RETSACP: A COMPUTER PROGRAM FOR ANALYSIS OF ROCKET ENGINE THERMAL STRAINS WITH CYCLIC PLASTICITY

by
Roy W. Miller
Atkins & Merrill Inc.
Ashland, Mass.

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H.G. Price, Project Manager
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SUMMARY

A computer program, designated RETSCP, for the analysis of Rocket Engine Thermal Strains with Cyclic Plasticity is described in detail. RETSCP is a finite element program which employs a three dimensional isoparametric element. The program treats elasto-plastic strain cycling including the effects of thermal and pressure loads and temperature dependent material properties. Theoretical aspects of the finite element method are discussed and the program logic is described. A RETSCP User's Manual is presented including sample case results.
INTRODUCTION

A new generation of high performance liquid rocket engines is being considered for Space Transportation System applications. The high performance goal for these engines demands high chamber pressures which result in high heat flux levels. Engine reusability is a prime objective. With the requirement of thermal and pressure cycling, the stress analyst must be able to define the life potential of a given design, considering cyclic fatigue where chamber wall stresses are sufficiently high to cause plastic strains.

The state of stress in regeneratively cooled rocket chambers varies in three dimensions. For such geometries, a numerical method of analysis must be employed. The numerical technique which has been given the most attention during the past decade is the finite element method. For an outstanding introduction to the finite element method, see Zienkiewicz's text, Reference 1.

The following report describes a finite element computer program designated RETSCP which was developed specifically for the purpose of Rocket Engine Thermal Strain analysis with Cyclic Plasticity. The program is an outgrowth of a General Electric program called ISOPAR, Reference 2.
ISOPAR employs a three-dimensional isoparametric element to compute the elastic stress distribution in structures which can be modeled with relatively few elements.

The transformation of ISOPAR into RETSCP followed a step-by-step approach. First, the program was expanded to allow for more elements in the structural model. Then, the capability of including thermal loads and computing thermal stresses was added. The program was next modified to allow non-zero prescribed displacements and to treat sliding boundaries. The symmetry condition in a rocket chamber is represented by a sliding boundary. Finally, plastic behavior with temperature dependent material properties was included. In conjunction with this final step, residual strains are output on punch cards to allow strain cycle restarts.

This report begins with a discussion of the theoretical aspects of the finite element method. The RETSCP program logic and computational scheme are then described. Finally, a RETSCP program User's Manual is given which includes sample case results. It is intended that a prospective program user can go directly to the User's Manual to obtain a working knowledge of the program. For application of the RETSCP program to specific rocket chamber analyses, see Reference 10.
The theory of the finite element method has been well documented in several texts (c.f., Reference 1). There are many types of elements which have been developed, Reference 3. The choice between elements is this: use many simple elements, or use few complex elements. The isoparametric element, Reference 4, is a very complex element which leads to accurate results with a course structural model.

In this section, the theory of the finite element method is described with specific reference to the isoparametric element which is used in the RETSCP program. The stress-strain analysis, application of boundary conditions, thermal loading, and bi-linear plasticity models are discussed in the context of the RETSCP program.
General Theory

The finite element method is a procedure for approximating a continuum by an assembly of distinct elements having a finite number of unknowns. For structural analysis, this amounts to solving the force-displacement equations for the element assembly subject to the prescribed boundary values. That is, the following system of equations is formulated and solved:

\[ \{F\} = [K]\{\delta\} \]  \hspace{1cm} (1)

where, \(F\) and \(\delta\) are the forces and displacements at the nodal points which connect the elements, and \([K]\) is the master stiffness matrix for the assembly. All symbols are defined in Appendix A. The appropriate force and displacement boundary conditions are used to obtain the solution to equation (1).

The master stiffness matrix is formed by assembling the individual stiffness matrices for each element. The element stiffness \([k]\) is determined by employing strain energy considerations. Apropos to these remarks, the strain within each element is related to the element nodal point displacements as follows:

\[ \{\varepsilon\} = [B]\{\delta\} \]  \hspace{1cm} (2)
For an elastic structure, the general stress-strain relationship is

\[ \{\sigma\} = [D] \{e\} \]  

(3)

Now, the aforementioned energy considerations (c.f. Reference 1) imply the following:

\[ [k] = \int [B]^T [D] [B] \, dV \]  

(4)

The functional relationship in equation (2) depends on the particular element employed. The detailed manner in which the integration, equation (4), is carried out also depends on the choice of element. The general procedure, however, is to solve the force-displacement equations for the assembly under the imposed boundary conditions.

Isoparametric Element

Following Reference 1, consider the eight node box element shown in Figure 1. The nodal points are located in space by their x-y-z coordinates in the rectangular right hand system. We introduce a set of parameters (ξ, η, ζ) such that their values are either +1 or -1 on the element faces. A set of eight linear functions of the parameters is then defined such that their functional value is +1 at each corresponding node and zero elsewhere.
That is,

\[ N_1 = \frac{1}{8} (1-\xi) (1-\eta) (1-\zeta) \]

\[ N_2 = \frac{1}{8} (1-\xi) (1+\eta) (1-\zeta) \]

\[ N_3 = \frac{1}{8} (1+\xi) (1+\eta) (1-\zeta) \]

\[ N_4 = \frac{1}{8} (1+\xi) (1-\eta) (1-\zeta) \]

\[ N_5 = \frac{1}{8} (1-\xi) (1-\eta) (1+\zeta) \]

\[ N_6 = \frac{1}{8} (1-\xi) (1+\eta) (1+\zeta) \]

\[ N_7 = \frac{1}{8} (1+\xi) (1+\eta) (1+\zeta) \]

\[ N_8 = \frac{1}{8} (1+\xi) (1-\eta) (1+\zeta) \]

Note that these functions apply when the node numbering is such that nodes 1-2-3-4 go clockwise around the bottom when viewed from the top and nodes 5-6-7-8 are above nodes 1-2-3-4 respectively.
Figure 1. Rectangular and parametric coordinate systems for eight node box element.
Now, the coordinates of any point within the element $x, y, z$ can be related to the coordinates of the eight nodal points $x_n, y_n, z_n$ by the following parametric expressions:

$$x = N_1 x_1 + N_2 x_2 + \ldots N_8 x_8 = (N_n)^T x_n$$

$$y = N_1 y_1 + N_2 y_2 + \ldots N_8 y_8 = (N_n)^T y_n$$

$$z = N_1 z_1 + N_2 z_2 + \ldots N_8 z_8 = (N_n)^T z_n$$

Equations (6) thus imply a relationship between $(x, y, z)$ and $(\xi, \eta, \zeta)$.

Bear in mind, that our objective is to evaluate the stiffness matrix for the three-dimensional box element, equation (4). Thus, we require detailed expressions for the $B$-matrix and $D$-matrix. The stress matrix, $D$-matrix, for an isotropic material with elastic modulus $E$, and Poisson's ratio $\nu$ is:

$$D = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1 & \nu/(1-\nu) & \nu/(1-\nu) & 0 & 0 & 0 \\ \nu/(1-\nu) & 1 & \nu/(1-\nu) & 0 & 0 & 0 \\ \nu/(1-\nu) & \nu/(1-\nu) & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2(1-\nu)} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2\nu}{2(1-\nu)} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2\nu}{2(1-\nu)} \end{bmatrix}$$

(7)
The $B$-matrix relates strain at any point in the element to the nodal point displacements. The general strain-displacement equations are:

$$
\begin{align*}
\begin{bmatrix}
\epsilon_x \\
\epsilon_y \\
\epsilon_z \\
\gamma_{xy} \\
\gamma_{yz} \\
\gamma_{xz}
\end{bmatrix} &= 
\begin{bmatrix}
\partial u / \partial x \\
\partial v / \partial y \\
\partial w / \partial z \\
\partial u / \partial y + \partial v / \partial x \\
\partial v / \partial z + \partial w / \partial y \\
\partial w / \partial x + \partial u / \partial z
\end{bmatrix}
\end{align*}
$$

We relate the displacements of a point in space $u$, $v$, $w$ to the nodal point displacements $\{u_n\}$, $\{v_n\}$, $\{w_n\}$ as follows:

$$
\begin{align*}
u &= N_1 u_1 + N_2 u_2 + \ldots + N_8 u_8 = (N_n)^T \{u_n\} \\
v &= N_1 v_1 + N_2 v_2 + \ldots + N_8 v_3 = (N_n)^T \{v_n\} \\
w &= N_1 w_1 + N_2 w_2 + \ldots + N_8 w_8 = (N_n)^T \{w_n\}
\end{align*}
$$

An element, such as this, for which the same shape function expresses the element geometry and displacement fields is called an isoparametric element.
Substitution of equations (9) into equation (8) gives,

\[
\begin{pmatrix}
\varepsilon_x \\
\varepsilon_y \\
\varepsilon_z \\
\gamma_{xy} \\
\gamma_{yz} \\
\gamma_{zx}
\end{pmatrix}
\begin{pmatrix}
\varepsilon \frac{\partial N_1}{\partial x} & 0 & 0 & \varepsilon \frac{\partial N_2}{\partial x} & 0 & 0 & \ldots & \varepsilon \frac{\partial N_8}{\partial x} & 0 & 0 \\
0 & \varepsilon \frac{\partial N_1}{\partial y} & 0 & 0 & \varepsilon \frac{\partial N_2}{\partial y} & 0 & \ldots & 0 & \varepsilon \frac{\partial N_8}{\partial y} & 0 \\
0 & 0 & \varepsilon \frac{\partial N_1}{\partial z} & 0 & 0 & \varepsilon \frac{\partial N_2}{\partial z} & \ldots & 0 & 0 & \varepsilon \frac{\partial N_8}{\partial z} \\
\varepsilon \frac{\partial N_1}{\partial y} & \varepsilon \frac{\partial N_1}{\partial x} & 0 & \varepsilon \frac{\partial N_2}{\partial y} & \ldots & \ldots & \varepsilon \frac{\partial N_8}{\partial y} & \varepsilon \frac{\partial N_8}{\partial x} & 0 & 0 \\
0 & \varepsilon \frac{\partial N_1}{\partial z} & \varepsilon \frac{\partial N_1}{\partial y} & 0 & \varepsilon \frac{\partial N_2}{\partial z} & \ldots & 0 & \varepsilon \frac{\partial N_8}{\partial z} & \varepsilon \frac{\partial N_8}{\partial y} & 0 \\
\varepsilon \frac{\partial N_1}{\partial z} & 0 & \varepsilon \frac{\partial N_1}{\partial x} & \varepsilon \frac{\partial N_2}{\partial z} & \ldots & \ldots & \varepsilon \frac{\partial N_8}{\partial z} & 0 & \varepsilon \frac{\partial N_8}{\partial x} & 0 & 0
\end{pmatrix}
\begin{pmatrix}
u_1 \\
v_2 \\
v_3 \\
v_4 \\
v_5 \\
v_6 \\
v_7 \\
v_8 \\
w_1 \\
w_2 \\
w_3 \\
w_4
\end{pmatrix}
\]

To evaluate the displacement derivatives in equation (10), we make use of the Jacobian matrix. That is,

\[
[J] = \begin{pmatrix}
\varepsilon \frac{\partial x}{\partial x} & \varepsilon \frac{\partial y}{\partial x} & \varepsilon \frac{\partial z}{\partial x} \\
\varepsilon \frac{\partial x}{\partial y} & \varepsilon \frac{\partial y}{\partial y} & \varepsilon \frac{\partial z}{\partial y} \\
\varepsilon \frac{\partial x}{\partial z} & \varepsilon \frac{\partial y}{\partial z} & \varepsilon \frac{\partial z}{\partial z}
\end{pmatrix}
\]

(11)
Substituting equations (6) into equation (11) gives,

\[
[J] = \begin{bmatrix}
\frac{\partial N_1}{\partial \xi} & \frac{\partial N_2}{\partial \xi} & \ldots & \frac{\partial N_8}{\partial \xi} \\
\frac{\partial N_1}{\partial \eta} & \frac{\partial N_2}{\partial \eta} & \ldots & \frac{\partial N_8}{\partial \eta} \\
\frac{\partial N_1}{\partial \zeta} & \frac{\partial N_2}{\partial \zeta} & \ldots & \frac{\partial N_8}{\partial \zeta}
\end{bmatrix}
\begin{bmatrix}
x_1 & y_1 & z_1 \\
x_2 & y_2 & z_2 \\
\vdots & \vdots & \vdots \\
x_8 & y_8 & z_8
\end{bmatrix}
\]

The derivatives in equation (12) are readily obtained by differentiating equations (5). This matrix applies for all elements and, thus, need only be evaluated once. Then, we can determine the Jacobian at any position once the nodal point coordinates have been specified.

It turns out that the derivatives with respect to the physical coordinates are related to the parametric coordinates as follows:

\[
\begin{bmatrix}
\frac{\partial N_1}{\partial x} & \frac{\partial N_2}{\partial x} & \ldots \\
\frac{\partial N_1}{\partial y} & \frac{\partial N_2}{\partial y} & \ldots \\
\frac{\partial N_1}{\partial z} & \frac{\partial N_2}{\partial z} & \ldots
\end{bmatrix} = [J]^{-1}
\begin{bmatrix}
\frac{\partial N_1}{\partial \xi} & \frac{\partial N_2}{\partial \xi} & \ldots \\
\frac{\partial N_1}{\partial \eta} & \frac{\partial N_2}{\partial \eta} & \ldots \\
\frac{\partial N_1}{\partial \zeta} & \frac{\partial N_2}{\partial \zeta} & \ldots
\end{bmatrix}
\]

(13)
The above matrix defines the elements of the B-matrix in equation (10). Thus, upon inverting the Jacobian matrix, the B-matrix can be readily evaluated at any point in the element.

Again we restate that our objective is to obtain the stiffness matrix, equation (4). Toward this goal we will make use of the following relation between element volumes in both coordinate systems:

\[ dV_{\text{xyz}} = |J| dV_{\xi\eta\zeta} \]  \hspace{1cm} (14)

where \(|J|\) is the determinant of the Jacobian matrix.

Then, the appropriate form of equation (4) to be evaluated is

\[ [k] = \iiint_{-1}^{1} [B]^T [D] [B] |J| d\xi d\eta d\zeta \]  \hspace{1cm} (15)

Equation (15) is evaluated numerically in the RETSCP program. The method employed is two point Gaussian integration based on the following quadrature formula:

\[ \int_{-1}^{1} f(\bar{\chi}) d\bar{\chi} = f(+0.57735027) + f(-0.57735027) \]  \hspace{1cm} (16)

Of course, the integration is carried out over three variables to evaluate equation (15). Thus, the terms in the integrand must be evaluated at eight Gauss points within the eight node box.
One key point remains to be made about the isoparametric element used in RETSCP. The element described above was based on eight linear shape functions, equations (5). The RETSCP element uses those eight functions plus the quadratic functions listed below:

\[
N_9 = 1 - \zeta^2 \\
N_{10} = 1 - \eta^2 \\
N_{11} = 1 - \zeta^2
\] (17)

Including these, the element has 33 degrees of freedom (11 functions times 3 dimensions). Thus, the quadratic terms imply a higher order element. The functions, equations (17), are not associated with any specific point in space. For this reason, they are termed nodeless variables. The nine internal variables are eliminated internally within the program by the technique described in Zienkiewicz, Reference 1. Physically this amounts to separately minimizing strain energy with respect to the variables which are independent of the surroundings (otherwise called static condensation, Reference 3).

Finally, the stiffness matrix is obtained for each isoparametric element by the above procedure. Then, the master stiffness matrix can be assembled for the entire structure.
Boundary Conditions

Once the master stiffness matrix has been assembled, the objective is to solve the governing equations subject to the appropriate boundary conditions. That is, to solve the system of equations (1), which are rewritten below:

\[
\begin{pmatrix}
F_1 \\
F_2 \\
\vdots \\
F_n
\end{pmatrix} =
\begin{pmatrix}
k_{11} & k_{12} & \cdots & \cdots & k_{1n} \\
k_{21} & k_{22} & & & \cdots \\
\vdots & \vdots & \ddots & & \vdots \\
k_{n1} & \cdots & & & k_{nn}
\end{pmatrix}
\begin{pmatrix}
\delta_1 \\
\delta_2 \\
\vdots \\
\delta_n
\end{pmatrix}
\] (18)

The stress boundary condition is automatically satisfied. Namely, forces at nodes on a free-surface are zero in the normal direction.

**Prescribed Boundary Forces:** Prescribed force values of \(P_j\) at the corresponding node are treated simply by replacing \(F_j\) by \(P_j\) in the force vector.
Prescribed Displacements: Prescribed displacement conditions are treated by modifying the force vector and stiffness matrix. Say the jth displacement is to be prescribed as $\alpha_j$. First, replace $F_j$ by $\bar{F}_j$ where

$$\bar{F}_j = F_j - \alpha k_{ji}$$  \hspace{1cm} (19)

Then, replace the jth row and column in the stiffness matrix by zero except $k_{jj}$ which is replaced by 1. This is tantamount to eliminating one equation; yet the size of the matrix is not reduced.

As an example of the above procedure, assume $u_1$ has the prescribed value $\alpha$. Then, the resulting equations are

$$\begin{bmatrix}
\alpha \\
F_2 - \alpha k_{12} \\
F_3 - \alpha k_{13} \\
\vdots \\
F_n - \alpha k_{1n}
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 & \cdots & \cdots & 0 \\
0 & k_{22} & k_{23} & \cdots & \cdots & k_{2n} \\
0 & 0 & k_{33} & \cdots & \cdots & \cdots \\
\vdots & \vdots & \vdots & \ddots & \cdots & \cdots \\
0 & 0 & 0 & \cdots & k_{nn}
\end{bmatrix}
\begin{bmatrix}
u_1 \\
u_2 \\
u_3 \\
\vdots \\
u_n
\end{bmatrix}$$  \hspace{1cm} (20)
Symmetry Condition: The symmetry condition is represented by zero displacement normal to the plane of symmetry and no restraint along the plane of symmetry (sliding boundary). The symmetry plane is often skew with respect to the physical coordinate axis. This is the case for a wedge segment with axi-symmetry. Thus, we will derive a transformation to treat skew boundary conditions.

Referring to Figure 2, the displacements in the \((x, y)\) system are \((u, v)\). The skew system \((x', y')\) has a rotation of the \(x\)-axis of magnitude \(\theta\) (positive for rotation of \(x\)-axis toward \(y\)-axis). The displacements are related as follows:

\[
\begin{bmatrix}
  u \\ v
\end{bmatrix} =
\begin{bmatrix}
  \cos \theta & -\sin \theta \\
  \sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
  u' \\ v'
\end{bmatrix} =
\begin{bmatrix} L \end{bmatrix}
\begin{bmatrix}
  u' \\ v'
\end{bmatrix}
\]

(21)

The original element properties were evaluated in the unprimed system, namely,

\[
{F} = [K]{\delta}
\]

(22)
The amount of work done is the same in both systems. That is,

$$\{F^*\}^T \{\delta^*\} = \{F\}^T \{\delta\} = \{F\}^T [L] \{\delta^*\} \quad (23)$$

or

$$\{F^*\} = [L]^T \{F\} = [L]^T [K] [L] \{\delta^*\} \quad (24)$$

Thus, we introduce the modified stiffness matrix below

$$[K^*] = [L]^T [K] [L] \quad (25)$$

If, the boundary conditions are introduced in skew coordinate directions; then, the corresponding force and displacement results are in the skew directions. The entire procedure is carried out internally within the program by multiplying
the appropriate rows and columns in the master stiffness matrix by the appropriate sin-cos terms. It goes without saying that only those nodes with skew coordinates need be treated. The final results are then transformed back into the physical coordinate systems.

Method of Solution

The set of governing equations is solved in the RETSCP program by Gaussian elimination. The master stiffness matrix is partitioned in the interest of computational efficiency. The governing equations can be written as matrix equations in terms of submatrices. For example,

$$
\begin{bmatrix}
\bar{K}_{11} & \bar{K}_{12} \\
\bar{K}_{21} & \bar{K}_{22}
\end{bmatrix}
\begin{bmatrix}
\Delta_1 \\
\Delta_2
\end{bmatrix}
= 
\begin{bmatrix}
F_1 \\
F_2
\end{bmatrix}
$$

(26)

The term $\Delta_1$ is eliminated from equation (26) to give:

$$
[K^*] \{\Delta_2\} = \{F^*\}
$$

(27)

where,

$$
[K^*] = [K_{22}] - [K_{21}] [K_{11}]^{-1} [K_{12}]
$$

(28)

$$
\{F^*\} = \{F_2\} - [K_{21}] [K_{11}]^{-1} \{F_1\}
$$

(29)
Equation (27) can be solved to give \( \{ \Delta_2 \} \) by premultiplying by the inverse matrix \([K^*]^{-1}\). Then, back substitution yields the following:

\[
\{ \Delta_1 \} = [\bar{K}_{11}]^{-1} \{ F_1 \} - [\bar{K}_{11}]^{-1} [\bar{K}_{12}] \{ \Delta_2 \} \tag{30}
\]

Alternatively, equation (27) can be partitioned and the same procedure reapplied to further reduce the system.

It should also be noted that the master stiffness is a banded matrix. This fact also leads to a simplification in the matrix manipulation. Consider the following:

\[
[K] = \begin{bmatrix}
\bar{K}_{11} & \bar{K}_{12} & 0 \\
\bar{K}^T_{12} & \bar{K}_{22} & \bar{K}_{23} \\
0 & \bar{K}^T_{32} & \bar{K}_{33}
\end{bmatrix}
\tag{31}
\]

Elimination of \( \bar{K}_{11} \) causes no change in \( \bar{K}_{23} \) or \( \bar{K}_{33} \). Thus, only \( \bar{K}_{22} \) need be modified. (See Reference 1).

**Thermal Strain Effects**

The previous development was based on elastic deformation of an isothermal structure. In this section, the method of including thermal effects is described; also, see Reference 5.
The temperature difference, referred to a stress free state, is input data for each element. Of course, a suitable average value must be used for each entire element. The free thermal growth of each element is computed. Based on the element stiffness, the nodal forces required to mechanically produce the thermal growth are determined. These forces are then added to the force vector of the entire assembly. Loads and deflections are computed as usual for the assembled structure. The stress results are adjusted by adding the fully restrained thermal stress level for each element. The result is then the actual mechanical stress state.

**Bi-Linear Plasticity**

The RETSCP program treats plastic material behavior by adjusting the material properties and iterating upon the elastic solution. This is the secant modulus procedure which was employed in many previous two dimensional finite element programs (c.f., References 6 and 7).

A complete treatment of plastic material behavior is given in Reference 8. For the purpose at hand, it is sufficient to say that total deformation theory is used; and, yielding is based on the Von Mises criteria. For each element in
the structure, the average value of the equivalent (or effective) stress is computed. That is, the average value of the following:

\[
\sigma_e = \frac{1}{2} \left[ (\sigma_x - \sigma_y)^2 + (\sigma_x - \sigma_z)^2 + (\sigma_y - \sigma_z)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2) \right]^{1/2}
\]

(32)

Then, according to the Von Mises yield criteria, yielding occurs if \( \sigma_e \) is greater than the yield stress from the uniaxial stress-strain test. For plastic behavior, equivalent stress and plastic strain are related via the uniaxial stress-strain curve as shown in Figure 3.

The RETSCP program employs a bi-linear approximation for the uniaxial stress-strain curve. The curve is defined by elastic modulus \( E \), yield stress level \( \sigma_y \), and plastic modulus \( mE \). Plastic modulus and yield can be input as functions of temperature. An example of the bi-linear stress-strain curve is shown on Figure 4.

The essence of the secant modulus formulation is as follows. First, conduct an elastic structural analysis. Compute effective stress and check each element for yielding. For elements which indicate yielding, define a new elastic modulus called the secant modulus. The secant modulus is based on the bi-linear stress-strain curve at the strain level corresponding to the elastic result; that is, \( \varepsilon_{total} \).
Figure 3. Relation between equivalent stress and equivalent plastic strain.

\[ \varepsilon = \varepsilon_p + \frac{\sigma_e}{E} \]

Figure 4. Bi-linear stress-strain curve.
Figure 5. Secant modulus plasticity iteration.

Associated with $\varepsilon_{\text{total}}$ is a bi-linear stress intercept $\sigma_{\text{new}}$. The secant modulus is defined below:

$$E_{\text{sec}} = \frac{\sigma_{\text{new}}}{\varepsilon_{\text{total}}}$$  \hspace{1cm} (33)

The secant Poisson's ratio, defined to give a consistent stress-strain relation, is as follows:

$$\nu_{\text{sec}} = \frac{1}{2} - \left(\frac{1}{2} - \nu\right)\frac{E_{\text{sec}}}{E}$$  \hspace{1cm} (34)
Now, an elastic analysis is again conducted. The stiffness matrix, however, is based on $E_{sec}$ and $\nu_{sec}$ for plastic elements and $E$ and $\nu$ for elastic elements. The entire procedure is repeated and convergence is achieved after a few iterative cycles. The process is indicated schematically in Figure 5.

Cyclic Loading

Two effects of cyclic loading must be considered. First, there is the effect of cycling on the material properties (see Reference 9). The effect of strain hardening (or softening) can be introduced in the program on a cycle by cycle basis; or, the cyclic stress-strain curve can be input.

The second effect is the result of plastic deformations during one half of the loading cycle. Upon removal of the load, residual stresses (or strains) result when plastic flow has occurred. The residuals, in fact, may be sufficiently large to also cause plastic deformation. Thus, a stress (or strain cycle) is generated.
The plastic strain components are related to the stress, effective stress, and effective plastic strain as follows:

\[
\begin{align*}
\varepsilon_{p_x} &= \frac{\varepsilon_{p}}{2\sigma_e} (2\sigma_x - \sigma_y - \sigma_z) \\
\varepsilon_{p_y} &= \frac{\varepsilon_{p}}{2\sigma_e} (2\sigma_y - \sigma_x - \sigma_z) \\
\varepsilon_{p_z} &= - (\varepsilon_{p_x} + \varepsilon_{p_y}) \\
\gamma_{xy} &= \frac{3}{2} \frac{\varepsilon_{p}}{\sigma_e} \tau_{xy} \\
\gamma_{yz} &= \frac{3}{2} \frac{\varepsilon_{p}}{\sigma_e} \tau_{yz} \\
\gamma_{xz} &= \frac{3}{2} \frac{\varepsilon_{p}}{\sigma_e} \tau_{xz}
\end{align*}
\]

(35)

For rocket engine configurations, the shear strains are relatively small. Another quantity of interest is the equivalent total strain. This value is computed from the total strain components as follows:

\[
\varepsilon_{et} = \sqrt{\frac{2}{3} [(\varepsilon_x - \varepsilon_y)^2 + (\varepsilon_x - \varepsilon_z)^2 + (\varepsilon_y - \varepsilon_z)^2 + 6(\gamma_{xy}^2 + \gamma_{xz}^2 + \gamma_{yz}^2)]}
\]

(36)

The plastic strain based on this value is then

\[
\varepsilon_p = \varepsilon_{et} - \frac{2}{3} \frac{1+v}{E} \sigma_e
\]

(37)
Equivalent total strain, in itself, has no physical significance. Within the RETSCP program, the plastic strain components and equivalent total strain are computed for each element which has yielded. The residual strain components are then provided as punch card output for successive run calculations.

The residual strains are read into the program as input data for the computation of successive loadings. The strains are combined with the thermal strains and analyzed in the same manner. That is, the loads at each nodal point required to produce the residual strain values are computed and added to the assembled load vector. This point will be emphasized by example in a later section of this document.
The RETSCP program logic is described in this section. The general logic is discussed and the program flow diagram is given. Some specific points are made concerning the subroutine details. The detailed listing of the RETSCP program is given in Appendix B.

General Logic

The general RETSCP program logic is to follow the analytical procedures outlined in the previous chapter to obtain the desired finite element results.

The computational logic is controlled by the main program RETSCP. Subroutines are called as required to perform specific calculations. An overlay structure for subroutines is employed to reduce core storage requirements. In this manner, a specific calculation is performed in a subroutine, the results are put onto tape storage (seven tape units are utilized), and core storage locations occupied by that subroutine are released for reuse.

The above core storage management procedures allowed the RETSCP program size (number of elements) to be greatly enlarged from the original ISOPAR program size. In fact, the program was enlarged to fully utilize the available core storage of the IBM 7094 computer.
The data is read into RETSCP from punch cards. For each element, the elastic properties and stiffness matrix are computed (FEM3D). The master stiffness matrix is formed and the boundary values are incorporated (MATRIX). The system of equation is solved by Gaussian elimination (SOLVE), and the resulting force and displacement values at each nodal point are printed out. The elastic stress components and equivalent stress values are computed for each element (STRESS). Now, if the equivalent stress exceeds the yield stress a plastic iteration is performed. The iteration consists of: first, compute the values of secant modulus and Poisson's ratio (STRESS); then, use these values to recompute the elastic properties and stiffness matrix for each element (FEM3D); finally, complete the solution steps above. When the required number of iterations have been performed, the stress results are printed and the residual plastic strains and current secant modulus values are punched on cards to allow cycling and restart.

The flow diagram representing the above steps is given in the following section.
Compute isoparametric data at each Gauss point (GP)

\[
\begin{bmatrix}
\frac{\partial N_1}{\partial \xi} & \cdots & \frac{\partial N_{11}}{\partial \xi} \\
\frac{\partial N_1}{\partial \eta} & \cdots & \frac{\partial N_{11}}{\partial \eta} \\
\frac{\partial N_1}{\partial \zeta} & \cdots & \frac{\partial N_{11}}{\partial \zeta}
\end{bmatrix}
\]

read in data and for each element call FEM3D

\[
D(6,6) = \frac{E(1-\nu)}{(1-2\nu)(1+\nu)}
\]

\[
\begin{bmatrix}
1 & \frac{\nu}{1-\nu} & \frac{\nu}{1-\nu} & 0 & 0 & 0 \\
\frac{\nu}{1-\nu} & 1 & \frac{\nu}{1-\nu} & 0 & 0 & 0 \\
\frac{\nu}{1-\nu} & \frac{\nu}{1-\nu} & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1-2\nu & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1-2\nu}{2(1-\nu)} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1-2\nu}{2(1-\nu)}
\end{bmatrix}
\]

\[\varepsilon_0 = a \Delta T\]
\[\delta_{thx} = \varepsilon_0 L_x\]
\[\sigma_0 = D\varepsilon_0\]

compute Equation (12) \[\mathcal{J} p\]
Set up stress matrix for each GP

\[ A (6, 33) = DB \]

Eliminate internal nodes

\[(C7)_{GP} = C7 (6, 24)\]

Compute stiffness matrix

\[ C(24, 24) = [K]_{GP} \]

\[ F_{th} = C\delta_{th} \]

Use linear interpolation to get stress matrix at center of each face from those at GP, DBA,(6,24) each face.
Set up stiffness matrix for each partition
\[
\begin{bmatrix}
    ST & ST \\
    ST & ST \\
    ST & ST \\
\end{bmatrix}
\]

Set up load vector
\[ F = F + F_{th} \]

Insert boundary values
Equation (20)
\[
\begin{bmatrix}
    0 \\
    F_2 - k\delta_1 \\
    F_3 - k\delta_2
\end{bmatrix} =
\begin{bmatrix}
    1 & 0 & 0 \\
    0 & ST & 0 \\
    0 & \cdots & \cdots
\end{bmatrix}
\begin{bmatrix}
    \delta
\end{bmatrix}
\]

SOLVE
Gaussian elimination--Equation (26)
\[
\begin{bmatrix}
    F_1 \\
    F_2
\end{bmatrix} =
\begin{bmatrix}
    \bar{k}_{11} & \bar{k}_{12} \\
    \bar{k}_{21} & \bar{k}_{22}
\end{bmatrix}
\begin{bmatrix}
    \delta_1 \\
    \delta_2
\end{bmatrix}
\]

result
\[
\begin{bmatrix}
    u_1 \\
    v_1 \\
    w_1 \\
    \vdots \\
    w_{\text{last}}
\end{bmatrix}
\]
\[ \sigma_e = \frac{1}{\sqrt{2}} \left[ \left( \sigma_x - \sigma_y \right)^2 + \left( \sigma_x - \sigma_z \right)^2 + \left( \sigma_y - \sigma_z \right)^2 + 6 \left( \tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2 \right) \right]^{\frac{1}{2}} \]

Elastic solution

Plastic iteration

Punch residual strains & secant values

Print results

\[ \sigma = D\varepsilon \]

END
Overlay structure

<table>
<thead>
<tr>
<th>RETSCP</th>
<th>MATM</th>
<th>ZEROM</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISOPAR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>READIN</td>
<td>FEM3D</td>
<td>MATM</td>
</tr>
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<td>MTINV</td>
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<tr>
<td>FACE</td>
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<td>SOLVE</td>
</tr>
<tr>
<td>STRESS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MTIN</td>
<td>MATMS</td>
<td>MATTMS</td>
</tr>
</tbody>
</table>

Location 0

24877 Unused Core

27067

COMMON

32767
The User’s Manual section contains all instructions necessary to prepare data for the RETSCP program. Modeling of the structure and preparation of the required input data cards are described in detail. Some comments about program output are included and sample case results are given.

**Input**

The input for RETSCP consists of punch card data which defines the structural geometry, boundary conditions, and materials properties.

The structure is divided into box shaped elements which are connected by corner nodes. The following procedure for locating nodes and elements is quoted directly from Reference 2.

(a) The 3-dimensional solid is divided by a number of non-intersecting surfaces. (Much like slicing a loaf of bread.) The surfaces need not be flat or parallel, though they frequently are.

(b) Each such surface is further subdivided by a number of non-intersecting lines. (Much like the lines on a piece of paper.) The lines need not be straight or parallel, though they frequently are.
(c) Each such line is further subdivided into a number of divisions to give the nodal points. Nodal points are numbered in sequence along each line, line by line, and surface by surface.

(d) The nodes on each surface are said to belong to the same partition. Partitions are numbered in sequence from one side of the solid to the other. (The first partition contains the first nodal points.)

(e) The number of divisions in adjacent lines can vary to provide for grading of the mesh.

(f) 8-noded box elements are formed between adjacent surfaces. They are numbered sequentially between each pair of adjacent surfaces. The numbering continues for successive adjacent surfaces in turn going from one side to the other of the solid structure. (Although in theory the boxes need not be "square", it is recommended that they be as "square" as the shape of the structure permits.) The first element has nodes in the first partition.

The detailed data cards required to execute the RETSCP program are listed below. Examples of the data preparation will be given in a subsequent section.
### Card Group 1: Identification Card

Number of Cards: 1  
Format: (11I4)

1. Number of partitions (9 maximum)  
2. Number of nodes (225 maximum/25 per partition maximum)  
3. Number of elements (96 maximum/32 per partition maximum)  
4. Number of prescribed displacement nodes (225 maximum)  
5. Number of materials (5 maximum)  
6. Number of degrees of freedom at each node (always 3)  
7. Number of nodes with applied loads (225 maximum)  
8. Starting plasticity iteration number: 1, no iterations or 2, iteration starting from elastic solution or n, iteration starting from punch card input based on iteration number (n-1).  
9. Final plasticity iteration number  
10. Punch output code for successive iterations: 0, no punch output or 1, provide punch output  
11. Residual stress code: 0, no residual strains input or 1, read residual strain card data
### Card Group 2: Coordinate Data

<table>
<thead>
<tr>
<th>Number of Cards:</th>
<th>1 per node in order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Format:</td>
<td>3F16.4</td>
</tr>
</tbody>
</table>

1. x-coordinate (inches)
2. y-coordinate (inches)
3. z-coordinate (inches)

### Card Group 3: Node Number Card

<table>
<thead>
<tr>
<th>Number of Cards:</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Format:</td>
<td>J4</td>
</tr>
</tbody>
</table>

1. Number of nodes

### Card Group 4: Partition Identification

<table>
<thead>
<tr>
<th>Number of Cards:</th>
<th>1 per partition in order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Format:</td>
<td>4I4</td>
</tr>
</tbody>
</table>

1. First element number in partition
2. Last element number in partition
3. First node number in partition
4. Last node number in partition
<table>
<thead>
<tr>
<th>Card Group 5: Materials Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Cards: 2 cards per material</td>
</tr>
<tr>
<td>Format: first card 3F16.4</td>
</tr>
<tr>
<td>second card 4F16.4</td>
</tr>
</tbody>
</table>

Card 1: 1. Young's modulus (psi)
2. Poisson's ratio
3. Coefficient of thermal expansion times $10^6$ (in/in/$^\circ$F)

Card 2: 1. Yield stress at reference temperature (psi), $\tau_0$
2. Yield temperature gradient (psi/$^\circ$F), $\lambda_1$
3. Plastic modulus times $10^3$ at reference temperature, $m_0$
4. Plastic modulus temperature gradient times $10^6$ ($1/\circ$F), $\lambda_2$

Note, Card 2 values above are based on the following equations:

\[
\sigma_y = \sigma_0 - \lambda_1 T \quad (38)
\]
\[
m = m_0 \times 10^{-3} - \lambda_2 T \times 10^{-6} \quad (39)
\]

The value of $T$ must correspond to the reference value on Card Group 7.
Card Group 6: Prestrain Data (can be omitted)

<table>
<thead>
<tr>
<th>Number of Cards: 1 per element</th>
</tr>
</thead>
</table>

Format: I6, 3F15.8

1. Element Number
2. Prestrain in x-direction
3. Prestrain in y-direction
4. Prestrain in z-direction

Card Group 7: Element Identification

<table>
<thead>
<tr>
<th>Number of Cards: 1 per element in order</th>
</tr>
</thead>
</table>

Format: 914, F10.3

1.-8. Eight nodal point numbers
9. Material Number
10. Temperature excess over reference value

The eight nodal numbers referred to above are obtained for each element:

(a) Pick a face to be called the top;
(b) Look down through the top to the bottom face;
(c) List node numbers clockwise around the bottom face (4 values);
(d) List coincident node numbers clockwise around the top face (4 values) starting with the node above the first node on the bottom face.
### Card Group 8. Element Number Card

- **Number of Cards:** 1
- **Format:** 14

1. **Number of elements**

### Card Group 9: Displacement Boundary Conditions

- **Number of Cards:** 1 for each node with prescribed displacement
- **Format:** 4I4, 4F16.8

1. **Nodal number**
2. 0 if x-displacement is prescribed; 1 if not
3. 0 if y-displacement is prescribed; 1 if not
4. 0 if z-displacement is prescribed; 1 if not
5. value of x-displacement (inches)
6. value of y-displacement (inches)
7. value of z-displacement (inches)
8. angle of rotation of x-axis toward original y-axis (deg.)

Sufficient displacement boundary condition data must be given to fix the body in space.
### Card Group 10: Force Boundary Conditions

**Number of Cards:** 1 per node with prescribed force  
**Format:** I4, 4F16.4

1. Nodal number  
2. x-force (pounds)  
3. y-force (pounds)  
4. z-force (pounds)

### Card Group 11: Iteration Data (can be omitted)

**Number of Cards:** 1 per element  
**Format:** I6, F20.2, F10.4

1. Element number  
2. Secant Young's modulus (psi)  
3. Secant Poisson's ratio
Output

The RETSCP output consists of punched cards and printed data.

Punch cards are provided in conjunction with plastic strain analysis. If requested per Card Group 1, the secant modulus and secant Poisson's ratio are punched after the final iteration of that run. This allows the iterative process to be continued without recomputing the initial iterations. For plasticity analysis, the residual plastic strain values are automatically punched for the final iteration of that run. This data can be input directly for subsequent strain cycling calculations (Card Group 6). Secant values and residual strains are automatically printed at the end of the printed output when the above cards are punched.

The printed output starts with a list of the input data. Note, that the formats may be slightly different from the input. For example, Cards 1 and 2 in Group 5 are printed in reverse order (Card 2, then Card 1). Also Card Groups 3 and 8 are omitted. The input data is printed for checking and debug purposes.
The forces and displacements at each nodal point are listed. Values are given in the rotated and rectangular coordinate systems. The nodal force data output was incorporated to allow numerical evaluation of the net section force (such as rocket engine thrust force).

Detailed stress-strain data is given for each element. The stress and strain components at the center of each element face are printed as well as the coordinates of the face center point. The average stress components for each element are also listed. The effective stress which is computed in the program is based on the average stress components. The yield check data are then summarized in the output. This summary consists of effective stress, yield stress, total strain, plastic strain, and secant values for each element.

If plasticity iterations are performed; then all of the above output data is given for each iteration. Samples of output data will be presented as part of the next section.
Sample Case Results

Three sample case solutions are presented in this section. The cases were selected to demonstrate the capabilities of the RETSCP program by successively introducing new concepts. Elastic behavior of an isothermal structure is treated first. Then, sliding boundaries and plastic strains are introduced. Finally, thermal loads and strain cycling are illustrated.

Cantilever Beam: Consider the cantilever beam with concentrated tip load shown in Figure 6. The material is steel and the tip load is sufficiently low that elastic behavior is guaranteed. The beam is divided into four elements as shown in Figure 6. The input data and computer output results are presented in Appendix C. The bending stress at the outer fiber is compared with the exact solution in Figure 7. The deflection of the nodal points normal to the neutral axis ($\delta_Z$) is compared with the exact result in Figure 8. This example illustrates that excellent results can be achieved with models having few elements.
Figure 6. Cantilever beam sample case configuration

Load: $P_z = 0.5$ lbs. (2.224 Newton)
Size: $L_x = 1.0$ in. (2.54 cm)
$L_y = 4.0$ in. (10.16 cm)
$L_z = 1.0$ in. (2.54 cm)
Matl.: $E = 30 \times 10^6$ psi (20.68 $\times 10^6$ N/cm$^2$)
Bending stress, \([\sigma_y]_z = -0.5 \text{ in} (-1.27 \text{ cm})\)

Figure 7. Outer fiber bending stress for cantilever beam example.
Figure 8. Nodal point deflection ($\delta_z$) for cantilever beam example.
Thick Wall Cylinder: The second example case is the stress distribution in a thick wall cylinder. Due to the symmetry, the structure can be modeled by the thin wedge segment shown in Figure 9. The boundary condition, with pressure load on the inner radius, is zero displacement in the tangential direction and freedom to move in the radial direction (symmetry condition). The finite element elastic stress results for the configuration shown in Figure 9 are compared with the exact plane-strain thick wall cylinder solution in Figure 10.

If the stress conditions in the cylinder are sufficiently large, yielding will occur. A closed form solution was obtained by Mendleson (Reference 8) based on the Tresca yield criteria (i.e., $\sigma_0 - \sigma_r > 0$). Yielding under conditions of internal pressure will occur from the inner wall to some radius $r = r_p = \rho_c$. The plastic and elastic stress distributions, according to Reference 8, based on bi-linear material behavior are as follows:

\[
\frac{\sigma_r}{\sigma_0} = \frac{C_2}{\rho_2} \left[ C_1 (\rho^2 - 1) - \frac{p}{\sigma_0} \right] + C_3 \left( \ln \rho - \frac{p}{\sigma_0} \right) \quad \left\{ \begin{array}{l} \rho \leq \rho_c \\ \rho > \rho_c \end{array} \right. 
\]

\[
\frac{\sigma_\theta}{\sigma_0} = \frac{C_2}{\rho_2} \left[ C_1 (\rho^2 + 1) + \frac{p}{\sigma_0} \right] + C_3 \left( 1 + \ln \rho - \frac{p}{\sigma_0} \right) 
\]
\[
\frac{\sigma_r}{\sigma_0} = C_4 \left[ \ln \rho_c - \frac{1 - \beta_c^2}{2} \frac{p}{\sigma_0} \right] - \frac{p}{\sigma_0 \rho^2} + C_1 \left( 1 - \frac{\rho^2}{\beta_c^2} \right) \rho > \rho_c
\]

\[
\frac{\sigma_\theta}{\sigma_0} = C_4 \left[ \ln \rho_c - \frac{1 - \beta_c^2}{2} \frac{p}{\sigma_0} \right] + \frac{p}{\sigma_0 \rho^2} + C_1 \left( \frac{1}{\rho^2} \right) \rho > \rho_c
\] (41)

\[
\sigma_z = \nu (\sigma_r + \sigma_\theta) \quad \text{all } \rho
\] (42)

where,

\[
\begin{align*}
C_1 &= \frac{\rho_c^2}{2} \frac{p}{\sigma_0}, \quad C_2 = \frac{m(1 - \nu^2)}{(1 - \nu^2)m} \\
C_3 &= \frac{1 - m}{1 - \nu^2 m}, \quad C_4 = \frac{1 - m}{(1 - \nu^2)m} 
\end{align*}
\] (43)

The quantity \( \beta \) is \( R_o/R_i \) and the value of \( \rho_c \) is computed from Equation (44) below:

\[
\frac{p}{\sigma_0} = \frac{\beta^2 - 1}{\beta^2} C_2 \left[ \frac{\rho_c^2}{2} + C_3 \left( \ln \rho_c - \frac{1 - \beta_c^2}{2 \beta_c^2} \right) \right]
\] (44)
Stress values for the configuration shown in Figure 9 were obtained by the finite element method and by closed form solution with results shown in Figure 11.

The difference between the two sets of results is due to the different yield criteria employed. Recall that RETSCP uses the Von Mises yield criteria; whereas, the closed form solution is based on the Tresca criteria.

Specific input data for the thick wall cylinder example is given in Appendix D along with the computed results. Note, that the elastic solution is generated as a by-product of the plastic analysis (first iteration). Summary data only is given for iteration numbers 2, 3, 4, and 5.
Figure 9. Configuration for thick wall cylinder example.
Figure 10. Elastic stress distribution in thick wall cylinder.
Figure 11. Stress distribution in plastic thick wall cylinder.
Heated Element Cycling: As a final example we consider a single cubic element which is cycled between two temperature limits. Two opposite faces of the cube are fixed. The temperature range is sufficiently great that the element stress exceeds the yield stress. Thus, this is an example of plastic thermal strain cycling.

The simple finite element model is shown in Figure 1. A sample of the data input and output are given in Appendix E. The corresponding stress-strain loop is depicted graphically in Figure 13.

As the material is cooled from its stress free state, elastic stresses are built up until the yield point is reached (point "a" in Figure 13). Continued cooling causes plastic strain to the level indicated by point "b". The total strain at "b" corresponds to the cooling thermal strain. The point "c" corresponds to the plastic strain residual due to cooling.

The point "c" is the starting point for the heating cycle. As the material is heated, elastic changes occur along the line c-d. Plastic changes due to heating occur along the line d-e-f. Point "e" corresponds to the residual stress state at the original reference temperature. Thus, the plastic strain resulting from the cooling half cycle is the prescribed displacement for a subsequent analysis.
Upon heating the cube, we follow the plastic strain line d-e to point "f". The plastic strain at "g" then gives rise to the residual stress state "i" as the material returns to its original temperature.

For multi-element structures, the residual stress-strain levels during plastic cycling are determined by inputing the plastic strain values of all elements and solving the residual stress equations for the assembly.
Figure 12. Configuration for heated element cycling example.

\( \sigma_0 = 5600 \text{ psi} \ (3,861 \text{ N/cm}^2) \)

\( m = 4.04 \times 10^{-3} \)

\( E = 17.65 \times 10^6 \text{ psi} \ (12.17 \times 10^6 \text{ N/cm}^2) \)

\( \nu = .33 \)

\( \alpha = 9.8 \times 10^{-6} \text{ in/in/}^\circ\text{F} \ (17.7 \times 10^{-6} \text{ cm/cm/}^\circ\text{C}) \)

\( \Delta T_{\text{hot}} = +200^\circ\text{F} \ (+111^\circ\text{C}) \)

\( \Delta T_{\text{cold}} = -200^\circ\text{F} \ (-111^\circ\text{C}) \)
Figure 13. Stress-strain loop for heated element cycling example.
APPENDIX A--SYMBOLS

B  Matrix of differential functions, Eq. (2), (10)
D  Elastic matrix, Eq. (7)
E  Modulus of Elasticity
E_{sec}  Secant modulus, Eq. (33)
F_j  Force at nodal point j
\overline{F}_j  Modified force vector, Eq. (19)
F^*  Equivalent force vector, Eq. (27)
     (in Gaussian elimination method)
F'  Force vector in skew coordinate system
J  Jacobian matrix, Eq. (11)
K  Master stiffness matrix, Eq. (1)
K^*  Equivalent stiffness matrix, Eq. (27)
     (in Gaussian elimination method)
\overline{K}  Partitioned stiffness matrix elements
k_{ji}  Element stiffness, Eq. (18)
L  Length, or transformation matrix for skew
    coordinate system, Eq. (21)
m  Plastic modulus ratio
m_0  Plastic modulus ratio at reference temperature
    times 10^3
N_n  Parametric functions at nodal point n, Eq. (5)
P  Load
p  Pressure
APPENDIX A--SYMBOLS, Cont'd

\( R_i \) Inner radius
\( R_o \) Outer radius
\( r \) Arbitrary radius
\( r_c \) Radius at yield surface
\( T \) Temperature
\( u_n \) Displacement of nodal point \( n \) in \( x \)-direction
\( u'_n \) Displacement of nodal point \( n \) in \( x' \)-direction
\( dV \) Differential element of volume
\( v_n \) Displacement of nodal point \( n \) in \( y \)-direction
\( v'_n \) Displacement of nodal point \( n \) in \( y' \)-direction
\( w_n \) Displacement of nodal point \( n \) in \( z \)-direction
\( x, y, z \) Cartesian coordinate system
\( x', y' \) Skew coordinate system

(rotated by angle \( \theta \) from \( x-y \))
APPENDIX A--SYMBOLS, Cont'd

α  Thermal expansion coefficient
α_j  jth prescribed displacement, Eq. (19)
β  Ratio R_o/R_i, Eq. (44)
β_c  Ratio R_o/r_c
γ_{xy}, γ_{yz}, γ_{xz}  Shear strains components, Eq. (8)
γ_{xy}^P  Plastic shear strain, Eq. (35)
Δ  Displacement in the partitioned matrix, Eq. (26)
δ  Displacement matrix, Eq. (1), (2)
δ'  Displacement in the skew coordinate system, Eq. (23)
δ_n  Displacement at the nodal point n, Eq. (18)
e  Strain matrix, Eq. (2)
e_p  Plastic strain, Fig. 3
ε_{total}  Total strain, Eq. (33)
e_{et}  Equivalent total strain, Eq. (36)
e_{x}^P, e_{y}^P, e_{z}^P  Components of plastic strain in x, y, z directions
ξ, n, ξ  Parametric coordinate system, Fig. 1
θ  Angle of rotation of x-axis into the x'-axis in the skew coordinate system
ν  Poisson's ratio
ν_{sec}  Secant Poisson's ratio, Eq. (34)
σ  Stress
APPENDIX A--SYMBOLS, Cont'd.

\( \sigma_e \)  
Effective stress, Eq. (32)

\( \sigma_y \)  
Yield stress

\( \sigma_{\text{new}} \)  
New stress, Eq. (33)

\( \sigma_0 \)  
Yield stress at reference temperature, Eq. (40)

\( \sigma_r \)  
Radial stress component

\( \sigma_\theta \)  
Tangential stress component

\( \rho \)  
Dimensionless ratio \( \frac{r}{R_i} \)

\( \rho_c \)  
r/\( R_i \) where yield occurs at \( r \)

\( \tau_{xy} \)  
Shear stress component, Eq. (35)

\( \lambda_1 \)  
Yield temperature gradient

\( \lambda_2 \)  
Plastic modulus temperature gradient times \( 10^6 \) (1/°F)

Special Symbols:

\([ \_)\{ \)  
Matrices

\([ ]^T\)  
Transposed matrix form

\( |J| \)  
Determinant value of J matrix

\([ ]^{-1}\)  
Inverse matrix
APPENDIX B--RETSCL PROGRAM LISTING
C RV1(1,2) = PRESCRIBED VALUE OF DISPLACEMENT IN Y DIRECTION
C RV1(1,3) = PRESCRIBED VALUE OF DISPLACEMENT IN Z DIRECTION
C NSTART = FIRST NODE IN EACH PARTITION
C NEND = LAST NODE IN EACH PARTITION
C NFIRST = FIRST NODEAL POINT IN EACH PARTITION
C NLAST = LAST NODEAL POINT IN EACH PARTITION
C Y-LOADS IN X, Y AND Z DIRECTIONS
C E-FOURTH MECRIS
C P1-DISPLACEMENT RATIO
C
C COMMON (NPART,NLIN,NLEM,NNODE,NNY,NENF,NFIC,NIC)
C (NENF,NSTART,NEND,NFIRST,NLAST,NCY)
C (NFIC,NFIRST,NEND,NCY,NCY,NCY,NCY,NCY,NCY,NCY,NCY,NCY,NCY,NCY)
C (NITRO,NTSU,NDP,F1225,AV(225),AV(225),AV(225),AV(225),AV(225))
C (JN,JS,SE,2L1961,EMPL,PLM1225,PLM1225,PL1961)
C DIMENSION XE(6,3),XE(18)

55

VITX=1
REWIN 1
REWIN 2
REWIN 3
REWIN 4
REWIN 5
CALL ISOPAR
40 REWIN 2
REWIN 3
REWIN 4
CALL READIN
REWIN 2
REWIN 3
REWIN 4
CALL FACH
REWIN 4
CALL MATH
REWIN 3
REWIN 4

C SOLUTION OF TRIAGONAL MATRICES
C
C CALL SCLEI
REWIN 3

C CALCULATION OF STRESSES
C
C CALL STRESS
IF (NITK) 100,101
60 IF (NITK) 5000,5001
65 DO 75 KS=1,NLEM
READ (5,99) NXYNS,FIGCF,NSCF
75 WRITE (6,99) NXYNS,FIGCF,NSCF
80 DO 95 KS=1,NXYNS
REWIN 3
REWIN 4
REWIN 5
REWIN 6
REWIN 7
REWIN 8
REWIN 9
REWIN 10
DO 90 K=L+1,NLEM
90 NS = K
*
JJ = MOD(J, 11)
MOD(I) = JJ
DO 85 I = 1, J:
85 X(I, I) = (JJ, IX)
90 CALL FF = F(I, X, SEC(LK), E, SEE(LK), MUD(LK), A2L(LK), J, 4, LK, E, PL)
REWIND 2
REWIND 4
CALL FACT
REWIND 4
CALL MATEX
REWIND 4
CALL SCLVE
REWIND 2
CALL STRESS
95 CONTINUE
10 IF (MIP) 10, 100, 52
96 CONTINUE
DJ 50 NA = 1, NCE:
PUNCH 55, M4, SEC(NM), WSCC(NM)
98 WRITE (4, 99) N4, SEE(NM), WSCC(NM)
94 FORMAT (16, F20.2, F10.4)
100 STOP
END
SUBROUTINE ISOPAR

COMMON APAR, NPCIN, AL, LC, M, NBGNH, NVM, NFRE, NCONC,
LINE, NCONTS, NST, NEND, NFRST, NLAST, NLYNS, NCY
2, OUTL(175), SYLDO(96), EMD(96), NSE(96), EM(96), EWESEC(96)
3, NIT, NTS, DP, NF, 225, BV(225), AM(225), 31, XI(1), 1(225), X(225, 3)
4, NOX(96), R(1), A(96), T(96), ALPHA(225), EPL(96, 3)
DIMENSIONS A(18, 31), ANX(18, 31), APX(18, 31), AJN(18, 11, 3)

30 CONTINUE
GAUSS = .57735C26
DO 10 K = 1, 4
   DO 10 L = 1, 3
10 A(K, L) = CAUSS
   A(K, L) = GAUSS
11 A(K+1, 2) = A(K, 1)
   A(K+1, 1) = A(K, 2)
12 A(K+2, 2) = A(K, 3)
   A(K+2, 1) = A(K, 3)
   A(K+3, 1) = A(K, L)
   A(K+3, 0) = A(K, L)
60 DO 14 K = 1, 8
   A(K, 1) = 0.125*A(MX(K, 2) - AMX(K, 3))
   A(K, 2) = 0.125*APX(K, 2) - APX(K, 3)
   A(K, 3) = 0.125*APX(K, 2) - APX(K, 3)
   A(K, 4) = 0.125*APX(K, 2) - APX(K, 3)
   A(K, 5) = 0.125*APX(K, 2) - APX(K, 3)
   A(K, 6) = 0.125*APX(K, 2) - APX(K, 3)
   A(K, 7) = 0.125*APX(K, 2) - APX(K, 3)
   A(K, 8) = 0.125*APX(K, 2) - APX(K, 3)
14 DO 15 K = 1, 8
   A(K, 9) = -2.0*A(K, 1)
   A(K, 10) = 0.0
XSORAR  H PRICE

XSORAR  -  CFN  SOURCE STATEMENT  -  IPN(S)  -

AJN(K, 11, 1) = 0.0
AJN(K, 5, 2) = 0.0
AJN(K, 10, 3) = -2.0A(K, 2)
AJN(K, 11, 2) = 0.0
AJN(K, 5, 3) = 0.0
AJN(K, 10, 3) = 0.0
AJN(K, 11, 3) = -2.0A(K, 3)

15 CONTINUE
WRITE(11) ((AJJ(K, L, M), K=1, 8), L=1, 11), M=1, 3)
RETURN
END
SUBROUTINE READ

CREADIN READ DATA AND COMPUTING STIFFNESS
CREADIN S LEVY JUNE 5, 1971

COMMON NPART, NPOIN, NELM, NBOUND, NNM, NFRAC, NCNGC,
NPOIN, NSTART(I), NEND(I), NFIRST(I), NLAST(I), NINES, NCY
2, JTH17(175), SYLD(96), EM(96), SEC(96), EMOD(96), EM(96), ESEC(96)
3, NITX, NITY, NIT, NDP, NF225, BV(225), UI(3225), MB(225), M2(225, 3)
4, NODX(50, 81), A21(96), TEP(56), ALPH(225), EPL(96, 3)
DIMENSION NRO(I), E(1), P1(1), X(8, 3), A1(1), S1(4), S1(4, 52, 4), E1(1), E(2) 16
10 FORMAT (1111)
   READ (5, 10) NPART, NPOIN, NELM, NBOUND, NNM, NFRAC, NCNGC, NITX, NITY, NIT, NDP
   !, NCY
11 FORMAT (5, 10) WRITE (6, 11) NPART, NPOIN, NELM, NBOUND, NNM, NFRAC, NCNGC, NITX, NITY, NIT, NDP
   !, NCY
14 DO 30 I = 1, NPOIN
   READ (5, 35) (X(I, J), J = 1, 3)
30 WRITE (6, 37) (X(I, J), J = 1, 3)
35 FORMAT (14, 3F16.4)
37 FORMAT (14, 3F16.4)
38 FORMAT (4F16.4)
39 FORMAT (14, 4F16.4)
READ (5, 1) NCARD
IF (NCARD = NPOIN) 110, 111, 112
110 STOP
111 CONTINUE
   NO 60 J = 1, NPART
   READ (5, 10) NSTART(I), NEND(I), NFIRST(I), NLAST(I)
60 WRITE (6, 10) NSTART(I), NEND(I), NFIRST(I), NLAST(I)
   NO 64 I = 1, NNM
   READ (5, 38) S1(I), S2(I), CML(I), C2(I)
   WRITE (6, 39) I, S1(I), S2(I), CML(I), C2(I)
64 WRITE (6, 39) I, S1(I), S2(I), CML(I), C2(I)
IF (NCY = 0) 200, 201, 202
200 CONTINUE
   NO 250 J = 1, NELM
   READ (5, 260) IX, EPL(I, 1), EPL(I, 2), EPL(I, 3)
250 WRITE (6, 260) IX, EPL(I, 1), EPL(I, 2), EPL(I, 3)
260 FORMAT (16, 3F15.8)
201 CONTINUE
24 DO 85 J = 1, NELM
   READ (5, 11) (NOD(J), J = 1, 8), NCP, TEMPLK
   WRITE (6, 11) (NOD(J), J = 1, 8), NCP, TEMPLK
85 NOD = 1, 8
JJ = NOD(I)
NOD = (K, I = 1, NELM)
NO 85 IX = 1, 3
85 XL = X(J, IX) = X(J, IX)
A21(LK) = ALL(NCP)
CALL FEMP30 (X5, E1(NCP), PL(NCP), NO, LK, ALL(NCP), CML(LK), EPL)
117
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XREAD  ENF SOURCE STATEMENT  IFN(S) -

SYNL(IK)=S(INEP)-S2(INEP)  T=Z(LK)
FNLK)=0014 M1(INEP)-0JJO01 E2(NLP)  T=WH(LK)
EMDL(IK)=E1(INEP)
ESEC(LK)=EMDL(LK)
EFLK)=P1NEP)

DO 50 I=1,NAOUN
READ (5,66) VI,J1,VA(J1),J=1,3,ALPHA(J1)
WRITE (5,66) VI,J1,NA(J1),J=1,3,ALPHA(J1)
FORMAT (414,1F16.8)

CALL ZEROM(U,3,225)
IF (INCCKC) 1,1,2
CONTINUE
2 CONTINUE
DO 69 I=1,NCUNC
READ (5,37)K,U(1,K),U(2,K),U(3,K)
WRITE (6,37)K,U(1,K),U(2,K),U(3,K)
CONTINUE
RETURN
END
SIEFTC XEM3C DECK

SUBROUTINE FEM3D(X,E1,PRI,NONE,LK,ALT,TEMX,EP)
C
CFEM3D     FEM3D ISO-PARAMETRIC, S. LEVY JUNE 4, 1971
             AFTER CLough
C
C X CONTAINS COORDINATES OF 8 NODES AT THE CORNERS OF THE ELEMENT.
C NODES 5 TO 8 GO CLOCKWISE WHEN LOOKING DOWN ON THE BOX TOP.
C NODES 1 TO 4 ARE ON THE BOTTOM BELOW 5 TO 8 RESPECTIVELY.
C E1 MODULUS
C PRI POISSON'S RATIO
C C STIFFNESS MATRIX
C
DIMENSION CC(33,33),C(24,21),X(8,3),P(6,6),9(6,33),
     IA(6,33),NODE(8),DZA(3,31),TP(3,11),AJM(3,11,8),
     ECM(33,23),C49(9,9),C51(9,241),C6(9,31),C7(6,24)
3.0/TP(241,TP(241),SNUT(61),PSNUT(61),EP(96,3)
REWNC 1
REWNC 2

NOW TO GET THE D MATRIX.

CALL ZEROM(D,5,6)
CALL ZEROM(EP5NUT,1,6)
CALL ZEROM(SNUT,1,6)
EPS=AIL*TEMX=.000001
EPSNUT(1)=EPS +EP(LK,1)*.01
EPSNUT(2)=EPS +EP(LK,2)*.01
EPSNUT(3)=EPS +EP(LK,3)*.01
TA=1.*C-PP1
TP=TA-PC1
TC=E1*TA/(TP*1.0*PP1)
D111=TC
D113=TC*PP1/TA
D131=C11(1,3)
D121=C11(1,3)
D123=C11(1,3)
D133=C11(1,3)
D211=C1(1,1)
D213=C1(1,3)
D231=C1(1,3)
D233=C1(1,3)
D311=C1(1,1)
D313=C1(1,3)
D321=C1(1,3)
D323=C1(1,3)
D331=C1(1,1)
D333=C1(1,3)
WRITE (5) (ID(I,J),I=1,6),J=1,6),1*SNUT(J),J=1,61
CALL ZEROM(C3,33,33)
300 FEAM(31)((AJM(L,K,J),J=1,8),K=1,11),L=1,3)
ON 2JO NGAUSS=1,9
5 CONTINUE
CALL MATM(AJM(1,1,NGAUSS),X,DZA,3,8,3)
4 CONTINUE

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CALL MATINV(C49, DTK) 49
3 CONTINUE
CALL MATMID(A, AJM(1:1, 1:1), APJ, TP, J, 31)

C HOW TO GET THE H MATRIX

202 CONTINUE
CALL ZERIM (R, 6, 32)
DO 413 J = 1, 11
IF (J, J.EQ.8) K = J + 2
IF (J, J.GT.1) K = J - 5
A(L, 3K + 1) = TP (I, J)
B(3, 3K + 2) = TP (2, J)
B(3, 3K + 3) = TP (3, J)
B(4, 3K + 1) = TP (2, J)
B(4, 3K + 2) = TP (1, J)
B(5, 3K + 2) = TP (3, J)
B(5, 3K + 3) = TP (2, J)
A(6, 3K + 1) = TP (3, J)
413 B(I, J) = TP (I, J)
20 CONTINUE

C HOW WE FORM THE STIFFNESS MATRIX C

CALL MATM(D, A, AP, 6, 6, 33)
WRITE (2) (A(I, J), I = 1, 6, J = 1, 33)
126 CALL MATM (A, ACC, 32, 6, 33)
DO 40 J = 1, 33
DC 40 K = 1, 33
40 C(I, J, K) = C(I, J, K) + ACC (I, J, K) * DTK

100 1 CONTINUE
200 CONTINUE
DO 100 K = 1, 8
100 BACKSPACE 2
DO 414 K = 1, 9
DO 414 J = 1, 9
414 C(I, J, K) = C(I, J, K)

1002 CONTINUE
CALL MTDV(C49, DTK)
1003 CONTINUE
DO 415 J = 1, 9
DO 415 K = 1, 24
415 C(I, K) = C(I, K)
CALL MATM(C5, C5, C6, 9, 9, 24)
1004 CONTINUE
CALL MATM(C5, C6, C24, 9, 24)
1005 CONTINUE
DO 420 J = 1, 24
DO 420 K = 1, 124
420 C(I, J, K) = C(I, J, K) * C31(J, K + 9)
M1 = NODEC(11)
TDI = TD C11 = 0
TDI = TD C21 = 0
TDI = TD C31 = 0
K = 3
DO 2100 I = 1, 3

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NT=MODEL(1)
NO 210C J=1,3
K=K+1
2100 TOIS(K)= (X(I,J)-X(1,J))*PSMOT(J)
   CALL MATMC(105,UTH,24,24,1)
   WRITE (8) JTH(J,J=1,24),NUDE(J,J=1,8)
100G CONTINUE
WRITE(?) (C(I,J),J=1,24),K=1,24),NUDE(J,J=1,8),LK
419 NO 600 NGAUS=1,8
41G CONTINUE
READ(2) (A(I,J),I=1,6),J=1,133
   CALL MATMC(105,C7,6,9,24)
600 CONTINUE
1000 RETURN
END
SUBROUTINE DINV(A,M,ICLUM)

MATRIX INVERSION WITH VALUE OF INTERIMANT 6/9/71

A IS MATRIX BEING INVERTED
M IS MATRIX SIZE

DIMENSION PIVOT(9),INDEX(9,2),INDEX(9,1),PINDEX(9)

INITIALIZATION

10 DETERM=1.0
15 DO 20 J=1,M
20 PIVOT(J)=0
30 DO 95 I=1,M

SEARCH FOR PIVOT ELEMENT

40 ANAME=C
45 DO 80 J=1,M
90 IF (INDEX(J,J+1)) .LT. 0
60 IF (INDEX(I,J)) .LT. 0
70 IF (INDEX(I,J)) .LT. 0
80 IF (INDEX(M,J)) .LT. 0
90 INDEX=INDEX+1
30 CONTINUE
110 INDEX=INDEX+1

INTERCHANGE rows TO PUT PIVOT ELEMENT ON ORIGINAL

120 IF (INDEX-I) 
130 DETERM=-DETERM
150 M=120 I=1
160 SWAP=(I,J)
170 SWAP=(I,J)
200 SWAP=(I,J)
260 INDEX(INDEX-1)=INDEX
270 INDEX=INDEX
280 SWAP=(I,J)

DIVIDE PIVOT ROW BY PIVOT ELEMENT

300 DETERM=(I,J)
340 D) AND I=J
350 DETERM=(I,J)
600 DETERM=(I,J)

REDUCE NON-PIVOT ROWS
SUBROUTINE FACE

FACE STRESS COMBINATION, JUNE 6, 1971, S. LEVY

COMMON NAPRT, NPOIN, NLEM, NBOUN, NY, NFREE, NCONG,
INPMN2, NSTART(9), NEND(9), NFIRST(9), NLAST(9), NINES, NCO
2 TUTH(75), SYLD(96), LEM(96), SC(96), EMOD(96), EMT(96), EHSQ(96)
3 NINTX, NINT, NITE, NNP, NF1(225), NF2(225), UI(3, 225), UI8(225, 3)
4, NMODX(96, 8), K2L(96), TEMP(96), ALPH(225), EPL(96, 3)
DIMENSION OMAA(0, 24), OBA(4, 24), OI(3, 8), OI(3), ALPHA(8), NFACE(4, 6)
1, ODHA(6, 24), YI(3), ODSUM(6, 24)

NFACE(1, 1) = 1
NFACE(2, 1) = 2
NFACE(3, 1) = 3
NFACE(4, 1) = 4
NFACE(1, 2) = 5
NFACE(2, 2) = 6
NFACE(3, 2) = 7
NFACE(4, 2) = 8
NFACE(1, 3) = 9
NFACE(2, 3) = 10
NFACE(3, 3) = 11
NFACE(4, 3) = 12
NFACE(1, 4) = 13
NFACE(2, 4) = 14
NFACE(3, 4) = 15
NFACE(4, 4) = 16
NFACE(1, 5) = 17
NFACE(2, 5) = 18
NFACE(3, 5) = 19
NFACE(4, 5) = 20
NFACE(1, 6) = 21
NFACE(2, 6) = 22
NFACE(3, 6) = 23
NFACE(4, 6) = 24

21 DO 200 NFACSS = 1, 8
200 READ(4) ((OMAA(I, J, NGAUSS), J = 1, 6), I = 1, 8), (XX(I, NGAUSS), I = 1, J),
1, (MODE[I], I = 1, 8), LL
CALL ZERO(MDSUM, 6, 24)
6 DO 300 NXX = 1, 6, 2
9 N1 = NFACE(1, NXX)
22 N2 = NFACE(2, NXX)
33 N3 = NFACE(3, NXX)
44 N4 = NFACE(4, NXX)
55 N5 = NFACE(1, NXX + 1)
66 N6 = NFACE(2, NXX + 1)
77 N7 = NFACE(3, NXX + 1)
88 N8 = NFACE(4, NXX + 1)
11 DO 301 J = 1, 6
99 DO 301 K = 1, 24
22 DBI(J, K) = 0.25*(OMBA(J, K, Y1) + OMAA(J, K, N6) + OMAA(J, K, N7) + OMAA(J, K, N8) +
1) DBA(J, K) = 0.25*(OMBA(J, K, N1) + OMAA(J, K, N2) + OMAA(J, K, N3) +
1) OMAA(J, K, N4)
DO 302 J=1,6
  Y(J)=0.25*(XX(J,N5)+XX(J,N6)+XX(J,N7)+XX(J,N8))
302 7(J)=6.25*(XX(J,N1)+XX(J,N2)+XX(J,N3)+XX(J,N4))
DO 303 K=1,24
  T(A)=1.36*DBA(J,K)+366*DBB(J,K)
  DBR(J,K)=+.366*DBA(J,K)+1.36*DBB(J,K)
303 DBR(J,K)=TA
WRITE (2) ((DBA(I,J),I=1,6),J=1,24),(Z(1),I=1,3),NOD(N1),NL.(N2),
   L(N(3)),NOD(N4),LL,(NOD(1),I=1,8)
WRITE (2) ((DBB(I,J),I=1,6),J=1,24),(Y(1),I=1,3),NOD(N5),NCD(N6),
   NOD(N7),NOD(N8),LL,(NCD(1),I=1,8)
300 CONTINUE
DO 320 I=1,6
DO 320 J=1,24
DO 310 NG=1,8
310 DOUM(I,J)=125*DBA(I,J,NG)
320 CONTINUE
WRITE (2) ((DSUM(I,J),I=1,6),J=1,24)
IF(LLL .NE. ALEEM) GO TO 21
100 CONTINUE
RETURN
END
$IEFTC XMATRIX DECK

SUBROUTINE MATRIX

COMMON NPAR,TPOIK,NELEM,ABOUN,NUM,NFREC,NDCON,
INPOIN,NSTART,NS,NGOST(N1),NLAST,LLINES,NCY
2,UTH(1375),SYLD(961),EM(961),ESC(961),EMOD(961),EK(961),EWE(961)
3,NIanax,NTS,NTR,NTR51,NF(225),R(225,3),U(3,225),X1(225,3),X(225,3)
4,NQDX(56,8),A2L(56),TEMP(96),ALPHA(225),ETP(96,8),
DIMENSION UI(75),NODE(18),C(24,24),UUU(75),ST(75,15),UTH(24)

REWIND 8
CALL ZEROM(UTHM,1,,75)
DO 10 N=1,NELEM
REAC (B) (UTHM,J,J=1,24),(NODE(J),J=1,8)
L=0
DO 10 J=1,8
C PUT THERMAL LOAD INTO ROTATED SYSTEM
DO 13 N=1,NBGN
IF (NODE(J)-NF(NZ)) 13,12,13
12 NZ=3*(J-1)
ALP=ALPHA(NZ)/57.29583
UONE=UTHM(NJZ+1)
UW=UTHM(NJZ+2)
UTHM(NJZ+1)=UONE*CO(S2(ALF)+UW*SIN(ALP))
UTHM(NJZ+2)=UONE*SIN(ALP)+UW*SIN(ALP)
13 CONTINUE

C COMPLETE
DO 10 K=1,3
L=K
J5=3*(NODE(J)-J)+K
10 UTHM(J5)=UTHM(J5)+UTHM(L)
37 FORMAT (14,F16.4)
INTEF = 0
CALL ZEROM(UUU,1,,75)
DO 70 II=1,NPART
REWIND 8
CALL ZEROM(ST,75,15)
975 CONTINUE

NST=NSTAP(III)
เหน=เหน(JIII)
K=NIAXT(JIII)
L=NLAST(JIII)
IF(II=NEP,NP) KEN=NLAST(JIII)
IF(II=EQ,NP) KEN=NLAST(I)
MINUS = K-1
LMINUS=2*(L-MINUS)
DO 80 LL=1,NELEM
84 CONTINUE

DO 86 KL=1,8
80 CONTINUE
IF (MODE(KK)-K) 902, 131, 131
131 IF (MODE(KK)-L) 132, 132, 39C
132 NVFREE*(NWE(KK)-K)
N=NFREE*(NJO(KL)-K)
I=FREE*(KK-1)
J=FREE*(LL-1)
IF (N) PGC, 9DC, 9JC 900 ND 5 NJ=1, NVFREE
90 NVJ=1, NVFREE
90 MJ=M+1
NNJ=NN+KJ
IM=1+IM
JW=J+AK
5 STM(MJ,NNJ) = STMM(MI,NNJ) + C(IM,NNJ)
800 CONTINUE
80 CONTINUE
980 CONTINUE
411=FREE*(MI-1)+1
MJ=1+MJ
NJ=1+NL
IF (II-NPARI) 5115, 5116, 9115
9115 NA=1, FREE*(NAST II+1)-VINUS)
GO TO 5117
9116 NA=1, NA=1
9117 NA=NA-1
411=1+1
98 C ST IS PUT IN ROTATED SYSTEM
98 440 ND=K, L
440 DO 440 NZC=1, 1, NSKUK
IF (NS-ALK(NZC)) 440, 425, 444
405 NJZ=3*(IZ-K)
405 ALP=ALPHA(NZC), 1/57.2953
405 470 NZT=1, NA1
405 STONE=ST(NZT+1, NA1)
405 STTM=ST(NZT+2, NA1)
405 ST(I, IZ) = STONE*COS(ALP) + STTM*COS(ALP)
405 ST(I, NZT+2) = STONE*SIN(ALP) + STTM*SIN(ALP)
470 CONTINUE
440 CONTINUE
440 DO 440 NZC=1, KEND
440 DO 440 NZC=1, NA1
450 NJZ=3*(IZ-Y)
450 ALP=ALPHA(NZC), 1/57.2958
450 490 NZT=1, M1
450 STONE=ST(NZT+1, M1)
450 STTM=ST(NZT+2, M1)
450 ST(I, IZ+1) = STONE*COS(ALP) + STTM*COS(ALP)
450 ST(I, NZT+2) = STONE*SIN(ALP) + STTM*SIN(ALP)
490 CONTINUE
480 CONTINUE
C EVERYTHING BELOW IS IN ROTATED SYSTEM
480 WRITE (7) M1, N1, M1, NA1, (ST(I, J), I=1, M1, J=1, NA1)
480 I, (I, J), I=1, M1, J=MM1, NA1)
480 JN=0
480 DO 981 J=K, L
DO 981 I=1,3
JNJ=JNJ+1
JS=JS+J=1+1

981 UU(JNJ)=UU(U(JNJ)+UU(I,J)+UU(J)+UU(J,J))+U(I,J)
CALL ZEROM(UU,1,75)

C
INTRODUCTION OF PRESCRIBED DISPLACEMENTS

C
DO 290 I=1,NBOUND
M=MFI(I)-K
MM=MFI(I)-1
KKEND=KEND-NFI(I)
IF (M) 290,242,242
242 IF(KKEND) 290,243,243
243 DO 230 J=1,NFREE
IF (MF(I,J)) 230,345,23
345 NMI = NFREE*MFI(J)
KLEA=KFREE*(K-K+1)
DO 1345 KLEA=KLEA+1
KLEA=KFREE*MFI(J)
UU(J,J)=UU(J,J) + ST(KLEA,NMI)*RV(I,J)
CONTINUE

1345 CONTINUE
IF (J(I)-APART) 1233,1239,1239
1233 IF (NPAR(I)-1) 1221,1230,1231
1231 LEA=LEA+1
1232 CONTINUE
IF (MNI=LL+1) 1234,1234,1234
1234 NMX=MNI
KLEA=0
DO 1235 KLEA=LEA,N1
KLEA=KLEA+1

1235 UU(KLEA)=MU(U(KLEA)-ST(NMX,KLEA)*BV(I,J))
CONTINUE

239 CONTINUE
7345 CONTINUE
230 CONTINUE
290 CONTINUE

DO 4344 I=1,NCU
M=MFI(I)-K
KKEND=KEND-NFI(I)
IF (M) 4347,4242,4242
4242 IF (KKEND) 4347,4243,4243
4243 DO 4247 J=1,NFREE
IF (M1(I,J)) 4247,4344,4247
4344 NMI=NFREE*MFI(J)
KLEA=KFREE*(K-K+1)
DO 4345 KLEA=LEA+1
JNJ=JNJ+1
IF (KLEA+0,K1) UU(JNJ)=RV(I,J)
ST(KLEA,NMI)=C
IF (KLEA=NC-NMI) GO TO 4345
LLR=(KEND-K+1)*NFRE
DO 4346 KL=1,LLR
ST(NMI,KL)=C
4346 CONTINUE
ST(NMI,NMI)=C
4345 CONTINUE
4247 CONTINUE
4347 CONTINUE
INTER=MEN
MJ=NFREE-MINUS+1
MJ=NFREE+1
M=MJ-M-1
IF (II=NPART) 115, 116, 115
115 NA=NFREE-MLAST(I+1)-MINUS
GO TO 117
116 NA=NA+1
117 M=NA-M
MM=M+1
8 FORMAT (15,E13.4)
7 FORMAT (15,13.4)
6 FORMAT (14,P4,N4, ((ST(I,J)), I=1, M), J=1, M), ((ST(I,J)), I=1, M), J=MM, NA),
1((U(I)), I=1, M)
3 FORMAT (1H1, 10X, 3HII= [4,6X, 2HN= 14, 6X, 2HN= 14) ///)
4 FORMAT (10X, 5HCHECK ///)
RETURN
END
SUBROUTINE MTINV(A,N,NSIZE)

C MATRIX INVERSION MODIFIED 6/9/71 BY S. LEVY
C A IS MATRIX TO BE INVERTED
C N IS MATRIX SIZE
C NSIZE IS MEMORY SIZE
C
DIMENSION A(NSIZE,NSIZE)
30 DO 55C I=1,N
50 DO 55I=1,N
60 DO 55I=1,N

C DIVIDE PIVOT ROW BY PIVOT ELEMENT
C
50 DO 55C J=1,N
50 DO 55C J=1,N
50 DO 55C J=1,N

C REDUCE NON-PIVOT ROWS
C
200 DO 55C I=1,N
200 DO 55C I=1,N
200 DO 55C I=1,N

C CONTINUE
C RETURN
C
SUBROUTINE MATMUL(A, B, M, L, P, N, SIZE)  
C
C MATRIX MULTIPLICATION  
C
DIMENSION D(M,L), B(N,L), C(N,SIZE)  
C N = N1 + N2  
DO 110 J=1,L  
   DO 101 I=1,N  
   101 C(I,J)=A(I,J)*B(J,N1)+B(J,N2)  
110 CONTINUE  
RETURN  
END
SUBROUTINE MATMUL(D,G,DR,L,M,NSIZE)
C
C MATRIX MULTIPLICATION TRANSPOSED DB(L)=D(MX1)*B(M);
C
DIMENSION (NSIZE,NSIZE),DB(NSIZE),D(L,NSIZE)
C
NSIZE IS MEMORY SIZE
ON 110 I=1,L
DB(I)=C
DO 110 K=1,M
110 DB(I)=DB(I)+D(I,K)*B(K)
RETURN
END

C
SUBROUTINE STRESS

C STRESS CALCULATION OF STRESSES.

C

COMMON XPAI, MP, NDEF, XJ, N, L, M, N
DPDMN, NDEF, NDE
XSTATS  M PRICE  
XSTATS  --  EFN  SOURCE STATEMENT  --  IFNS() --

01 62C  I1=J,3  
   JX=J5+J  
   I3=I1+I1-3+J  
   J3=J+J3+J1-3+J

620  DEF(I13)=W(I13)+V(JX)
   CALL MATH(DMA,DEF,SIG,6,24,1)

632  WRTL (6,1G) LL1(MDNN111,1=I,4),DAX,GRAY,DAZ
   DNO 633  K=1,3  
   SNOUT(K+3) = SIG(K+3)

633  SNOUT(K+3) = SIG(K+3)  
   WRITE (6,31) (SNOUT(J),J=1,6)
   CALL MATH(DSNO,SIG,6,6,6,11)
   WRITE (6,31) (SIG(111),I=1,6)

200  CONTINUE  
   READ (21) (NSUM(I,J),I=1,6,J=1,24)
   CALL MATH(OSUM,DEF,SIG,6,24,11)
   DNO 634  K=1,3  
   SNOUT(K+3) = SIG(K+3)

634  SNOUT(K+3) = SIG(K+3)  
   CALL MATH(DSNO,SIG,6,6,1)
   WRITE (6,39) LL1(SIG(K),K=1,6)
   SXL1=2.*SIG(1)-SIG(2)-SIG(3)
   SYL1=2.*SIG(2)-SIG(1)-SIG(3)
   SIE=1.5*(SIG(1)+SIG(2))**2+2*(SIG(1)-SIG(2))**2+2*(SIG(2)-SIG(3))**2
   1.5*(SIG(4)**2+2*SIG(5)**2+2*SIG(6)**2)**0.5

SIE(11)=S1

88 39 FORMAT (4X/27H AVERAGE STRESS FOR ELEMENT 13/1X 6F16.6/4X)  
   IFILL=AELEM 21,1,400,100

30 FORMAT (1X,6E16.6)

10 FORMAT (1X,J4,2X,11X,6I5,6X,3F14.6)

31 FORMAT (1X,J4,6F16.6)

100  CONTINUE  
   WRITE (6,33) MITX
   DNO 30C J=1,NELEM
   ETOT=SIG(J)+ESIC(J)
   ESTAR=SYL(J)/EMUD(J)
   IF (ETOT.LT.ESTAR) G1 T1 350
   SIGNAL=SYL(J)**2/ETOT(J)**4 J(J)**4/400(J)**4 ETOT
   ESIC(J)=SIGNAL/ETOT
   EPLAS=ETOT**SIGNAL**EMUD(J)
   ESIC(J)=.5*Salen(J)**2SEC(J)**SMUD(J)
   GO TO 320

350  SIGNAL=SIG(J)
   EPLAS=SIG(J)**
   ESIC(J)=EW(J)
   ESIC(J)=SMUD(J)

330  CONTINUE  
   SX(J)+100.*EPLAS*SYL(J)/SIG(J)
   SYL(J)+50.*EPLAS*SYL(J)/SIG(J)
   SIG(J)+100.*EPLAS*SYL(J)/SIG(J)
   SIG(J)+100.*EPLAS*SYL(J)/SIG(J)
   SIG(J)+100.*EPLAS*SYL(J)/SIG(J)
   SIG(J)+100.*EPLAS*SYL(J)/SIG(J)

300  WRITE (6,34) JETOT,EPLAS,SIGNAL,SYL(DJ),
   ESIC(DJ),ESIC(J)

321 FORMAT (1X,J4,4X//4H ELEMENT 4X 16HEQUIVALENT TOTAL 4X 1 8HPLASTIC 2HSTRAIN COMPONENTS (PERCENT) / 8H NUMBER 4X 2 16HSTRAIN (PERCENT) 4X SHR-DIP 10X SHY-DIR 10X SDE-DIR //)

322 FORMAT (16,8X F10.5,3F15.5)

323 FORMAT (16,3F15.8)
IF (INITX=0) 320, 31C, 323
31C WRITE (6,321)
   DO 315 J=1,NELM
      SX=-(SX(J)+SY(J))
      SY(J)=SY(J)+PL(J,1)
      SY(J)=SY(J)+PL(J,1)
      SZ=SZ+FPL(J,3)
      WRITE (6,322) J,SIGE(J),SX(J),SY(J),SZ
   PICH= 323, J,SX(J),SY(J),SZ
315 CONTINUE
320 CONTINUE
33 FORMAT (1H1 10X /// 18H YIELD CHECK AFTER 14, 12H ITERATIONS
   3 /// 4X THELEMENT 5X
   1 5HSTIAL 5X 7HPLASTIC 3X 9HEFFECTIVE 4X 5HSTRAIN 6X
   2 6HSECANT 7X 6HSECANT / 16X 6HSTRAIN 4X 6HSTRAIN 4X
   4 6HSTRESS 7X 6HSTRESS 5X 7HMODULUS 6X 7HPICISSON ///
34 FORMAT (18,1F14.6,F10.6, F11.1,F1.1,F14.1,F13.4) /}
RETURN
END
APPENDIX C--CANTILEVER BEAM EXAMPLE--
INPUT AND OUTPUT DATA
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Cantilever Beam Example

FORTRAN STATEMENT

$DATA

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IBRAHIM

PROJECT NUMBER 4880
BEGIN EXECUTION.

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UNUSED CORE

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*010* EXIT IN RETSCP
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| 12806.568684   | -2613.592595       | 2548.242737            | 0.000034 0.000000 0.000000 |
| 2              | 5                 | 7                      | 0.042525 0.376125 0.000000 |
| 12906.56545P   | -2613.598114       | 2548.242584            | 0.000034 0.000000 0.000000 |
| 2              | 6                 | 8                      | 0.045800 0.251200 0.050000 |
| 11293.71466C   | -2412.355569       | 2219.454742            | 0.000029 0.000000 0.000000 |
| 2              | 9                 | 12                     | 0.009250 0.501050 0.050000 |
| 13432.423394   | -2814.201493       | 2877.305183            | 0.000038 0.000000 0.000000 |
| 2              | 5                 | 6                      | 0.009250 0.375300 0.050000 |
| 12911.234467   | -2610.774450       | 2550.122040            | 0.000028 0.000000 0.000000 |
| 2              | 12                | 11                     | 0.085053 0.377250 0.050000 |
| 12901.912554   | -2616.459653       | 2546.563190            | 0.000039 0.000000 0.000000 |

**AVERAGE STRESS FOR ELEMENT 2**

<p>| 12806.568684   | -2613.596832       | 2548.242645            | 0.000000 -0.000415 -0.000000 |
| 2              | 10                | 12                     | 0.035975 0.625950 -0.100000 |
| 15929.484766   | -562.924266        | 2561.735535            | 0.000047 0.000000 0.000000 |
| 3              | 9                 | 11                     | 0.035975 0.625950 0.000000 |
| 15928.484676   | -562.924362        | 2561.735199            | 0.000047 0.000000 0.000000 |
| 3              | 10                | 12                     | 0.039250 0.501050 0.050000 |
| 13479.377512   | -5165.955913       | 2678.288482            | 0.000041 -0.000000 0.000000 |
| 3              | 13                | 14                     | 0.03705 0.750850 0.050000 |
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| 15929.884277  | -5682.943054 | 2561.735321 | 566.559593 | -0.000895 | 0.000222 |
| 4              | 14           | 16           | 26          | 18         | 0.100000 | 0.031375 | 0.030825 | 0.000000 |
| 19147.27244    | -5027.131952 | 2533.037699 | 743.408600 | -0.002248 | 0.000126 |
| 4              | 13           | 15           | 16          | 17         | 0.        | 0.031375 | 0.030825 | 0.000000 |
| 19147.272497   | -5027.122559 | 2533.037944 | 743.412033 | -0.002259 | 0.000295 |
| 4              | 14           | 16           | 13          | 15         | 0.        | 0.032703 | 0.750850 | 0.050000 |
| 17695.941162   | -8666.768775 | 2262.291887 | 689.110559 | -0.032008 | 0.000081 |
| 4              | 17           | 20           | 18          | 18         | 0.        | 0.030053 | 0.950800 | 0.050000 |
| 20599.615479   | -9407.504249 | 2797.777466 | 797.710608 | -0.02510 | 0.000154 |
| 4              | 13           | 14           | 17          | 18         | 0.        | 0.030053 | 0.950800 | 0.050000 |
| 19147.272525   | -5026.516632 | 2534.312195 | 503.690582 | -0.031179 | 0.000322 |
| 4              | 20           | 16           | 19          | 15         | 0.        | 0.062750 | 0.801650 | 0.050000 |
| 19130.751054   | -5027.737305 | 2525.763489 | 983.129929 | -0.033322 | 0.000178 |

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| 19147.272524   | -5027.127177 | 2530.307811 | 743.416263 | -0.002270 | 0.000105 |
| 5              | 18           | 20           | 22          | 22         | 0.        | 0.029425 | 0.875775 | 0.100000 |
| 21041.31777    | -10956.171725 | 2521.085938 | 824.498390 | -0.002161 | 0.000301 |
| 5              | 17           | 19           | 23          | 21         | 0.        | 0.029425 | 0.875775 | 0.100000 |
| 21041.327316   | -10956.174169 | 2521.08927 | 824.505510 | -0.002174 | 0.000276 |
| 5              | 18           | 20           | 17          | 19         | 0.        | 0.030500 | 0.450800 | 0.050000 |
| 20194.01543    | -10723.885010 | 2367.533558 | 802.556496 | -0.002085 | 0.000339 |
| 5              | 21           | 24           | 22          | 23         | 0.        | 0.028000 | 0.900750 | 0.050000 |
| 21889.122117   | -11589.566895 | 2674.663825 | 846.447272 | -0.002106 | 0.000642 |
| 5              | 17           | 18           | 21          | 22         | 0.        | 0.075000 | 0.050000 |
| 3              | 20           | 24           | 22          | 23         | 0.        | 0.000046 | 0.000000 | 0.000000 |
| 21047.52277    | -10978.720337 | 2517.197225 | 555.042702 | -0.002458 | 0.000181 |
| 5              | 21           | 24           | 23          | 23         | 0.        | 0.059500 | 0.876550 | 0.050000 |
| 21034.625127   | -10934.731079 | 2524.974670 | 1098.961090 | 0.         | 0.037077 | 0.000000 |

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| 6              | 22           | 24           | 26          | 26         | 0.        | 0.028150 | 0.925725 | 0.100000 |
| 22042.347185   | -12452.948094 | 2439.703918 | 903.426712 | -0.000897 | 0.000060 |
| 6              | 21           | 23           | 27          | 25         | 0.        | 0.028150 | 0.925725 | 0.100000 |
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APPENDIX E--HEATED ELEMENT CYCLING EXAMPLE-
INPUT AND OUTPUT DATA

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