57) + (1.61)(2.14) \\
&= 0.70 - 3.20 + 3.45 = +0.95 \\
\Sigma M &= +0.70(0.005) - 3.20(0.184) + 3.45(1.337) \\
&= 0.335 - 0.589 + 3.343 = +4.057
\end{align*}
\]

The points Tran's (11) data gives generate a curve with an imbalance of positive force and positive moment. The imbalance is perhaps within tolerable experimental error for the data gathered (0.02Py and 0.027My where Py equals axial load at yield, My equals moment at yield) but the accuracy of balance for use of the residual stress
Figure 8. Residual stress from Tran(11)
distribution in the M-P-Ø program are much more restrictive (0.00005Py and 0.001 My). Comparing the results of the balancing program for Tran's (11) curve and the approximate solution, close agreement is found confirming the computer code. A complete check of the program is given in Appendix I. Using the simple approximation, it can be shown that changing the portion of the curve from $x/d = 1.0$ to $x/d = \pi$ so that the summation of forces is zero still leaves a positive unbalanced moment.

What then can be done to develop a curve based on Tran's (11) data that will satisfy $\Sigma F = 0$ & $\Sigma M = 0$? The first portion (to $x/d = 1.0$) of Tran (11) & Chen-Ross (4) curves are of the same shape although of different amplitude and therefore, a modification of the portion of the curve from $x/d = 1.0$ to $x/d = \pi$ seemed to be a good possibility. This is the area that previous investigators have regarded as being of lesser importance probably due to the rapidly decreasing magnitude of residual stress; although it is the most important area for accomplishing static equilibrium.

On viewing the simplified model, it is quite apparent that the positive area past $x/d = 1.0$ is far too large to be balanced by the negative area close to the summation axis. Changing the negative area has little effect on the summation as does changing the even closer positive area. Changing the area from $x/d = 1.0$ to $x/d = \pi$ so that the
forces balance does not balance moments as was previously shown. Further adjustment is required. Changing the area labeled (3) in Figure 9 requires changing (1) to maintain a force balance. Changing (3) enough to get $M = 0$ requires lowering the stress level to $0.016 \sigma_y$ from $x/d = 1.0$ to $x/d = \pi$. Then calculating the area and moment for the portion of the curve from $x/d = 1.0$ to $x/d = \pi$, the amount of change to area (1) that is required for equilibrium can be solved for. With a known value for area (1), the maximum stress at the weld can be solved for. This calculation indicates the stress at the weld would be $2.758\sigma_y$ times the yield stress when the ultimate stress for the tube as determined by Tran (11) is $1.14\sigma_y$ times the yield stress. A residual stress of $2.758\sigma_y$ yield at the weld is not reasonable or possible. Nor does the rapid decrease of residual stress at $x/d = 1.0$ to a level of $0.016 \sigma/\sigma_y$ through the rest of the curve seem logical.

A more likely solution is to change area (3) to be larger positive in the section $x/d = 1.0$ to $x/d = 2.0$ and balance that with a smaller negative from $x/d = 2.0$ to $x/d = \pi$ (Fig. 10). This shape begins to look similar to Chen and Ross's (4) curve (see Figure 13) but the magnitudes are different. The only viable alternative is to assume the residual stress pattern is not symmetrical about the weld axis. There is no available evidence to support the assumption that the residual stress distribution
Figure 9.
Approximate curve

\[ \frac{X}{d} = 0.1 \]

\[ \alpha = 5.7295 \]

\[ L.A. = (1 - \cos \alpha)(0.9035) \]

\[ = 1.337 \]

\[ L.A. = 0.184 \]

\[ \frac{X}{d} = 0.3 + 0.35 = 0.65 \]

\[ \frac{X}{d} = 1.00 + \frac{2.14}{2} = 2.071 \]

\[ L.A. = 0.005 \]
Figure 10. Approximate curve
is not symmetric. Tran took measurements from each half of the tube but he did not select mirror image points. Chen and Ross (4) also took values around the tube but did not separate the reported values in their representation of the data.

If the values for the portion of the curve from $x/d = 0$ to $x/d = 1.0$ are held constant and only the portion of the simplified curve from $x/d = 1.0$ to $x/d = \pi$ is changed it is possible to show that for any selected point of change from positive to negative, there is only one unique set of areas that will satisfy summation of forces and summation of moments equal to zero.

Summarizing then it is possible to use a simplified model of any residual stress curve to check for an approximate summation of forces and moments. Then using a more detailed description of the curve, e.g. 20 to 100 values around the tube scaled from a sketch of the curve, and using the previously described summation program, a more exact check for balance can be made. If the result is outside the required accuracy limit, the ordinates of the curve can be adjusted and the balance rechecked. By choosing unit values of change over one part of the curve, an indication of the effect of changing those ordinates on the total balance can be obtained. Using that information for further refinement makes the required iteration procedure converge on the required accuracy limit very quickly.
Using this technique, it is possible to balance a possible curve shape in less than ten trial runs with the summation program. No attempt is made to find a mathematical expression describing these curves.
CHAPTER IV

RESIDUAL STRESS DISTRIBUTION CURVES

Tran (11) has shown a curve that represents the data points obtained from his measurements by the hole drilling technique (Fig. 11). By dividing the curve into sixty-two segments and scaling the ordinate of the residual stress at each point and inputing these values into the summation program, an indication of the degree of imbalance was obtained. The summation of moments gave an imbalance of 10.9% My and the summation of forces an imbalance of 0.7% Py, both of which are certainly within experimental tolerance. The problem is that the M-P-Ø Program requires a much higher degree of accuracy: 0.1% My and 0.005% Py. Therefore, some adjustment of the curve is required.

Returning to a simplified model of this curve (Fig. 12) an approximate balance of forces and moments can be attempted. The areas labeled 1, 2 and 3 can be idealized as forces concentrated at the center of gravity of the areas. Force 1 is positive and close to the crown, Force 2 is negative and within \(x/d = 1.0\) and Force 3 is positive at approximately \(x/d = 2.0\). Forces 2 and 3 are close to equal but of opposite sign.
Figure 11. Residual Stress [Tran(II)]
Force 1x very small lever arm = very small +M

Force 2x small lever arm = small -M

Force 3x larger lever arm = large +M

Summation = Large +M

When Force 2 and 3 are nearly equal in magnitude, it is not possible to obtain static equilibrium. Therefore the curve Tran (11) suggests cannot be balanced without some major changes to the ordinates of the residual stress curve.

Chen and Ross (4) have shown a curve describing the residual stress distribution (Fig. 13) which they obtained from a combination of their measurements and theoretical considerations done by Marshall (7). The first portion of the curve from $x/d = 0.0$ to $x/d = 1.0$ is similar in shape to Tran's but of a different magnitude. This curve does not match all of their data points, but was selected based on close agreement. Dividing the curve into 62 segments as was done on the previous curve, scaling the ordinates and using the summation program gave results that could be compared with equilibrium and the results from Tran's curve (Fig. 13). The summation of moments gave an imbalance of 0.4% $M_y$ and a Force imbalance of 0.06% $F_y$. This is again outside the limit required making further adjustment necessary. Selecting portions of the curve to change, it was discovered that very slight changes in the latter ($x/d \geq 1.0$) portion of the curve affected the total moment balance appreciably. The part of the curve
Figure 13. Residual Stress [Chen & Ross (3,4)]
with the most difference between the actual data points and the suggested curve were selected for change. After five iterations through the summation program, adequate approximation of equilibrium was obtained. Comparing the final curve with the starting curve (Fig. 14) it can be seen that the change required was small. Even though equilibrium is approximated with this curve, it does not consistently match the data presented by Chen and Ross (4) and Tran (11) particularly over the portion from \( x/d = 1.0 \) to \( x/d = \pi \). Other possibilities needed to be explored.

One alternative is to use an average between Chen and Ross's curve and Tran's over the range \( 0 \leq x/d \leq 1.0 \) with a positive and negative maximum between \( 1.0 \leq x/d \leq \pi \). As has been previously demonstrated, this is the minimum number of fluctuations that can render a possible solution. After balancing the curve to the required limit, it can be seen that the required curve areas imply larger positive and negative stresses over the latter portion than can be justified by the available data (Fig. 15).

Examining the curve shape in general, for changes in the first maximum of compressive stress, the behavior of the later portions of the curve can be predicted. Assuming that the curve crosses the axis at approximate multiples of \( x/d = 1.0 \) and beginning with a curve like Chen and Ross's (Curve 1 Fig. 16) it is possible to show what changes will need to be made to maintain equilibrium.
Figure 14. Residual Stress, Balanced [Chen & Ross (3,4)] - Curve
Figure 15. Residual Stress [First Section Average - Chen & Ross (3,4) - Tran(I)] Curve 2
Figure 16. Fluctuation in Curve Shape
for a change in magnitude of the first negative maximum. Curve Number 1 is in equilibrium. If Curve 2 is generated by adjusting Point 1 to a different magnitude and it is assumed the curve still crosses the axis at multiples of \( x/d = 1.0 \), the general shape for \( x/d = 1.0 \), assuming a smooth curve, is determined by consideration of moment and force equilibrium. Adjusting Point 1 to a larger negative magnitude means Point 2 must also increase in magnitude to balance the additional negative force from the change in Point 1. The moments are not in balance now since equal forces have been added but at different lever arms. Therefore Point 3 must be adjusted to generate more negative moment to balance the positive moment from adjusting Point 2. Adding negative force from 3 means point 2 will have to increase which again results in a moment imbalance, although one of smaller magnitude. Continuing the iteration between the portion of the curve at 2 and 3 will result in a unique solution with larger final magnitudes for Points 2 and 3. Therefore the portion of the curve from \( x/d = 1.0 \) to \( x/d = \pi \) is very sensitive to changes in magnitude of Point 1.

An example of this sensitivity is the consideration of a curve generated by smoothing out Tran's curve from \( x/d = 0.0 \) to \( x/d = 1.0 \) (Fig. 17). After balancing the curve as previously described, the ordinate of the positive maximum was three times the yield stress which is consider-
Figure 17. Residual Stress [First portion, smoothed curve from Tran(I)]
ably greater than the stress at the weld. This means the single data point Tran found at approximately $x/d = 0.8$ is inaccurate and should not be considered in generating a curve, since the condition of equilibrium demands unrealistic stresses using the point.

In general, a smooth curve shape with a maximum tensile stress at $x/d = 0$, a maximum compressive stress at $x/d < 1.0$, and zero stress at approximately $x/d = 1.0$, $x/d = 2.0$ and $x/d = 3.0$ will exhibit an easily determined behavior for changes in the magnitude of the first compressive maximum. It has been shown herein that using a base curve of this shape, small changes in the compressive stress maximum at $x/d < 1.0$ require larger changes in the remaining tensile and compressive stress regions. It is, therefore, possible to modify the effect of a reported data point on the smooth curve by considering the change required in the rest of the curve. A data point which causes, by its inclusion in a smoothed curve shape, an unreasonable stress distribution for the other parts of the curve can be identified using this method.

Several other curves were generated in an attempt to use the combined data from Chen and Ross (3,4) and Tran (11). The most consistant results were obtained from a curve using the first part of Chen and Ross's curve from $x/d = 0.0$ to $x/d = 1.0$ and forcing the latter portion of the curve to one positive maximum and one negative maximum with the curve approaching zero at $x/d = \pi$ (Fig. 18).
Figure 18. Residual Stress [Chen & Ross (3,4) forced to two maximums] - Curve 3
Three curves of the several curves developed were selected to generate M-P-Ø curves with: a balanced version of Chen and Ross's curve (Curve 1, Fig. 14), section from x/d = 0.0 to x/d = 1.0 average between Tran and Chen and Ross's (Curve 2, Fig. 15), and Chen and Ross's curve forced to two maximums from x/d = 1.0 to x/d = π (Curve 3, Fig. 18).
CHAPTER V

M-P-\( \phi \) CURVE GENERATION

Once the description of the residual stress distribution was complete, Wagner's (13) program was used to generate M-P-\( \phi \) curves. It is important to understand the method that Wagner's program uses to calculate these curves. There are four major stages: assigning the appropriate value of residual stress and strain to each element, application of a percentage of the stub column yield load to each element, assigning a curvature to the cross section, and calculating the moment corresponding to a state of equilibrium. For one value of axial load at one curvature, the moment is then calculated. By repeating these steps for several axial loads at different curvatures, it is possible to generate a family of M-P-\( \phi \) curves. Several intermediate steps are involved in each of the four major stages (Fig. 19).

In the first stage of the program all of the required data is read; number of layers, number of elements, diameter of tube, wall thickness, modulus of elasticity, yield stress, the number of axial load values, and the number of curvature values. Then the values of axial load and curvature are read. The program has the option of using
START

Assign appropriate residual stress and strain ($\varepsilon_r$) value to each element.

STAGE 2

Apply axial load ($P$) and calculate the strain ($\varepsilon_a = P/AE$)

Calculate the total strain ($\varepsilon_t = \varepsilon_r + \varepsilon_a$) for each element

Using $\varepsilon_t$ and the stress-strain relationship find the total force on the cross section ($F$).

STAGE 3

$F = P$

No

Adjust $\varepsilon_a$

Yes

Assign a value of curvature

Determine the strain on each element due to curvature ($\varepsilon_\theta$)

Calculate the total strain for each element ($\varepsilon_t = \varepsilon_r + \varepsilon_a + \varepsilon_\theta$)

STAGE 4

Using $\varepsilon_t$ and the stress-strain relationship; determine the total force ($F$) and the bending moment ($M$) on the cross section

$F = P$

No

Adjust the location of the neutral axis.

Yes

STOP

Figure 19 Flow diagram for calculation of M-P-\(\theta\) data
a tabulated stress-strain curve or a bilinear stress-strain curve and this information is entered next. The residual stress and strain is read in and the applicable value assigned to each element. For each layer the average radius, arc length of the elements and the area of the elements is calculated. From the results of Tran's work it is apparent that consideration of layers in the tube wall is not required for the description of the residual stress-strain distribution since these do not vary through the thickness of the wall. The strain, curvature, bending moment and axial load at first yield are calculated next. Then the distance from each element to the centroid of the cross section, the total cross sectional area, plastic modulus, flexural stiffness, plastic hinge moment and shape factor are determined. The description of the problem is now complete.

The next stage is to apply the first axial load (expressed as a percentage of Py) to the cross section and calculate the axial strain. An iteration loop is performed next to determine the correct value of axial strain. This is required since it is possible for the summation of the residual strain and the axial strain on any particular element to exceed the yield value. In these cases the summation of the elemental stress available to resist the axial load is less than predicted by elastic theory. The residual stress distribution is an initial condition and
cannot be changed, therefore the additional force must be supplied by the elements that have not yet reached yield. The stress distribution and magnitude is determined by increasing the strain on all elements by the same amount and then calculating the resulting stress using the material stress-strain information (tabulated input of any stress-strain curve or a bilinear curve as previously described). The summation of available elemental stress at each increment of strain is compared to the total applied force and when they are approximately equal the iteration is stopped and the values for each element are stored for further use.

The next stage involves assigning a value of curvature to the cross section. The neutral axis is assumed initially to be at the centroid of the cross section and the corresponding strain at each element is calculated. The summation of strain due to residual stress, axial load and the imposed curvature is limited to the strain at first yield as previously described for residual stress plus axial load for each element. The resulting strains are used with the material stress-strain information to determine the resulting stress for each element. These stresses are summed and the resulting total thrust is compared with the applied axial load. If the axial load and thrust are not equal the location of the neutral axis is shifted and the strains recalculated. The iteration is continued until approximate equality is reached.

The last stage is to calculate the summation of moments for the final stress-strain state. The result is a
value of moment at a particular curvature for one value of axial load. This gives one point for determining one M-P-Ø curve. The process for finding the moment is repeated for each curvature at one value of axial load. That gives all the points of the M-P-Ø curve for that particular axial load. The program then selects the next value of axial load and begins at stage two repeating the process of solving for moment at each value of curvature until all values of axial load input have been used. The values of moment, axial load and curvature are then output in tabular form. This information can then be used in the failure load program as described by Wagner (13).

In order to completely study the effect of the residual stress distribution on failure loads it is necessary to determine the effect orientation of the axis of bending with respect to the axis of the weld has on the M-P-Ø curve. The concern is to find the weakest axis of bending to be sure that the controlling case has been found. The axis of bending selected by Wagner (12,13) passed through the weld (Fig. 20) for which results for the M-P-Ø curves were compatible with theory (1,2,5,8). Considering the axis orientation with the weld at the top of the pipe and the bending axis through the horizontal diameter as the zero or reference point, any orientation can be described as the number of degrees of rotation of the bending axis from the reference position. Thus the orientation Wagner
Figure 20. Orientation of Axes and Residual Stress Distribution [Wagner, (12, 13)]

Wagner's Axis of Bending

Reference Axis

Weld

28.0 ksi
12.3 ksi
4.8 ksi

90°
(12,13) selected would be at 90° from the reference. When any other orientation was selected, the results were not consistent with theoretical considerations (1,2,5,8). The moments were not approaching the value for full plastic moment at large values of curvature. (Figs. 21,22,23). Clearly there was a significant problem with either the proposed residual stress distribution or with the program.

The first step was to verify the results obtained by Wagner for the distribution used with the orientation of 90° from the reference. Comparing the results for this orientation of bending axis showed exact agreement with the work done by Wagner (12,13).

Inputing zero residual stress and checking several axis orientations also showed exact agreement with the theoretically predicted behavior of the M-P-∅ curves.

In order to pinpoint the problem Wagner's distribution (see Figure 20) was used. The axis of bending was assumed at the reference position and a summation of moments accomplished for the cross section at the end of each iteration to determine the correct axial strain. (This is described in the second stage of the program, see Fig. 19). Residual stresses were output to verify that there was no change occurring. (They are input constants and should not change.) The total stresses and strains were also output to verify that they did not exceed yield during the iteration procedures. All of the output verified the
Figure 21. M-P-φ Curve 1 (Chen & Ross)
Figure 2.2. M-P-\( \phi \) Curve 2 (First Section Average)
Figure 23. M-P-\( \phi \) Curve 3 (Chen & Ross forced to two maximums)
procedure with the exception of the summation of moments after finding the "correct" axial strain and corresponding stress. The summation of moments at this point should be equal to zero since the residual stress distribution is in equilibrium to begin with and only axial load has been added. Because the program does not alter the residual strain or the axial strain after this point in the program any imbalance produced here will be unchanged at the end of the iterations. The strains due to curvature are added after this and the total limited to the described material properties. The strain due to curvature at this value of axial load is calculated by subtracting strain. This strain due to curvature is used to find the stress on each element. Summing moments for these values the moment for the entire cross section is obtained. The thrust is calculated and compared to the applied force and they are not equal. The neutral axis is shifted and the moment and thrust are recalculated. This procedure in no way affects the values of strain that were solved for due to axial load. Therefore, if the cross section is not in static equilibrium after the solution for strains due to axial load, it will still not be in equilibrium after the "correct" location of the neutral axis has been found and the corresponding moment calculated.

The result of the summation of moments after completing the iteration to find the "correct" axial strain was not equal to zero in any case tested except for those with no
residual stress and those with $90^\circ$ orientation of axis of bending with respect to the reference. The disparity between the theoretical plastic moment and the calculated moment for the $P/Py$ ratio was compared to the moment imbalance created during the solution for axial strain and found to be equal. In other words the sum of the calculated moment at some large curvature plus the moment created in the solution for axial strain equals the theoretically predicted plastic moment. It would seem the simplest solution would be to compute the moment due to curvature by a summation using the total stress instead of only that part of the stress due to curvature. That way the moment imbalance is incorporated in the final moment. The problem with this solution is that while the $M-P-\phi$ curve has the correct starting point and is correct for large values of curvature, the middle portion has its shape changed considerably by the moment imbalance. The solution, then is to eliminate the moment imbalance created before entering the iteration loop to find the moment due to curvature. In this manner a residual stress distribution that is in static equilibrium will have an axial stress distribution added to it and the final result will also be in static equilibrium. This model is then showing the same behavior as the actual physical cross section.

To eliminate the moment imbalance, the first step was to determine how the imbalance is created. When the
axial strain is being solved for the first step is to apply a uniform strain to the cross section computed from the average axial stress, P/A, and the material properties of the cross section. The axial strain is added to the residual strain for each element and the stress from this sum is limited by the described material properties (either tabulated or bilinear stress strain curve). If the sum of axial strain and residual strain is larger than the strain at first yield the available stress will be less than the average axial stress. That means the summation of thrust on the cross section will be less than the applied axial load. Therefore the strain over all the elements is incremented and the summation recalculated. This procedure continues until approximate agreement is reached between the calculated thrust and the axial load. If some of the elements above the center of gravity of the cross section are very close to yield from residual strain alone, the increase in strain for axial load will put them over yield. The stress available for axial load from them is less than the average, therefore the strain is adjusted. This increase in strain does not cause much if any increase in stress available from the elements that were at or over yield in the first iteration. The other elements now have an increase in stress over the average P/A. As the iteration process continues the distribution of axial stress may become even more irregular as other elements yield. When
the iteration is complete the stress distribution is no
longer uniform and the center of gravity of the resulting
thrust is no longer located at the center of gravity of
the cross section. Therefore a moment has been created
during the iteration due to the yielding of some elements.
(Fig. 24)

To explain why there was no imbalance using this
program for the axis of bending taken through the weld
(90° to the reference) the residual stress distribution
used must be examined. The distribution used was assumed
to be symmetrical about the axis of the weld. Therefore
the change in stress due to axial load on each element is
also symmetrical about the axis of the weld. Since the
change in stress is symmetrical about this axis, the
resulting thrust is positioned somewhere along the axis.
Therefore summing moments about this axis yields zero
even though summation of moments about any other axis would
not be. The cross section is not in equilibrium but the
moment is only being taken about one axis in this program so
the imbalance goes undetected for this one special case
(axis of bending through the weld, 90° with respect to
reference chosen.) The M-P-Ø curves generated for this
case are then unaffected by the imbalance but for all
other cases they would be. The case with the largest
imbalance should be with the axis of bending at the refer-
ence position (perpendicular to the weld axis) and this was
confirmed by a test run of the program as written.
Figure 24. Moment Imbalance
The problem was identified and several possibilities for a solution were explored. The method selected was to add another iteration after determining the axial strain to eliminate the imbalance created. The value of curvature that would generate a moment equal to the unbalanced moment was calculated assuming the section to be elastic. The sign of this curvature was reversed thereby changing the sign of the moment. Strains were calculated based on this curvature and added to the strain determined for axial load plus residual stress. This in effect would cancel the unbalanced moment leaving the cross section in equilibrium. The curvature used is actually the reverse of the curvature generated by the uneven axial stress distribution, which means the section ends up with curvature equal to zero. The procedure actually assumes a curvature (elastic) and iterates to find the correct curvature (produced by uneven axial stress). The iteration also must still limit the stress to that determined from tabulated or bilinear stress-strain curves. The iteration also involves checking the summation of thrust on the elements against the applied axial load for approximate agreement. The revisions required to the program were extensive and are shown in Appendix II. Each axis rotation requires a separate run of the program.

Because various orientations of the bending axis were desired, the program was also modified to automatically
rotate the bending axis to any whole element increment
(for example: $360^\circ/80$ elements = $4.5^\circ$/element $45^\circ/4.5^\circ$/
element = 10 element rotation). Since a large number of
M-P-\(\phi\) curves were going to be generated, a graphics plot
program was written to automatically plot each set of curves
on a Cal-Com plotter. The plots for Wagner's residual
stress distribution and the suggested curve 3 are shown in
Figure 25. The results of these calculations agreed with
that predicted by consideration of the theoretical maximum
possible moment for each axial load ratio.

Another problem was discovered when these M-P-\(\phi\)
curves were used directly in the beam-column failure load
program. None of the iterative solutions supply exact
closed form solutions; they converge on a solution within
an acceptable degree of error. Since some error is inherent
in each iteration, the errors may accumulate. The degree of
error is still small but it means for some cases of axial
load with the curvature equal to zero, small positive or
negative moments appear when they should be equal to zero.
When the curves with these small negative moments were used
in the failure load program it caused instability in the
beam-column solution. It was discovered that the curve
interpolation portions of the program could not handle
negative numbers. The solution was to assign all the moments
at zero curvature to exactly zero as they should be. The
M-P-\(\phi\) curve generation program could be changed to auto-
Figure 25. M-P-Ø Curves from improved generation program
matically assign moment equal to zero for curvature equal to zero which would eliminate the need to change the output later. In this case, the program was not changed since the magnitude of the moment gives an indication of the composite accuracy of the manipulations of the program.

It should be noted that the M-P-Ø curves calculated for Wagner's (12,13) residual stress distribution exhibit a flattening effect when compared to the curves calculated for the suggested residual stress distribution (Curve 3, Figure 18). This means when using Wagner's distribution the section is weaker than would be predicted using the suggested distribution (Curve 3, Figure 18). It should also be noted that different axis orientations control the flattest (most critical) curve at different axial load ratios.

It should be noted that the M-P-Ø curves generated using the suggested residual stress distribution give more consistent results with respect to the controlling axis orientation for different slenderness ratios than by using the distribution suggested by Wagner (12,13).

Once the M-P-Ø curve generation and interpolation problems had been solved, the failure load program was used for the same sections and loading conditions that Wagner (13) used. M-P-Ø curves were generated for five axes orientations: 0°, 45°, 90°, 135°, and 180° with respect to the reference axis (perpendicular to weld axis), for Wagner's residual stress distribution and for the suggested
residual stress distribution. Each of these M-P-Ø curves were used in the beam-column failure load program. This was done since the M-P-Ø curves for Wagner's residual stress distribution indicated different axes orientations controlled for different P/Py ratios. The controlling results were then graphed as a failure load curve using the same format as shown by Sherman (9).

Figure 26 shows the resulting curve for Wagner's distribution at an orientation of 90° with respect to the reference axis.

The failure load results for the suggested residual stress distribution are shown in Figure 27 since the curves are close enough to those of Figure 26 as to make representation on the same figure difficult at this scale. The orientation of the axis for the suggested residual stress distribution (Curve 3 Figure 18) is 180° with respect to the reference axis. These curves were compared to available test data and reasonable agreement was indicated.
Figure 26. Beam column results - Wagner's distribution
Figure 27. Beam column results - curve 3 (Fig. 18).

- a Double curvature
- b Single end moment
- c Single curvature
CHAPTER VI

CONCLUSIONS

Comparing the balanced residual stress curve (Curve 3) with the curves determined by the sectioning method, hole drilling method and Wagner's assumed distribution, the balanced curve suggested for use (Curve 3 Figure 18) appears to be a smooth curve more closely modeling the test data (Fig. 28). Figure 29 shows a comparison of M-P-Ø curves for no residual stress, Wagner's distribution, that deduced from member behavior and the balanced residual stress curve (Curve No. 3). Sherman (9) presents a curve showing the effect of residual stress on strength under axial load which is shown in Figure 30 with the points determined using the residual stresses from Curve 3 (Figure 18) added to it. Using the same data as Sherman used in the beam column failure load program but with the balanced residual stress distribution of Curve 3 (Figure 18) instead of Wagner's curves, new points are determined which are plotted on Sherman's Figure 6 to show the effect of the balanced distribution (Fig. 31).

While there are large differences in the shape of the M-P-Ø curves as previously described (Figure 25, 29), the effect on the interaction curve for failure loads is
Figure 28. Longitudinal residual stress distribution curves

Curve I: Curve of sectioning method
Curve II: Curve of hole drilling method
Curve III: Curve of assumed distribution (Sherman)
Curve IV: Curve of balanced distribution (Curve 3)
Figure 29. Moment-curvature relationships

- a. No residual stress
- b. Assumed residual stress of curve 3
- c. Assumed residual stress, Sherman
- d. Deduced from member behavior
Figure 30. Effect of residual stress on strength under axial load.
Figure 31. Effect of residual stress
slight. The maximum difference between predicted failure loads is in the neighborhood of five percent. The failure load curve as described from M-P-Ø curves using the suggested residual stress distribution shows an increase in predicted strength over the failure load curve using the M-P-Ø curves as described by Wagner's residual stress distribution (Figure 26, 27, 30, 31). This agrees with the prediction based on the shape of the M-P-Ø curves (Figure 25, 29).

The interaction curve obtained using the M-P-Ø curve generated based on the suggested residual stress distribution (Curve 3 Figure 18) does not exactly conform to the test data as plotted but that is to be expected for several reasons. One is the possible error in the physical test data, another is the small errors that are inherent in the process of curve interpolation and iterative solution for axial load, moment and failure load; another is the use of a perfect bilinear stress-strain curve instead of using tabulated data from physically testing a coupon from the member tested. The degree of agreement is acceptable in light of these considerations and the use of the suggested residual stress distribution is recommended for future research into the behavior of welded steel tubes in combined bending and axial load.

It is further recommended that the M-P-Ø curve generation program be changed to facilitate more rapid use of the program. A data file should be created that would
contain the stresses and strains on each element that result for each axial load ratio used. These stresses and strains can be obtained using the first portion of the M-P-Ø curve generation program as re-written in this study. The stresses and strains that result from the application of residual stress plus axial stress after the moment imbalance has been resolved are the ones that should be saved. By storing these stresses and strains, the program would not be required to recalculate them for each axis rotation thereby reducing the computer time used.

Summarizing, the residual stresses present in a welded steel tube can be modeled by a smooth curve that describes stresses such that the cross section is in equilibrium.

Curve 3 (Fig. 18) models the existing test data well, is in equilibrium and exhibits consistent behavior in the M-P-Ø and beam column failure load program. This curve is suggested for use in further research on the behavior of steel tube columns. The effect of these residual stresses on the predicted failure load of tubular beam columns is significant and should not be ignored. The difference in failure load predicted by this family of curves was five percent at the maximum, indicating that the exact shape of all parts of the residual stress curve is not required to obtain good results. Because of the large strength reductions indicated by use of the residual stress
distribution described by Curve 3 (Figure 18) in the beam-column failure load program, it is evident that residual stresses can not be ignored when calculating failure loads in steel tube beam columns.
REFERENCES


APPENDIX I

CURVE BALANCING COMPUTER PROGRAM
CURVE BALANCING PROGRAM

DATA INPUT

NOTE: Use of the punch output option gives the user a deck of cards with the stress-strain information on them in proper form for direct input to the moment-thrust curvature program (average over element). Numbers at left indicate card columns.

A. Control Data; Curve Identity Number.

    FORMAT (2I3)
    1-3 Curve identity number
    4-6 Are stress-strain values to be punched on cards? (- or 0 no, + yes)

B. Control Data.

    FORMAT (I3, 5F12.4)
    1-3 Number of elements in 1/4 tube (Maximum number = 100)
    4-15 Outside diameter of tube (in.)
    16-27 Tube wall thickness (in.)
    28-39 Distance from crown to center of moment (in.)
    40-51 Modulus of elasticity (ksi)
    52-63 Yield stress (ksi)

C. Residual Stress Values from Distribution Curve

    FORMAT (F9.6)
    1-9 Residual stress (ksi)
    (Distribution curve ordinates)
FLOW DIAGRAM

RESIDUAL STRESS DISTRIBUTION CURVE BALANCING

START

READ: NC, IP

READ: NELE, ØD, T, DC E, FY

CALCULATE: \( X(N) = \text{Arc Distance, Radius at Wall, Py, My, Accuracy Limits.} \)

PRINT HEADINGS

READ: RESIDUAL STRESS CURVE ORDINATES \( Y(N) \)

DO 240 FOR EACH ELEMENT

IF \( Y(N) \):

100

90

110

0
CALCULATE $X_0$, $C_{G1}$, $C_{G2}$

$A_1$, $A_2$

GO TO 220

110

IF $Y(N+1)$

0

196

CALCULATE $C_{G1}$, $C_{G2}$, $A_1$, $A_2$

GO TO 220

IF $Y(N+1) - Y(N)$

0

CALCULATE $C_{G1}$, $C_{G2}$, $A_1$, $A_2$

GO TO 220

CALCULATE $A_1$, $C_{G1}$

$A_2=0$, $C_{G2}=0$

GO TO 220

CALCULATE $C_{G1}$, $C_{G2}$

$A_1$, $A_2$

GO TO 220
IF \( Y(N+1) \)

-\( Al=0, A2=0 \)
  \( CG1=0, CG2=0 \)
  GO TO 220

+\( CALCULATE \)
  \( CG1, CG2=0 \)
  \( A1, A2=0 \)
  GO TO 220

IF \( Y(N+1) \)

-\( 120 \)

+\( 170 \)

190

CALCULATE
  \( CG1, CG2=0 \)
  \( A1, A2=0 \)

220

\( Al=Al*T*FY \)
\( A2=A2*T*FY \)

IF \( CG1 \)

-\( 0 \)

+\( LEVER ARM 1 = 0 \)

CALCULATE
  LEVER ARM 1
- IF CG2
- LEVER ARM 2 < 0
  - CALCULATE LEVER ARM 2
  - CALCULATE MOMENT
  - SUM OF FORCES
  - SUM OF MOMENTS
  - PRINT FORCE 1, LEVER ARM 1
  - FORCE 2, LEVER ARM 2
  - SUM FORCES, SUM MOMENTS

240
- IF IP
  - 0
  - FOR EACH ELEMENT
    - CALCULATE AVERAGE STRESS & STRAIN,
      FORCE, SUM FORCES
      MOMENT, SUM MOMENTS
  - PRINT RESULTS AND PUNCH STRESS & STRAIN

STOP
THE PURPOSE OF THIS PROGRAM IS TO SUM FORCES AND MOMENTS FOR LONGITUDINAL RESIDUAL STRESSES IN A CIRCULAR CROSS SECTION.
I = NUMBER OF STRESS LOCATIONS, E = YOUNG'S MODULUS, FY = YIELD STRENGTH.
OD = OUTSIDE DIAMETER OF TUBE, T = THICKNESS OF WALL OF SECTION.
DC = DISTANCE FROM CROWN TO CENTER OF MOMENT.
NC = CURVE NUMBER.
IP = 0 NO CARDS PUNCHED.
   = 1 STRESS + STRAIN PUNCHED.
DIMENSION X(100), Y(100)
1 IREAD=2
2 IWRITE=5
3 READ (IREAD+15) NC, IP
4 15 FORMAT (213)
5 PFA D (IREAD+10) NELE, OD, T, DC, E, FY
6 10 FORMAT (13,5F12.4)
7 R=(OD-T)*0.50
8 I=NELE*2+1
9 UX=3.141592654/(I-1)
10 X(1)=0.0000
11 DO 25 K=2,1
12 25 X(N)=UX*K*(N-1)
13 DI=(2.0*K)-T
14 PY=3.141593/4.0*(OD*OD-DI*D)*FY
15 XMY=(3.141593/64.0)*(OD**4.0-DI**4.0)*(2.0/OD)*FY
16 STOPF=0.00005*PY
17 STOPM=0.001*XMY
18 K=I-1
19 WRITE (IWRITE, 29) NC
20 29 FORMAT (' *** THIS IS CURVE NUMBER', I3)
21 SUMA=0.0
22 SUMN=0.0
23 WRITE (IWRITE, 30)
24 30 FORMAT (' AREA 1 LEVER ARM AREA 2 LEVER ARM
1 SUM FORCES SUM MOMENTS ')
25 READ (IREAD+40) (Y(N), N=1, I)
26 40 FORMAT (F9.6)
DO 240 N=1,K
29 IF (Y(N)) 100,90,110
30 IF (Y(N+1)) 180,95,180
31 A1=0.0
32 A2=0.0
33 CGL=0.0
34 CG2=0.0
35 GO TO 220
36 100 IF (Y(N+1)) 120,190,170
37 110 IF (Y(N+1)) 170,190,130
38 120 IF (Y(N+1)-Y(N)) 150,135,140
39 130 IF (Y(N+1)-Y(N)) 140,135,150
40 135 A1=(X(N+1)-X(N))*Y(N)
41 CGL=(X(N+1)+X(N))/2.0
42 A2=0.0
43 CG2=0.0
44 GO TO 220
45 140 CGL=(X(N+1)+X(N))/2.0
46 150 CGL=(X(N+1)+X(N))/2.0
47 A1=(X(N+1)-X(N))*Y(N+1)
48 A2=(X(N+1)-X(N))*Y(N)-Y(N+1))/2.0
49 GO TO 220
50 170 XO=(X(N+1)-X(N))*(1.0)*(Y(N))/(Y(N+1)-Y(N))
51 CGL=(XO/3.0)+X(N)
52 CGL=(2.0*X(N+1)+X(N)+X0)/3.0
53 A1=(XO+Y(N))/2.0
54 A2=(X(N+1)-(X(N)+X0))*Y(N+1)/2.0
55 GO TO 220
56 180 CGL=(2.0*X(N+1)+X(N))/3.0
57 CGL=0.0
58 A1=(X(N+1)-X(N))*Y(N+1)/2.0
59 GO TO 220
A2=0.0
GO TO 220
CG1=(X(N+1)+2.0*X(N))/3.0
CG2=0.0
A1=(X(N+1)-X(N))*Y(N)/2.0
A2=0.0
220 A1=I1+1+2.0*X(N)/3.0
CG2=0.0
A1=I1+1+2.0*X(N)/3.0
A2=0.0
A1=A1*T*FY
A2=A2*T*FY
IF (CG1) 222,221,222
221 D1=0.0
GO TO 223
222 D1=I1+1-COS(CG1/R)*H-DC
223 IF (CG2) 225,224,224
224 D2=0.0
GO TO 226
225 D2=(1.0-COS(CG2/R))*R-DC
226 SM=A1*C1+A2*D2
SUMA=SUMA+A1+A2
SUM=SUM+SM
WRITE (IWRITE,230) A1,D1,D2, SUMA, SUM
230 FORMAT (E15.7)
240 CONTINUE
WRITE (IWRITE,250) SUMA,STORP,SUM,STORP
250 FORMAT (SUM FORCES = E15.7,) 0.00005FY = E15.7/ SUM MOMENTS = E15.7, 0.001MY = E15.7)
WRITE (IWRITE,260)
260 FORMAT (ELEMENT STRESS STRAIN FOR
1CF MOMENT SUM FORCES SUM MOMENTS)
IF (IP) 265,265,264
264 READ (IREAU,275)
265 SAVE=0.0
SAVE=0.0
DO 260 N=1,K
AVGS=((Y(N)+Y(N+1))/2.0)*FY
AVGSR=AVGS/E
260
AVGF = AVG*S*DX*R*T
SAVF = SAVF + AVGF
AVGM = AVGF*(1.0 - COS(N*DX - 0.5*DX))*R
SAVM = SAVM + AVGM
WRITE (WRITE, 270) N, AVG*S, AVGS, AVG, AVGM, SAVF, SAVM
270 FORMAT (I8, 7X, 6E15.7)
280 CONTINUE
CALL LINK(EXEC)
END
Figure 32. Example for testing curve program

<table>
<thead>
<tr>
<th>AI</th>
<th>D1</th>
<th>A2</th>
<th>D2</th>
<th>M1</th>
<th>M2</th>
<th>Sum M</th>
</tr>
</thead>
<tbody>
<tr>
<td>180.0</td>
<td>0.196</td>
<td>60.0</td>
<td>0.087</td>
<td>35.292</td>
<td>5.233</td>
<td>40.525</td>
</tr>
<tr>
<td>90.0</td>
<td>1.382</td>
<td>60.0</td>
<td>9.773</td>
<td>124.393</td>
<td>-482.568</td>
<td>164.918</td>
</tr>
<tr>
<td>-90.0</td>
<td>5.362</td>
<td>-60.0</td>
<td>18.939</td>
<td>-1613.975</td>
<td>-586.374</td>
<td>-317.650</td>
</tr>
<tr>
<td>-180.0</td>
<td>8.967</td>
<td>-60.0</td>
<td>-3586.837</td>
<td>-1136.315</td>
<td>-11485.508</td>
<td>-1897.954</td>
</tr>
<tr>
<td>-300.0</td>
<td>14.148</td>
<td>-60.0</td>
<td>-2242.420</td>
<td>-10793.567</td>
<td>-10432.235</td>
<td>10317.576</td>
</tr>
<tr>
<td>-180.0</td>
<td>19.927</td>
<td>-60.0</td>
<td>2934.361</td>
<td>12330.00</td>
<td>3436.111</td>
<td>10356.684</td>
</tr>
<tr>
<td>-90.0</td>
<td>24.916</td>
<td>-60.0</td>
<td>6636.617</td>
<td>32435.33</td>
<td>3358.192</td>
<td>10317.576</td>
</tr>
<tr>
<td>90.0</td>
<td>32.604</td>
<td>60.0</td>
<td>18.939</td>
<td>12330.00</td>
<td>-13727.927</td>
<td>10432.235</td>
</tr>
<tr>
<td>180.0</td>
<td>36.870</td>
<td>60.0</td>
<td>37.650</td>
<td>6636.617</td>
<td>3358.192</td>
<td>10317.576</td>
</tr>
<tr>
<td>300.0</td>
<td>41.101</td>
<td>60.0</td>
<td>37.650</td>
<td>6636.617</td>
<td>3358.192</td>
<td>10317.576</td>
</tr>
<tr>
<td>75.0</td>
<td>43.247</td>
<td>75.0</td>
<td>44.776</td>
<td>12330.00</td>
<td>3436.111</td>
<td>10356.684</td>
</tr>
<tr>
<td>-75.0</td>
<td>45.293</td>
<td>75.0</td>
<td>45.815</td>
<td>3397.003</td>
<td>3436.111</td>
<td>10356.684</td>
</tr>
</tbody>
</table>

Compare with program output (next page)
<table>
<thead>
<tr>
<th>AREA 1</th>
<th>LEVER ARM</th>
<th>AREA 2</th>
<th>LEVER ARM</th>
<th>SUM FORCES</th>
<th>SUM MOMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.18000000E+03</td>
<td>0.1960707E+00</td>
<td>0.60000000E+02</td>
<td>0.6721241E-01</td>
<td>0.24900000E+03</td>
<td>0.40000000E+02</td>
</tr>
<tr>
<td>0.90000000E+02</td>
<td>0.1382143E+00</td>
<td>0.90000000E+00</td>
<td>0.16400000E+03</td>
<td>0.33000000E+03</td>
<td>0.12500000E+03</td>
</tr>
<tr>
<td>-0.90000000E+02</td>
<td>0.5361871E+00</td>
<td>0.90000000E+00</td>
<td>0.24000000E+03</td>
<td>0.31800000E+03</td>
<td>0.25100000E+03</td>
</tr>
<tr>
<td>-0.18000000E+03</td>
<td>0.696531E+00</td>
<td>0.60000000E+00</td>
<td>0.977291E+00</td>
<td>0.91000000E+00</td>
<td>0.25100000E+03</td>
</tr>
<tr>
<td>-0.30000000E+03</td>
<td>0.1414785E+00</td>
<td>0.90000000E+00</td>
<td>0.30000000E+00</td>
<td>0.67020000E+00</td>
<td>0.67020000E+00</td>
</tr>
<tr>
<td>-0.18000000E+03</td>
<td>0.192667E+00</td>
<td>0.60000000E+00</td>
<td>0.18930000E+00</td>
<td>0.10000000E+00</td>
<td>0.11400000E+00</td>
</tr>
<tr>
<td>-0.30000000E+03</td>
<td>0.2491577E+00</td>
<td>0.90000000E+00</td>
<td>0.90000000E+00</td>
<td>0.13700000E+00</td>
<td>0.13700000E+00</td>
</tr>
<tr>
<td>0.90000000E+02</td>
<td>0.3260401E+00</td>
<td>0.90000000E+00</td>
<td>0.54000000E+00</td>
<td>0.10000000E+00</td>
<td>0.10000000E+00</td>
</tr>
<tr>
<td>0.18000000E+03</td>
<td>0.368709E+00</td>
<td>0.60000000E+00</td>
<td>0.3764992E+00</td>
<td>0.10000000E+00</td>
<td>0.10000000E+00</td>
</tr>
<tr>
<td>0.30000000E+03</td>
<td>0.411062E+00</td>
<td>0.90000000E+00</td>
<td>0.54000000E+00</td>
<td>0.10000000E+00</td>
<td>0.10000000E+00</td>
</tr>
<tr>
<td>0.75000000E+02</td>
<td>0.4324709E+00</td>
<td>0.75000000E+02</td>
<td>0.447507E+02</td>
<td>0.10000000E+00</td>
<td>0.10000000E+00</td>
</tr>
<tr>
<td>0.75000000E+02</td>
<td>0.4529335E+00</td>
<td>0.75000000E+02</td>
<td>0.4561478E+02</td>
<td>0.10000000E+00</td>
<td>0.10000000E+00</td>
</tr>
</tbody>
</table>
MOMENT-THRUST-CURVATURE PROGRAM

DATA INPUT

NOTE: The last data card must assign the outside diameter a value of zero to stop the program.
Numbers at left indicate card columns.

A. Control Data; Cross Section and Material Properties.

FORMAT (4I5, 4E15.5)

1-5 Actual stress-strain data used?
(+=Yes; -1=No)

6-10 Residual stresses used?
(1=Yes; 0=No)

11-15 Number of layers of elements.
(Max. = 5)

16-20 Number of elements in 1/4 circle of one layer.
(The product of the last two numbers must not exceed 50.)

21-35 Outside diameter (in.)

36-50 Wall thickness (in.)

51-65 Modulus of elasticity. (ksi)

66-80 Yield stress. (ksi)

B. Data and Time of Run

FORMAT (4I5)

1-5 Month

6-10 Day

11-15 Year

16-20 Time (001 - 2400)
C. Control Data

FORMAT (7I5)

1-5 Number of P/PY values
(Max. = 12)

6-10 Number of PHI/PHIY values
(Max. = 25)

11-15 KSKIP
(1=1 stress-strain data for one half tube)
(=2 stress-strain data for entire tube)

16-20 Rotation of bending axis
(Number of elements)

21-25 Curve identification number

26-30 Are curves to be plotted?
(- or 0 = No)
(+ = Yes)

31-35 Are M-P-PHI values to be punched on cards?
(- or 0 = No)
(+ = Yes)

D. Axial Load Values

FORMAT (6F10.5)

1-10 P/PY values (Always Positive)

E. Curvature Values

FORMAT (5F10.5,/,5F10.5,1,5F10.5,1,5F10.5,1,5F10.5)

1-10 PHI-PHIY values (Always Positive)

11-20

21-30
NOTE: The data for one problem is now complete if the actual stress-strain data and residual stresses are not used. If both options are used, the stress-strain curve data is read in first.

F. Stress-Strain Curve Data
1. Control Card
   FORMAT (I5)
   1-5 Number of tabulated points on stress-strain curve.
2. For each tabulated point
   FORMAT (2E15.5)
   1-15 Stress value
   16-30 Strain value

G. Residual Stress Data
1. Time of Residual Stress Calculation
   FORMAT (4I5)
   1-5 Month
   6-10 Day
   11-15 Year
   16-20 Time
2. For each element
   FORMAT (2E15.5)
   1-15 Stress value
   16-30 Strain value
FLOW DIAGRAM

CALCULATION OF MOMENT-THRUST-CURVATURE DATA

START

998

Read: NBS, IRS, NLYR, NELE
      OD, WT, E, PY

Is OD greater than 0.0?

Yes

Read ID1, ID2, ID3, ID4

No

STOP

Read NP, NPHI, KSKIP
      ROTA, IDCUR, IPLT, IPUN

Read P/Py values.

Read Ø/Øy values.
Is tabular stress-strain data used?

Yes

Read stress-strain data.

No

Are residual stresses used?

Yes

Read residual stress data.

No

Calculate for each layer:

Average radius
Arc length of elements
Area of elements.
Calculate the following:

Strain, curvature, bending moment and axial load at first yield.

The distance from each element to the centroid of the cross section.

The total cross sectional area, plastic modulus, flexural stiffness, plastic hinge moment and shape factor.

Calculate
Summation of forces and moments for residual stress distribution

Are summations Over accuracy limit?

Print Warning
Do 500 for each P/Py value.

Apply an (a new) axial load and calculate the corresponding axial strain (P/AE).

Is tabular stress-strain data used?

Yes

Go To 600

No

Go To 300

Are residual stresses used?

Yes

Go To 300

No

Axial stress = P/A

Go To 600
Comment:
This is the beginning of an iteration to determine the correct axial strain.

Is tabulated stress-strain data used?
Yes
  Go To 21
No

For each element:
  Calculate the total strain (Axial strain + residual strain)
  Interpolate the corresponding stress value - SUBROUTINE INTERP
  Calculate the force on the element.

Calculate the total force on the cross section.

Go To 75
For each element:

Calculate the total strain (Axial strain + residual strain)

Determine the corresponding stress value from the bilinear stress-strain relationship.

Calculate the force on the element.

Calculate the total force on the cross section.

Let "DIFF" = The total force on the cross section - the applied axial load.

Is "DIFF" nearly equal to 0.0?

Yes

Adjust the axial strain

Go To 300

No
Calculate the unbalanced moment from residual + axial strain

Calculate curvature from unbalanced moment

Locate neutral axis at the centroid of the cross section

Have iterations to balance axial stress been exceeded? Yes
Print Stop

Have iterations to find neutral axis been exceeded? Yes
Print Stop

Is tabulated stress-strain data used? Yes
Go To 525
For each element

Calculate strain due to bending
Calculate the total strain
(Axial strain + residual strain + strain due to unbalanced curvature)

Interpolate the corresponding stress value -
SUBROUTINE INTERP

Calculate the force on the element

Calculate total moment for curvature stress and total moment for total stress

Go To 535

525

For each element

Calculate strain due to bending
Calculate the total strain

Determine the corresponding stress value from the bilinear stress - strain relationship

Calculate total moment for curvature stress and total moment for total stress
Calculate total force

Let "force" be the net force on the cross section

Is "force" nearly equal to 0.0

Yes

No

Go To 548

Adjust neutral axis location (sign of unbalanced curvature included)

Go To 515

Is the total moment due to residual stress + axial stress + unbalanced curvature less than 0.001 My?

No

Find new unbalanced curvature

Go To 548
Write axial load ratio summation of moments after balancing cross section for axial + residual strain.

Is bending axis rotated?

Yes

Rotate axis of bending write; number of degree rotated

Write; residual stress, residual strain, axial stress (after balancing)

Do 400 for each $\phi/\phi_y$ value.

No

Assume a (a new) curvature value.

Locate the neutral axis at the centroid of the cross section.

Go To 509
For each element

Calculate the strain due to bending

Calculate the total strain (Axial strain (balanced) + residual strain + strain due to bending)

Interpolate the corresponding stress value - SUBROUTINE INTERP

Calculate the force on the element

Calculate the total force and bending moment on the cross section.

Go To 89
For each element:

Calculate the strain due to bending.

Calculate the total strain.

Determine the corresponding stress value from the bilinear stress-strain relationship.

Calculate the total force and bending moment on the cross section.

Let "FORCE" be the net force on the cross section.

Is "FORCE" nearly equal to 0.0? 

Yes

Adjust the location of the neutral axis.

No

Go To 71

Go To 450
71

Save the total moment calculated.

400 - Continue to next $\phi/\phi_Y$ value.

Return to original residual stress distribution

500 - Continue to next $P/P_Y$ value

Print results

Call plot subroutine if specified

Punch results if specified

Go To 999
C *** AD - $\$$\$$\$$
C *** ADIFF - ABSOLUTE VALUE OF DIFF
C *** AINC - AMOUNT OF CHANGE IN ASTRM
C *** AP - ABSOLUTE VALUE OF P
C *** ARCL(I) - ARC LENGTH OF ELEMENT IN LAYER 'I'
C *** AREA(I) - AREA OF ELEMENT IN LAYER 'I'
C *** AREAT - TOTAL AREA OF CROSS SECTION
C *** AST - P/AREAT
C *** ASTRN - STRAIN DUE TO AXIAL LOAD
C *** AVGK(I) - AVERAGE RADIUS TO LAYER 'I'
C *** C - TOTAL COMPRESSION FORCE
C *** CT - -C/T
C *** DIFF - DIFFERENCE BETWEEN FORCE AND P
C *** CTA - ABSOLUTE VALUE OF CI
C *** DINC - AMOUNT OF CHANGE IN D
C *** DRSTS(I,J)=DUMMY RESIDUAL STRESS
C *** DRSTN(I,J)=DUMMY RESIDUAL STRAIN
C *** DASTS(I,J)=DUMMY AXIAL STRESS
C *** E - MODULUS OF ELASTICITY
C *** EFRC - ELEMENTAL FORCE
C *** EMOE - ELEMENTAL MOMENT
C *** F - FLEXURAL STIFFNESS
C *** FORCE - TOTAL FORCE ON CROSS SECTION
C *** FY - YIELD STRESS
C *** IBAT = +1 = BATCH PROCESSING
C *** -1 = TIMESHARING
C *** IRS - +2 = RESIDUAL STRESSES USED
C *** -1 = RESIDUAL STRESSES NOT USED
C *** KSKIP = 1 = STRESS - STRAIN DATA SUPPLIED FOR ONE HALF TUBE
C *** 2 = STRESS - STRAIN DATA SUPPLIED FOR ENTIRE TUBE
C *** MSTRN - STRAIN DUE TO CURVATURE
C *** MTHI(I,J) - MOMENT-THRUST-CURVATURE DATA
C *** MY - MOMENT AT FIRST YIELD
C *** NBS - +1 = ACTUAL STRESS-STRAIN DATA USED
C *** -1 = BILINEAR STRESS-STRAIN RELATIONSHIP
C *** NFLE - NUMBER OF ELEMENTS IN 1/4 CIRCLE IN ONE LAYER
C ** HFE2 - NUMBER OF ELEMENTS IN 1/2 CIRCLE IN ONE LAYER
C ** NFL=NUMBER OF LAST ELEMENT
C ** NEPL=NUMBER OF ELEMENTS PER LAYER
C ** NEN=NEXT ELEMENT NUMBER
C ** NFS=NUMBER OF ELEMENT AT START
C ** HETOT = TOTAL NUMBER OF ELEMENTS IN 1/2 CIRCLE
C ** NL=LAYER NUMBER
C ** NLYR = NUMBER OF LAYERS OF ELEMENTS
C ** NP = NUMBER OF P/PY VALUES IN THIS RUN
C ** NPHI = NUMBER OF PHI/PHY VALUES IN THIS RUN
C ** NS=SIDE NUMBER
C ** NSS=NUMBER OF SIDE AT START
C ** NTP = NUMBER OF TABULATED POINTS ON STRESS-STRAIN CURVE
C ** OD = OUTSIDE DIAMETER OF TUBE
C ** P = APPLIED AXIAL LOAD
C ** PHY = CURVATURE AT FIRST YIELD
C ** ROTA = ANGLE OF ROTATION EXPRESSED AS NUMBER OF ELEMENTS TO NEW
C ** AXIS
C ** RSTRN(IJ) = RESIDUAL STRAIN AT ELEMENT 'IJ'
C ** RSTPS(IJ) = RESIDUAL STRESS AT ELEMENT 'IJ'
C ** SFCT = SHAPE FACTOR
C ** STRNY = STRAIN AT FIRST YIELD
C ** T = TOTAL TENSILE FORCE
C ** TDIST(IJ) = DISTANCE FROM ELEMENT TO NEUTRAL AXIS
C ** THETA = ANGLE FROM TOP OF CROSS SECTION TO ELEMENT
C ** TLYR = THICKNESS OF EACH LAYER OF ELEMENTS
C ** TMOM = TOTAL MOMENT ON CROSS SECTION
C ** WT = WALL THICKNESS OF TUBE
C ** X = STRAIN VALUE
C ** YD = $$$$$$$
C ** XDIFF = VALUE OF DIFF ON PREVIOUS ITERATION
C ** XFRC = VALUE OF FORCE ON PREVIOUS ITERATION
C ** XMP = PLASTIC HINGE MOMENT
C ** XVAL(K) = STRAIN VALUE ON STRESS-STRAIN CURVE
C ** (NOTE DIFFERENT MEANING IN RESIDUAL STRESS PROGRAM)
C ** Y = INTERPOLATED STRESS VALUE
C *** YVAL(K) - STRESS VALUE ON STRESS-STRAIN CURVE
(C NOTE DIFFERENT MEANING IN RESIDUAL STRESS PROGRAM
1 DIMENSION KSTRS(100,2), RSTRN(100,2)
2 DIMENSION ASTRS(100,2)
3 DIMENSION DIST(100), TDIST(100), XVAL(20), YVAL(20)
4 DIMENSION AVGR(5), AREAE(5), ARCI(5)
5 DIMENSION ASTBA(100,2), UNGTS(100,2)
6 DIMENSION USTRS(100,2), BSTRN(100,2), UASTS(100,2)
7 REAL MTPHI(25,14), MY, MMY, MSTRS, MSTRN, AMY2, MTP2(25,14)
8 INTEGER ROTA
9 COMMON MTPHI, NP, NPHI, AROT, IDCUR
10 IF(1BAT) 8, 999, 9
11 IF(IBAT) 8, 999, 9
12 8 IREAD=10
13 IWRIT=6
14 GO TO 998
15 9 IREAD=2
16 IWRIT=5
17 998 READ(IREAD,100) NBS, IRS, NLRY, NELE, OD, WT, EF
18 100 FORMAT(4I5,4E15.5)
19 IF(00) 999, 999, 3
20 3 READ(IREAD,103) ID1, ID2, ID3, ID4
21 103 FORMAT(4I5)
22 NELE2=NELE*2
23 NETOT=MNYR*NELE2
24 DO 5 I=1, NLRY
25 DO 10 J=1, NELE2
26 IJ=J+(I-1)*NELE2
27 DIST(IJ)=0.0
28 TDIST(IJ)=0.0
29 10 CONTINUE
30 AVGR(I)=0.0
31 AREAE(I)=0.0
32 ARCI(I)=0.0
33 5 CONTINUE
34 READ(IREAD,110) NP, NPHI, KSKIP, ROTA, IDCUR, IPLT, IPUM
110 FORMAT(7I5)
111 IF (KSKIP) 121,123,124
121 WRITE (IWRT,122)
122 FORMAT (' ENTER KSKIP VALUE = 0,1 OR 2')
123 GO TO 999
124 WRITE (IWRT,122)
125 GO TO 999
126 READ (IREAD,120) (MTPHI(I,1),I=1,NP)
127 READ (IREAD,130) (MTPHI(I,2),I=1,NPHI)
128 IF (NBS) 11,11,12
129 READ (IREAD,140) NTP
130 FORMAT(5F10.5)
131 IF (NBS) 11,11,12
132 READ (IREAD,150) YVAL(I),XVAL(I),I=1,NTP)
133 130 FORMAT(2L15.5)
134 11 CONTINUE
135 IF (IRS) 16,16,17
136 17 CONTINUE
137 READ (IREAD,155) IR1,IR2,IR3,IR4
138 155 FORMAT(4I5)
139 DO 9878 LN=1,NLYR
140 DO 9878 NS=1,KSKIP
141 DO 9878 NE=1,NELE2
142 IJ=NELE2*(LN-1)+NE
143 IF (NS.GT.1) IJ=NELE2*LN-(NE-1)
144 READ (IREAD,160) RSTRS(IJ,NS),RSTRN(IJ,NS)
145 9878 CONTINUE
146 IF (ROTA) 127,16,127
147 127 AROT=(180.0/NELE2)*ROTA
148 IF (KSKIP) 128,16,16
149 128 DO 129 JU=1,NETOT
150 RSTRS(IJ,2)=RSTRS(IJ,1)
71  RSTRN(IJ,2)=RSTRN(IJ,1)
72  129 CONTINUE
73    KSKIP=2
74  160 FORMAT(2E15.5)
75    TLYF=WT/NLYR
76    DO 25 I=1,NLYR
77    AVGR(I)=(CJ-2.0*I*TLYR+TLYR)*0.5
78    ARCI(I)=(3.141593*AVGR(I))/NELE2
79    AREA(I)=ARCI(I)*TLYR
80  25 CONTINUE
81    STRN1=FY/E
82    PHIY=2.0*STRNY/OD
83    AREAT=0.0
84    MY=0.0
85    Z=0.0
86    DO 30 J=1,NLYR
87    ARC=ARCI(I)/2.0
88    DO 35 J=1,NELE2
89    JJ=J+(I-1)*NELE2
90    ARC=ARC+ARCI(I)
91    THETA=ARC/AVGR(I)
92    DIST(IJ)=AVGR(I)*COS(THETA)
93    EMOM=DIST(IJ)*PHIY*F*AREAE(I)*DIST(IJ)
94    MY=MY+EMOM
95  35 CONTINUE
96    AREAT=AREAT+2.0*AREAE(IJ)*NELE2
97    DO 50 JJ=1,NELE
98    IJJ=JJ+(I-1)*NELE2
99    Z=Z+DIST(IJJ)*AREAE(I)
100  50 CONTINUE
101  30 CONTINUE
102    PY=AREAT*FY
103    MY=MY*2.0
Z = 2 * Z
F = E * (MY * OD) / (2.0 * FY)
IF(NBS) 18, 18, 19
18 XMP = FY * Z
GO TO 7
19 XMP = YVAL(NTP) * Z
7 SFAC = XMF / MY
WRITE(IWRT, 190)
190 FORMAT(1H1, '///', + 45H STRUCTURAL TUBE MOMENT-THRUST-CURVATURE DATA )
WRITE(IWRT, 195) ID1, ID2, ID3, ID4
195 FORMAT(/, 6H DATE = I2, 1H /, I2, 1H /, I2, 1H /, I2, /, 6H TIME = I5)
WRITE(IWRT, 205) NELE, NLYR
205 FORMAT(/, 6H NELE = I3, /, 6H NLYR = I2)
WRITE(IWRT, 200) OD, WT, FY
WRITE(IWRT, 210) PY, MY, PHY, F, SFAC
210 FORMAT(/, 25H OUTSIDE DIAMETER = E15.5, 5H IN. /,
+ 25H WALL THICKNESS = E15.5, 5H IN. /,
+ 25H MODULUS OF ELASTICITY = E15.5, 5H KSI /,
+ 25H YIELD STRESS = E15.5, 5H KSI )
WRITE(IWRT, 221) IDCUR
221 FORMAT(/, '*** CURVE IDENTITY NUMBER = ', I7, '***', //)
IF(NBS) 38, 38, 39
WRITE(IWRT, 220)
220 FORMAT(/, '25H STRESS-STRAIN CURVE DATA /,
+ 4X, 23H STRESS STRAIN /,
+ 5X, 23H (KSI) (IN/IN) )
WRITE(IWRT, 230) (YVAL(I), XVAL(I), I = 1, NTP)
230 FORMAT(2E15.5)
38 CONTINUE
IF(IERS) 36, 36, 37
37 WRITE(IWT,240) IR1,IR2,IR3,IR4
240 FORMAT(///,28H RESIDUAL STRESS-STRAIN DATA /// ,
+6H DATE=I2,1H/I2,1H/I2,1H/I2,6H TIME=I5/// ,
+4X,34HELEM. NO. STRESS STRAIN /// ,
+13X,22H(IS1) (IN/IN) )
   DO 9860 KS=1,KSKIP
   IF (NS-1) 251,251,249
249 WRITE (IWT,9879)
9879 FORMAT(///, ' RESIDUAL STRESS-STRAIN DATA (OTHER SIDE) ')
251 CONTINUE
   DO 9880 LN=1,NLYR
   DO 9880 NE=1,NELE2
   IJ=MCLE2*(LN-1)+NE
   WRITE (IWT,250) IJ,RSTRS(IJ,NS),RSTRN(IJ,NS)
250 FORMAT(15,3X,2€15.5)
9880 CONTINUE
   RSP=0.0
   RSM=0.0
   DO 43 IJ=1,NETOT
   I=(IJ+NELE2-1)/NELE2
   DO 43 KKK=1,KSKIP
   RSP=RSP+AREAE(I)*RSTRS(IJ,KKK)
   RSM=RSM+AREAE(I)*RSTRS(IJ,KKK)*DIST(IJ)
43 CONTINUE
   IF (KSKIP-2) 44,45,45
   RSP=2.0*RSP
   RSM=2.0*RSM
44 ARSP=ABS(RSP)
45 ARSM=ABS(RSM)
   IF (ARSP-0.0001*PY) 45,45,46
   IF (ARSM-0.002*KY) 36,36,46
46 WRITE (IWT,47) RSP,RSM
47 FORMAT(///, '**** WARNING - RESIDUAL STRESS DISTRIBUTION INPUT HAS
     1 UNBALANCED AXIAL FORCE OR MOMENT IN EXCESS OF LIMITS 0.001*PY OR
     2 0.002*KY ***',/// 'AXIAL FORCE = *E15.5,'MOMENT = *E15.5)
36 CONTINUE
C *** FOR EACH AXIAL LOAD RATIO
   DO 500 K=1,NP
161  AD=1.0
162  NN=0
163  P=-P*TFH1(K,1)
164  ASTRN=P/(AREAT*E)
165  AINC=0.1*STRNY
   C *** IF NEITHER OPTION IS USED (NBS AND IRS = -1) ASTRN IS CORRECT.
166  IF(NBS) 310,310,300
167  IF(IRS) 310,310,300
   C *** CALCULATE STRESS DUE TO AXIAL LOAD.
168  350 AST=P/AREAT
169    DO 60 IJ=1,NETOT
170       ASTRS(IJ,1) = AST
171       ASTRS(IJ,2) = AST
172    60 CONTINUE
173   GO TO 565
   C *** START ITERATION TO FIND CORRECT ASTRN.
C *** (40 ITERATIONS ALLOWED)
174   300 NN=NN+1
175    IF(NN.GT.40) GO TO 996
176    FORCE=0.0
177    ASM=0.000
178    TSM=0.000
C *** FIND THE STRESS ON EACH ELEMENT AND THE TOTAL FORCE
C *** FOR THE CURRENT ASTRN VALUE
C *** IF NBS = +1 USE ACTUAL STRESS-STRAIN DATA
C *** IF NBS = -1 USE BILINEAR STRESS-STRAIN RELATIONSHIP
180   IF(NBS) 21,21,22
181 22 CONTINUE
182    DO 70 IJ=1,NETOT
183       I=(IJ+NELE2-1)/NELE2
184    70 CONTINUE
185      X = ASTRN + RSTRN(IJ,KKK)
186    CALL INTKP(NTP,XVAL,YVAL,X,Y)
187   ASTRS(IJ,KKK) = Y - RSTRS(IJ,KKK)
188          FORCE = FORCE + AREA(E(I)) * ASTRS(IJ, KKK)
189          70 CONTINUE
190          GO TO 76
191          21 CONTINUE
192          DO 75 IJ=1, NETOT
193          1 = (IJ + MF2 - 1) / NEFL2
194          DO 74 KKH=1, KSKIP
195          X = ASTRN + RSTRS(IJ, KKK)
196          IF (STRNY = ABS(X)) 31, 31, 32
197          31 ASTRS(IJ, KKK) = SIGN(FY, X) - RSTRS(IJ, KKK)
198          TSTRS = ASTRS(IJ, KKK) + RSTRS(IJ, KKK)
199          ASM = ASK + ASTRS(IJ, KKK) * AREA(E(I)) * DIST(IJ)
200          TSM = TSM + TSTRS * AREA(E(I)) * DIST(IJ)
201          GO TO 74
202          32 ASTRS(IJ, KKK) = X*E - RSTRS(IJ, KKK)
203          TSTRS = ASTRS(IJ, KKK) + RSTRS(IJ, KKK)
204          ASM = ASK + ASTRS(IJ, KKK) * AREA(E(I)) * DIST(IJ)
205          TSM = TSM + TSTRS * AREA(E(I)) * DIST(IJ)
206          74 FORCE = FORCE + AREA(E(I)) * ASTRS(IJ, KKK)
207          75 CONTINUE
208          76 CONTINUE
209          IF (KSKIP < LT.2) FORCE = 2.0 * FORCE
210          DIFF = FORCE - P
211          ADIFF = ABS(DIFF)
212          AP = ABS(P)
C *** IS THE FORCE EQUAL TO THE APPLIED AXIAL LOAD (600 = YES, 52 = NO)
213          IF (ADIFF = 0.0001 * PY) 600, 600, 52
C *** CALCULATE NEW ASTRN
C *** IF NM = 1, XDIFF IS NOT DEFINED.
214          52 IF (NM = LT.2) GO TO 360
C *** IF XDIFF HAS CHANGED SIGN THE CORRECT SOLUTION HAS BEEN PASSED.
215          IF (DIFF / XDIFF) 59, 600, 360
216          59 AD = 0.5
217          360 XDIFF = DIFF
218          AINC = SIGN (AINC * AD * DIFF)
219          ASTRN = ASTRN - AINC
GO TO 300
C *** FOR EACH CURVATURE VALUE
600 CONTINUE
C *** CALCULATE MOMENT (UNBALANCED)
TMUNB=0.0-
DO 505 IJ=1,NETOT
I=(IJ+NELE2-1)/NELE2
DO 504 KKK=1,KSKIP
UNBTS(IJ,KKK)=ASTRS(IJ,KKK)+RSTRS(IJ,KKK)
504 TMUNB=TMUNB+UNBTS(IJ,KKK)*AREAF(I)*DIST(IJ)
505 CONTINUE
C *** CALCULATE THE UNBALANCED CURVATURE INDUCED BY AXIAL FORCE
C *** BALANCING ON THE CROSS SECTION
S=MY/FY
PHIUB=(-TMUNB/S)/E
C *** CALCULATE UNBALANCED STRAINS AND STRESSES
PINC=ABS(PHIY/10.0)
NL=0
NPL=0
509 XD=1.0
NPL=NPL+1
IF (NPL.GT.50) GO TO 574
510 DINC=0.1*AVGR(I)
NL=0
D=0.0
DO 510 IJ=1,NETOT
TDIST(IJ)=DIST(IJ)
510 CONTINUE
515 NL=NL+1
IF (NL.GT.30) GO TO 570
C=0.0
T=0.0
TMOM=0.0
TMOMT=0.0
C *** FOR EACH ELEMENT
C *** FIND THE STRAIN INDUCED BY MOMENT UNBALANCE
C *** THE TOTAL STRAIN, THE TOTAL STRESS
C *** IF NBS = +1 USE ACTUAL STRESS-STRAIN DATA
C *** IF NBS = -1 USE BILINEAR STRESS STRAIN RELATIONSHIP
IF (NBS) 525, 525, 520
249
250 CONTINUE
520 DO 524 IJ=1, NETOT
251 I=(IJ+NELE2-1)/NELE2
252 MSTRN=TDIST(IJ)*PHIUB
253 DO 524 KKK=1, KSKIP
254 X=ASTRN+RSTRN(IJ,KKK)+MSTRN
255 CALL INTRP(INTP, XVAL, YVAL, X, Y)
256 MSTRS=Y-ASTR(IJ,KKK)-RSTRS(IJ,KKK)
257 ASTBA(IJ,KKK)=MSTRS
258 EFFC=ARFAE(I)*MSTRS
259 TMS=MSTRS+ASTR(IJ,KKK)+RSTRS(IJ,KKK)
C *** FIND THE TOTAL COMRESSIVE AND TENSIILE FORCES ON THE
C *** CROSS SECTION DUE TO MOMENT
IF (EFFC) 521, 521, 522
261 521 C=C+EFFC
262 GO TO 523
263 522 T=T+EFFC
264 523 TMOM=TMOM+EFFC*TDIST(IJ)
265 TMOM=TMOM+TMS*ARFAE(I)*DIST(IJ)
266 524 CONTINUE
267 GO TO 525
268 525 CONTINUE
269 DO 534 IJ=1, NETOT
270 I=(IJ+NELE2-1)/NELE2
271 MSTRN=TDIST(IJ)*PHIUB
272 DO 534 KKK=1, KSKIP
273 X=ASTRN+RSTRN(IJ,KKK)+MSTRN.
C *** IS THE TOTAL STRAIN GREATER THAN THE STRAIN AT FIRST YEILD
C *** (526=YES, 527=NO)
C *** FIND A NEW NEUTRAL AXIS LOCATION
304 DINC=SIGN(DINC*XD*FORC)
305 D=D+DINC
306 IF (PHIUB) 516,517,517
307 516 SPHI=-1.0
308 GO TO 518
309 517 SPHI=1.0
310 518 GO 547 JJ=1,NETOT
311 TDIST(IJ)=DIST(IJ)+D*PHI
312 547 CONTINUE
313 GO TO 515
314 548 CONTINUE
315 IF (ABS(TMOMT)-0.001*MY) 560,560,550
C *** IF NPL=1 XMOMT NOT DEFINED
316 550 IF (NPL.LT.2) GO TO 554
C *** IF XMOMT CHANGES SIGN THE CORRECT SOLUTION HAS BEEN PASSED
317 IF (TMOMT/XMOMT) 552,560,554
318 552 PINC=0.25*DINC
C *** FIND NEW UNBALANCED PHI ANGLE
319 554 IF (TMOMT) 556,560,558
320 556 PHIUB=PHIUB+PINC
321 XMOMT=TMOMT
322 GO TO 509
323 558 PHIUB=PHIUB+PINC
324 XMOMT=TMOMT
325 GO TO 509
326 560 TMASKS=0.0
327 NO 562 JJ=1,NETOT
328 I=(I+NELE2-1)/NELE2
329 NO 562 KKK=1,SKIP
330 ASTRS(IJ,KKK)=ASTKS(IJ,KKK)+ASTBA(IJ,KKK)
331 EFRC=RFAE(I)*IASTRS(IJ,KKK)+RSTRS(IJ,KKK)
332 562 TMASKS=TMASKS+EFRC*DIST(IJ)
333 WRITE (19,580)
334 580 FORMAT ('AXIAL LOAD RATIO TOTAL MOMENT FOR RESIDUAL '1/19X,'+ A
AXIAL STRESS AFTER BALANCING')
335 WRITE (1,RI,564) MTPHI(K,1),TMASRS
336 564 FORMAT (3X,F5.2,10X,E15.5)
337 565 IF (ROTA) 426,426,601
338 601 IF (ROTA-NELE2) 401,402,402
339 401 NSS=1
340 MFS=ROTA+1
341 GO TO 403
342 402 NSS=2
343 MFS=2*NELE2-ROTA
344 '403 NFPL=NELE2*2'.
C *** SAVE RSTR ANS RSTRN IN ASTBA AND UMRTS
345 DO 404 KKK=1,1,1
346 DO 404 IJ=1,NETOT
347 ASTBA(IJ,KKK)=RSTRS(IJ,KKK)
348 404 UMRTS(IJ,KKK)=RSTRN(IJ,KKK)
349 DO 415 NL=1,NLYR
350 I=1+(NL-1)*NELE2
351 J=NES+(NL-1)*NELE2
352 DSTRS(I,J)=RSTRS(J,NSS)
353 DSTRN(I,J)=RSTRN(J,NSS)
354 DASTS(I,J)=ASTRS(J,NSS)
355 MEN=J
356 NS=NSS
357 DO 415 IJ=2,NFPL
358 IF (NS-1) 416,405,406
359 405 MEN=MEN+1
360 GO TO 407
361 406 MEN=MEN+1
362 407 IF (MEN-(NL-1)*NELE2) 416,410,408
363 408 IF (MEN-(NELE2+1)-(NL-1)*NELE2) 411,409,416
364 409 MEN=MEN-1
365 NS=2
366 GO TO 411
367 410 MEN=1+NELE2*(NL-1)
368 NS=1
369 411 IF (IJ-NELE2) 412,412,413
370  I=I+1*(NL-1)*NCLE2
371  J=1
372  GO TO 414
373  I=NEPL-(1J-1)+(NL-1)*NCLE2
374  J=2
375  USTRS(I,J)=RSTRS(NEN,NS)
376  DSTRN(I,J)=RSTRN(NEN,NS)
377  UASTS(I,J)=ASTS(NEN,NS)
378  CONTINUE
379  GO TO 425
380  WRITE (IWRIT,417)
381  417 FORMAT ("ERROR IN AXIS TRANSFORMATION - REENTER ROTATION")
382  GO TO 999
383  WRITE (IWRIT,420) AROT
384  420 FORMAT ("RESIDUAL STRAIN - STRAIN DATA FOR TRANSFORMED AXIS, ROTATION = \"F10.4\" DEGREES FROM WELD AXIS")
385  DO 421 KKK=1,NSkip
386  DO 421 IJ=1,NETOT
387  RSTRS(IJ,KKK)=RSTRS(IJ,KKK)
388  RSTRN(IJ,KKK)=RSTRN(IJ,KKK)
389  ASTRS(IJ,KKK)=ASTS(IJ,KKK)
390  CONTINUE
391  WRITE (IWRIT,427)
392  427 FORMAT ("STRESS STRAIN AXIAL STRESS +\',5X,\',15.5) (KSI) (IN/IN) (KSI)")
393  DO 429 KKK=1,NSkip
394  WRITE (IWRIT,422) KKK
395  422 FORMAT ("SIDE NO. \',I5)
396  DO 429 IJ=1,NETOT
397  WRITE (IWRIT,428) IJ,RSTRS(IJ,KKK),RSTRN(IJ,KKK),ASTR(IJ,KKK)
398  428 FORMAT (I5,3X,3E15.5)
399  CONTINUE
400  DO 400 L=1,NPHI
FOR EACH ELEMENT

C *** FOR EACH ELEMENT
C *** FIND THE STRAIN DUE TO CURVATURE ONLY, THE TOTAL STRAIN.
C *** THE TOTAL STRESS AND THE DUE TO CURVATURE ONLY.
C *** IF NBS = 1 USE ACTUAL STRESS-STRAIN DATA
C *** IF NBS = -1 USE BILINEAR STRESS-STRAIN RELATIONSHIP

IF(NBS) 23, 23, 24

C *** FOR EACH ELEMENT
C *** FIND THE STRAIN DUE TO CURVATURE ONLY, THE TOTAL STRAIN.
C *** THE TOTAL STRESS AND THE DUE TO CURVATURE ONLY.
C *** IF NBS = 1 USE ACTUAL STRESS-STRAIN DATA
C *** IF NBS = -1 USE BILINEAR STRESS-STRAIN RELATIONSHIP

C *** FOR EACH ELEMENT
C *** FIND THE TOTAL COMPRESSIVE AND TENSILE FORCES ON THE
C *** CROSS-SECTION AND THE TOTAL MOMENT

IF(EFRC) 61, 61, 62
61 C=C+EFRC
62 T=T+EFRC
67 TMOM=TMOM+EFRC*TDIST(IJ)
80 CONTINUE
GO TO 69
23 CONTINUE
DO 90 IJ=1,NETOT
T=(IJ+NELE2-1)/NELE2
MSTRN=MSTR(IJ)*PHI
DO 90 KKA=1,KSKIP
X = ASTRN + RSTRN(IJ,KKK) + MSTRN
90 CONTINUE

C. *** IS THE TOTAL STRAIN GREATER THAN THE STRAIN AT FIRST YIELD
C. *** (41 = YES, 42 = NO)

41 IF(STRNY-AUS(X)) 41,41,42
42 MSTRS = SIGN(FY,X) - ASTRS(IJ,KKK) - RSTRS(IJ,KKK)
43 EFRC=AREA(I)*MSTRS
44 TSTRS=MSTRS+RSTRS(IJ,KKK)+RSTRS(IJ,KKK)

C. *** FIND THE TOTAL COMRESSIVE AND TENSILE FORCES ON THE CROSS SECTION
C. *** AND THE TOTAL MOMENT

45 IF(EFRC) 66,66,68
66 C=C+EFRC
67 T=66+EFRC
68 THISTMOM=THOM+EFRC*TDIST(IJ)
GO TO 69
TM2 = TM2 + DIST(IJ) * TSTRS * AREA(I)
450 CONTINUE
451 C = C + 1
452 IC = C
453 T = T * 10.0
454 IT = IT
455
C *** IF 'T' AND 'C' ARE BOTH SUFFICIENTLY SMALL - STOP
456 IF (IC) 96, 97, 97
457 IF (IT) 71, 71, 96
458 IF (T) 72, 72, 73
459 CT = -C/T
460 CT = ABS(1.0 - CT)
C *** IS ABS(C) NEARLY EQUAL TO ABS(T) (71 = YES, 72 = NO)
461 IF (CTA - 0.01) 71, 71, 72
C *** IF NM = 1 THEN XFRG IS NOT DEFINED
462 IF (NM.LT.2) GO TO 91
C *** IF THE TOTAL FORCE HAS CHANGED SIGN THEN THE CORRECT
C *** SOLUTION HAS BEEN PASSED
463 IF (FORCE / XFRG) 81, 71, 91
464 XD = 0.5
465 XFRG = FORCE
C *** FIND NEW NEUTRAL AXIS LOCATION.
DINC = SIGN(DINC *XD* FORCF)
D = D + DINC
IF (PHI) 86, 87, 87
86 SPHI = 1.0
GO TO 88
87 SPHI = 1.0
AO DO 85 IJ = 1, NETOT
85 TLIST(IJ) = ULIST(IJ) - D*SPHI
CONTINUE
85
GO TO 45U
71 K2 = K + 2
72 MMY = TMOM/MY
73 MMY2 = TM2/MY
74 IF (KSKIP .LT. 2) MMY = 2.0 * TMOM/MY
IF (KSKIP .LT. 2) MMY2 = 2.0 * TM2/MY
76 MTPHI(I, K2) = MMY
77 MTP2(I, K2) = MMY2
78 CONTINUE

C *** RETURN TO ORIGINAL PATTERN OF RESIDUAL STRESS AND STRAIN
79 IF (.NOT. ROTA) 500, 500, 498
80 DO 499 KKK = 1, KSKIP
81 DO 499 IJ = 1, NETOT
82 RSTRS(IJ, KKK) = ASTBA(IJ, KKK)
83 RSTRN(IJ, KKK) = UNBTS(IJ, KKK)
84 CONTINUE
85 WRITE(IWRT, 170)
86 170 FORMAT(/,11X,'*** M/My FOR A GIVEN COMBINATION OF P/PY AND PHI/PHI
87 + Y ****', 18X, 'PHI/ P/PY=', 5(6X, 'P/PY=')
88 WRITE(IWRT, 175) (MTPHI(I, I), I = 1, NP)
89 175 FORMAT(6H PHII, 3X, F5.2, 5(6X, F5.2), /, 6H **, 3X, F5.2, 5(6X, F5.2)
90 DO 93 I = 1, NPHI
91 WRITE(IWRT, 180) (MTPHI(I, J), J = 2, K2)
92 180 FORMAT(/, 6H PHII, 2X, F7.4, 5(4X, F7.4), /, 6H **, 2X, F7.4, 5(4X, F7.4)
93 CONTINUE
94 DO 94 I = 2, NPHI
95 WRITE(IWRT, 192) (MTP2(I, J), J = 2, K2)
500 192 FORMAT(/8X,F7.4,5(4X,F7.4)/,6H ** 12X,F7.4,5(4X,F7.4))
501 94 CONTINUE
502 90 IF (IPLT) 905,905,900
503 900 READ (IRSEL,901)
504 901 WRITE (IERSEL,902) PY,PHI,MY
505 902 FORMAT (3C15.6)
506 903 FORMAT (6F10.7,/6F10.7)
507 904 WRITE (IERSEL,901)(MPHI(I,J),I=1,MP)
508 DO 904 I=1,MPHI
509 WRITE (IFUN,903)(MPHI(I,J),J=2,K2)
510 903 FORMAT (7F10.7,/6F10.7)
511 904 CONTINUE
512 905 IF (IPLT) 998,998,990
513 990 CALL LINK(PLTMP)
514 996 WRITE(IWRT,245) MTPHI(K,1)
515 245 FORMAT(/4X,'AXIAL STRAIN EXCEEDS 40 ITERATIONS AT P/PY = ',F10.5)
516 GO TO 999
517 570 WRITE(IWRT,572) MTPHI(K,1)
518 572 FORMAT(/4X,'NEUTRAL AXIS ITERATION EXCEEDS 30 DURING AXIAL STRESIS MOMENT BALANCING AT P/PY = ',F10.5)
519 GO TO 999
520 574 WRITE(IWRT,576) MTPHI(K,1)
521 576 FORMAT(/4X,'ITERATION TO BALANCE AXIAL STRESS MOMENT INDUCED DURING AXIAL FORCE BALANCING EXCEEDS 50 AT P/PY = ',F10.5)
522 GO TO 999
523 997 WRITE(IWRT,255) MTPHI(L,2)
524 255 FORMAT(/4X,'NEUTRAL AXIS ITERATION EXCEEDS 50 ITERATIONS AT PHI/PHI = ',F10.5)
525 999 CONTINUE
526 CALL LINK(LEXEC)
527 END
C *** PLOT PROGRAM TO GRAPH MOMENT - AXIAL LOAD - CURVATURE DATA
C *** FROM THE OUTPUT OF MPPHI
1 DIMENSION XPTS(28),YPTS(28)
2 REAL *MTPHI(25,14)
3 COMMON MTPHI,NPHI,AROT,IDCUR
4 REAL MXY /*M/MY*/
5 REAL PHI(2) /*PHI */, 'PHI' /
6 REAL CM(4) /*CURV*/, 'C', 'CM', 'MBER', ' = '
7 REAL ROTA(7) /* RO.T', 'ATIO', 'N FR', 'ON W', 'ELD', 'AXIS', ' = '/
8 REAL PY(2) /*P/PY', ' = '/'
9 CALL PLOT (0.0, -29.0, -3)
10 CALL PLOT (1.0, 1.5, -3)
11 FCUR=IDCUR
12 CALL AXIS (0.0, 0.0, MXY, 4.0, 0.90, 0.0, 0.0, 2)
13 CALL AXIS (0.0, 0.0, PHI, -8, 15.0, 0.0, 0.0, 3)
14 CALL SYMB (3.93, -0.75, 0.14, CM, 0.0, 1.5)
15 CALL NUMB (999.0, 999.0, 0.14, FCUR, 0.0, 1)
16 CALL NUMB (999.0, 999.0, 0.14, ROTA, 0.0, 27)
17 CALL NUMB (999.0, 999.0, 0.14, AROT, 0.0, 2)
18 NPP1=NPHI+1
19 NPP2=NPHI+2
20 XPTS(NPP1)=0.0
21 XPTS(NPP2)=1.0
22 YPTS(NPP1)=0.0
23 YPTS(NPP2)=0.2
24 NP2=NP+2
25 K=0
26 NPP=NPHI
27 DO 20 J=3, NP2
28 K=K+1
29 PY=MTHPI(K+1)
30 DO 10 I=1, NPHI
31 XPTS(I)=MTHPI(I+1)
32 YPTS(I)=MTHPI(I,J)
33 10 CONTINUE
34 CALL LINE (XPTS,YPTS, NPP, 1, 0, 0)
35   XP=XPTS(IPHI)+0.5
36   YP=YPTS(IPHI)*5.0
37   CALL SYNE (XP,YP,0.07,PY,0.07)
38   CALL MINE (999.0,999.0,0.07,PPY,0.02)
39   20 CONTINUE
40   CALL PLOT (17.0,4.0,-3)
41   CALL LINK (EXEC)
42   END