A STUDY OF THE PLANE STRESS OR STRAIN FINITE ELEMENT ANALYSIS FOR SOLUTION OF STRESS DISTRIBUTION IN PLANE ELASTIC CONTINUA

by

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SYNOPSIS

The "finite element method" for solution of stress distribution in a plane elastic continuum is studied in this report. This approximate method of analysis can be used for obtaining a solution to previously intractable problems. An existing "finite element method" computer program is made operational as a requirement of the report. A simple problem will be solved using a classical "exact method" and will then be analyzed using the "finite element method" to get an idea of the correspondence of the results of the two methods. A problem for which a "classical method" does not exist will then be analyzed using the "finite element method" to illustrate the power of its application.

INTRODUCTION

Structural analysts are becoming increasingly aware of the power of numerical methods in providing reasonably accurate solutions to complex problems which heretofore relied upon approximate calculations of doubtful validity. The plane stress or strain finite element analysis is one of these numerical methods which, when coupled with a high-speed computer, can provide quick solutions that converge to "exact method" answers.

O. C. Zienkiewicz and Y. K. Cheung[1], in their book, have presented the theory behind the finite element method and a computer program which applies the plane stress or strain finite element analysis to a plane elastic continua.

The plane elastic continua is divided into a finite number of nodal points which are interconnected to form triangular elements. Force-displacement relationships are determined for these triangular elements. "Displacement method" equations[2] in matrix notation are formed with the displacements of the nodal points as unknowns. Inversion of the force-displacement matrix and multiplication by the force matrix leads to a solution for the unknown displacements. These displacements are used to calculate the stresses at the centroids of the triangular elements which are then converted to principal stresses and their angle of deviation from the original X-Y coordinate system.

The general "displacement method" equation is given as

$$\{F\}^e = [k]^e \{\delta\}^e + \{F\}_p^e \tag{1}$$

in which $\{F\}^e$ represents the force matrix composed of forces at the nodal points, $[k]^e$ represents the force-displacement or stiffness matrix determined from the element properties, $\{\delta\}^e$ represents the nodal displacement for a particular element, and $\{F\}_p^e$ represents the nodal forces due to body forces.

The general equation used to solve for the stresses is given as

$$\{\sigma\}^e = [S]^e \{\delta\}^e \tag{2}$$

in which $\{\sigma\}^e$ represents the stress matrix composed of the stress in the X- and Y-directions and the shear stress, and $[S]^e$ represents the stress-displacement matrix determined from the material properties. A further explanation of equations (1) and (2) will be given in the section on derivations.

The finite element method computer program taken from reference 1 and included in this report is written in FORTRAN IV language and in its present form is intended for use on an IBM 360-series computer.

Even though it is limited to the solution of problems which lie in the X-Y plane, the finite element program (FINELEM) has a wide range of application. Each element can have one of up to 10 different sets of elastic properties for a given problem and any constant thickness.

The program is not limited to isotropic materials. Anisotropic materials, which are "stratified" and have rotational symmetry in the plane of the strata, can also be solved. When the direction of the strata in a transversely isotropic material is inclined to the X-axis, a transformation matrix included in the program relates the stresses back to the major X-Y coordinates.

The accuracy of the stress solutions obtained using FINELEM is dependent upon the fineness of the triangular grid. An area of a certain problem with an expected high stress or variable stress should be divided into a finer grid than an area with an expected constant stress. An infinite number of combinations of loading conditions and support conditions can be approximated using this method.

In this report, a simple problem with a solution based on a well-known "classical" method is compared with the solution using FINELEM. The correctness of the program and the accuracy of the method is studied using this simple problem. Once the program is judged to be performing correctly, a complex problem is solved to illustrate the method's usefulness and versatility.

DERIVATIONS

The general equation

$$\{F\}^e = [k]^e \{\delta\}^e + \{F\}_p^e \tag{1}$$

containing the unknown displacements will now be presented in more detailed mathematical form.

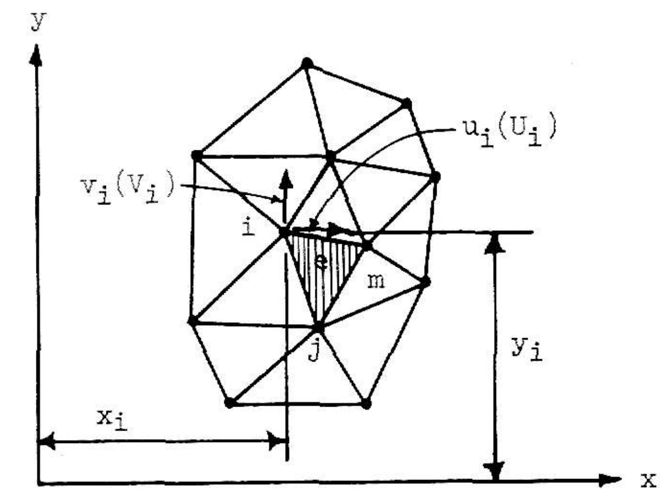


Fig. 1. A Plane Stress Region Divided Into Finite Elements.

A typical finite element, e, is defined by nodes i, j, m, etc., and straight-line boundaries. The displacements at any point within the element will be defined as a column vector, $\{f(x,y)\}$ or

$$\{f\} = [N]\{\delta\}^e = [N_i, N_j, N_m, \ . \ . \ .] \begin{Bmatrix} \delta_i \\ \delta_j \\ \delta_m \\ . \\ . \\ . \end{Bmatrix} \tag{3}$$

in which $[N]$ is a position matrix dependent upon the element geometry and $\{\delta\}^e$ is, as defined previously, a matrix composed of X and Y nodal point displacements for a certain element. In the case of plane stress

$$\{f\} = \begin{Bmatrix} u(x,y) \\ v(x,y) \end{Bmatrix} \tag{4}$$

represents horizontal and vertical translocation of a typical nodal point within the element and

$$\{\delta_i\} = \begin{Bmatrix} u_i \\ v_i \end{Bmatrix} \tag{5}$$

the corresponding displacements of a node i. The six components of element displacements are listed as a vector

$$\{\delta\}^e = \begin{Bmatrix} \delta_i \\ \delta_j \\ \delta_m \end{Bmatrix} \tag{6}$$

The displacements within an element are uniquely defined by these six values. Two linear polynomials

$$\begin{aligned} u &= \alpha_1 + \alpha_2 x + \alpha_3 y \\ v &= \alpha_4 + \alpha_5 x + \alpha_6 y \end{aligned} \tag{7}$$

represent the relationship between the displacements. If the nodal coordinates are inserted and the displacements equated to the appropriate nodal displacements, two sets of three simultaneous equations will arise in which the six constants α can be evaluated. For example,

$$
\begin{aligned}
u_i &= \alpha_1 + \alpha_2 x_i + \alpha_3 y_i \\
u_j &= \alpha_1 + \alpha_2 x_j + \alpha_3 y_j \\
u_m &= \alpha_1 + \alpha_2 x_m + \alpha_3 y_m
\end{aligned}
\tag{8}
$$

We can solve for α_1, α_2, and α_3 in terms of the nodal displacements u_i, u_j, and u_m. We would finally obtain for the horizontal displacement

$$
u = \frac{1}{2\Delta}\left[(a_i + b_i x + c_i y)u_i + (a_j + b_j x + c_j y)u_j + (a_m + b_m x + c_m y)u_m\right]
\tag{9}
$$

in which

$$
\begin{aligned}
a_i &= x_j y_m - x_m y_j \\
b_i &= y_j - y_m \\
c_i &= x_m - x_m \\
\\
a_j &= x_m y_i - x_i y_m \\
b_j &= y_m - y_i \\
c_j &= x_i - x_m \\
\\
a_m &= x_i y_j - x_j y_i \\
b_m &= y_i - y_j \\
c_m &= x_i - x_i
\end{aligned}
\tag{10}
$$

and where

$$2\Delta = \det\begin{vmatrix} 1 & x_i & y_i \\ 1 & x_j & y_j \\ 1 & x_m & y_m \end{vmatrix} = 2(\text{area of triangle} \quad ijm) \tag{11}$$

Similarly, the equation for vertical displacement would be

$$v = \frac{1}{2\Delta}\left[(a_i + b_i x + c_i y)v_i + (a_j + b_j x + c_j y)v_j + (a_m + b_m x + c_m y)v_m\right] \tag{12}$$

with the same coefficients as were given in equation (10).

We can represent the relationships in equations (9) and (12) in the form of equation (3)

$$\{f\} = \begin{Bmatrix} u \\ v \end{Bmatrix} = [N]\{\delta\}^e = [IN_i', IN_j', IN_m']\{\delta\}^e \tag{13}$$

with I a two by two identity matrix and

$$N_i' = \frac{(a_i + b_i x + c_i y)}{2\Delta}$$

$$N_j' = \frac{(a_j + b_j x + c_j y)}{2\Delta} \tag{14}$$

$$N_m' = \frac{(a_m + b_m x + c_m y)}{2\Delta}$$

The calculation of the coefficients can be simplified if the coordinates are taken from the centroid of the element. The relationships[1]

$$x_i + x_j + x_m = y_i + y_j + y_m$$

and (15)

$$a_i = \frac{2\Delta}{3} = a_j = a_m$$

would result.

The displacement functions above automatically guarantee continuity of displacements with adjacent elements.

The strains, ϵ, at any point can now be determined from the displacements known at all points within the element. Written in matrix notation, this relationship is

$$\{\epsilon\} = [B]\{\delta\}^e \qquad (16)$$

The total strain at any point within the element for the plane stress case can be defined in terms of the displacements by well-known relationships[3]

$$\{\epsilon\} = \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \dfrac{\partial u}{\partial x} \\ \dfrac{\partial v}{\partial y} \\ \dfrac{\partial u}{\partial y} + \dfrac{\partial v}{\partial x} \end{Bmatrix} \qquad (17)$$

Taking the appropriate partial derivatives of equations (9) and (12), we have

$$\{\epsilon\} = \frac{1}{2\Delta}\begin{bmatrix} b_i, & o, & b_j, & o, & b_m, & o \\ o, & c_i, & o, & c_j, & o, & c_m \\ c_i, & b_i, & c_j, & b_j, & c_m, & b_m \end{bmatrix}\{\delta\}^e \qquad (18)$$

which defines the matrix $[B]$ of equation (16).

The relationship between stress and strain will be linear assuming general elastic behavior; therefore,

$$\{\sigma\} = [D]\{\epsilon\} \tag{19}$$

where $[D]$ is an elasticity matrix containing the appropriate material properties. For the plane stress case, three components of stress correspond to the strains already defined

$$\{\sigma\} = \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} \tag{20}$$

The matrix $[D]$ is now obtained from the usual isotropic stress-strain relationship[3].

$$\begin{aligned} \epsilon_x &= \frac{1}{E}\sigma_x - \frac{\mu}{E}\sigma_y \\ \epsilon_y &= -\frac{\mu}{E}\sigma_x + \frac{1}{E}\sigma_y \\ \gamma_{xy} &= \frac{2(1+\mu)}{E}\tau_{xy} \end{aligned} \tag{21}$$

Solving for $\{\sigma\}$ in terms of $\{\epsilon\}$, we get the appropriate terms for the matrix

$$[D] = \frac{E}{1-\mu^2}\begin{bmatrix} 1 & \mu & 0 \\ \mu & 1 & 0 \\ 0 & 0 & \frac{(1-\mu)}{2} \end{bmatrix} \tag{22}$$

A similar matrix can be formed for the plane strain case. Let

$$\{p\} = \begin{Bmatrix} X \\ Y \end{Bmatrix} \tag{23}$$

be the distributed load on the element in which X and Y are the "body force" components and $\{p\}$ is defined as the distributed loads acting on a unit volume of material within the material with directions corresponding to those of the displacements $\{f\}$ at that point.

The simplest method to make the nodal forces statically equivalent to the actual boundary stresses and distributed loads is to impose an arbitrary (virtual) nodal displacement and to equate the external and internal work done by the various forces and stresses during that displacement.

Let the virtual displacement be $\{\delta*\}^e$ at the nodes. By equations (13) and (16), the displacement strains within the element would be equal to

$$\{f*\} = [N]\{\delta*\}^e \quad \text{and} \quad \{\epsilon*\} = [B]\{\delta*\}^e \tag{24}$$

respectively.

The work done by the nodal forces is equal to the sum of the products of the individual force components and corresponding displacements; that is, in matrix language

$$\left(\{\delta*\}^e\right)^T \{F\}^e \tag{25}$$

Similarly, the internal work per unit volume done by the stresses and distributed forces is

$$\{\epsilon*\}^T \{\sigma\} - \{f*\}^T \{p\} \tag{26}$$

or

$$\left(\left\{\delta *\right\}^{e}\right)^{T}\left(\left[B\right]^{T}\left\{\sigma\right\} - \left[N\right]^{T}\left\{p\right\}\right) \tag{27}$$

Equating the external work with the total internal work obtained by integrating over the volume of the element, we get

$$\left(\left\{\delta *\right\}^{e}\right)^{T}\left\{F\right\}^{e} = \left(\left\{\delta *\right\}^{e}\right)^{T}\left(\int \left[B\right]^{T}\left\{\sigma\right\} d(vol) - \int \left[N\right]^{T}\left\{p\right\} d(vol)\right) \tag{28}$$

Since this relation is valid for any value of the virtual displacement, the equality of the multipliers must exist. Therefore, substituting equations (16) and (19), we have

$$\left\{F\right\}^{e} = \left(\int \left[B\right]^{T}\left[D\right]\left[B\right] d(vol)\right)\left\{\delta\right\}^{e} - \int \left[N\right]^{T}\left\{p\right\} d(vol) \tag{29}$$

which is in the form of equation (1), the general equation with

$$\left[k\right]^{e} = \int \left[B\right]^{T}\left[D\right]\left[B\right] d(vol) \tag{30}$$

and

$$\left\{F\right\}_{p}^{e} = -\int \left[N\right]^{T}\left\{p\right\} d(vol) \tag{31}$$

The terms $\left[k\right]^{e}$ and $\left\{F\right\}_{p}^{e}$ can be written in simpler forms by performing the integrations indicated on a general triangular element.

Equation (30) can be written as

$$\left[k\right]^{e} = \int \left[B\right]^{T}\left[D\right]\left[B\right] t \, dx \, dy \tag{32}$$

where t is the constant thickness of the element and the integration is taken over the area of the triangular element. Since neither of the matrices in equation (32) contains x nor y, we have

$$[k]^e = [B]^T [D] [B] t \Delta \tag{33}$$

where Δ is the area of the triangle as defined by equation (11). The matrix $[k]^e$ appears in the program FINELEM in this form. Equation (31) can be written as

$$\{F\}_p^e = -\int [N]^T \begin{Bmatrix} X \\ Y \end{Bmatrix} dx\, dy \tag{34}$$

which, when further simplified[1], can be shown to be

$$\{F\}_p^e = \begin{Bmatrix} X \\ Y \\ X \\ Y \\ X \\ Y \end{Bmatrix} \frac{\Delta}{3} \tag{35}$$

This simply means that the total forces acting in x- and y-directions due to the body forces are distributed to the nodes in three equal parts. The matrix $\{F\}_p^e$ appears in FINELEM in this form.

General equation (1) is applicable to any typical element in a continuum. To obtain a complete solution for the entire continuum, two conditions - namely, displacement compatibility and equilibrium - have to be satisfied throughout. The requirement of displacement compatibility is automatically satisfied for a system of nodal displacements $\{\delta\}$

$$\{\delta\} = \begin{Bmatrix} \delta_1 \\ \cdot \\ \cdot \\ \cdot \\ \delta_n \end{Bmatrix} \tag{36}$$

in which all of the elements participate.

Since equation (1) establishes equilibrium within a typical element, all that is necessary for overall equilibrium is to establish equilibrium at the nodes of the structure.

Consider the structure to be loaded by external forces $\{R\}$

$$\{R\} = \begin{Bmatrix} R_1 \\ \cdot \\ \cdot \\ \cdot \\ R_n \end{Bmatrix} \tag{37}$$

applied at the nodes in addition to the distributed loads applied to the individual elements.

To establish equilibrium conditions for a typical node, i, each component of R_i has, in turn, to be equated to the sum of the component forces contributed by the elements meeting at the node. Thus, considering all the force components, we have

$$\{R_i\} = \sum \{F_i\} \tag{38}$$

the summation being taken over all the elements. The stiffness matrices of each element will clearly always be square and of the form

$$[k]^e = \begin{bmatrix} k_{ii} & k_{ij} & k_{im} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ k_{mi} & k_{mj} & k_{mm} \end{bmatrix} \tag{39}$$

in which k_{ii}, etc., are submatrices which are square and of the size $t \times t$, where t is the number of force components to be considered at the nodes. Introducing the characteristics of the element given by equation (1) and taking note only of the appropriate forces F_i, by using the submatrices of equation (39), the above equations become

$$\{R_i\} = \sum_{m=t}^{m=n} \sum [k_{im}]^a \{\delta_m\} + \sum \{F_i\}_p^a \tag{40}$$

The inside summation is taken over all the elements of the structure indicated by the superscript a. Once all elements have been considered, the overall system of equations is established.

Equation (40) can be written in a simpler form as

$$[K]\{\delta\} = \{R\} - \{F\}_p \tag{41}$$

in which the submatrices are

$$[K] = \sum_{m=t}^{m=n} \sum [k_{im}]^a$$

$$\{F\}_p = \sum \{F_i\}_p^a \tag{42}$$

with summations including all elements. The system of equations resulting from equation (41) can be solved once prescribed support displacements have been substituted.

Once the solution of the unknown displacements has been obtained, the stress and internal forces are obtained by applying equation (2) to each element in turn.

The general equation

$$\{\sigma\}^e = [S]^e \{\delta\}^e \qquad (2)$$

will now be presented in a more detailed mathematical form. Once the nodal displacements $\{\delta\}^e$ have been determined by solution of equation (1), the stresses at any point of the element can be found from the relationships in equations (16) and (19) which give

$$\{\sigma\}^e = [D][B]\{\delta\}^e \qquad (43)$$

The term

$$[S]^e = [D][B] \qquad (44)$$

is the element stress matrix as it will be found in FINELEM. In FINELEM the stresses are assigned to the centroid of each element and are converted to principal stresses and their directions.

In order to reduce the physical size of the stiffness matrix, equation (33), a partitioning scheme is used. The nodal points of the structure are divided into a number of partitions. Only the elements concerned with the nodal points in a particular partition are used in the calculations.

The partitioning system is known as a "tridiagonal" system. Physically, this corresponds to the fact that the partitions are connected in series, as illustrated in Figure 2.

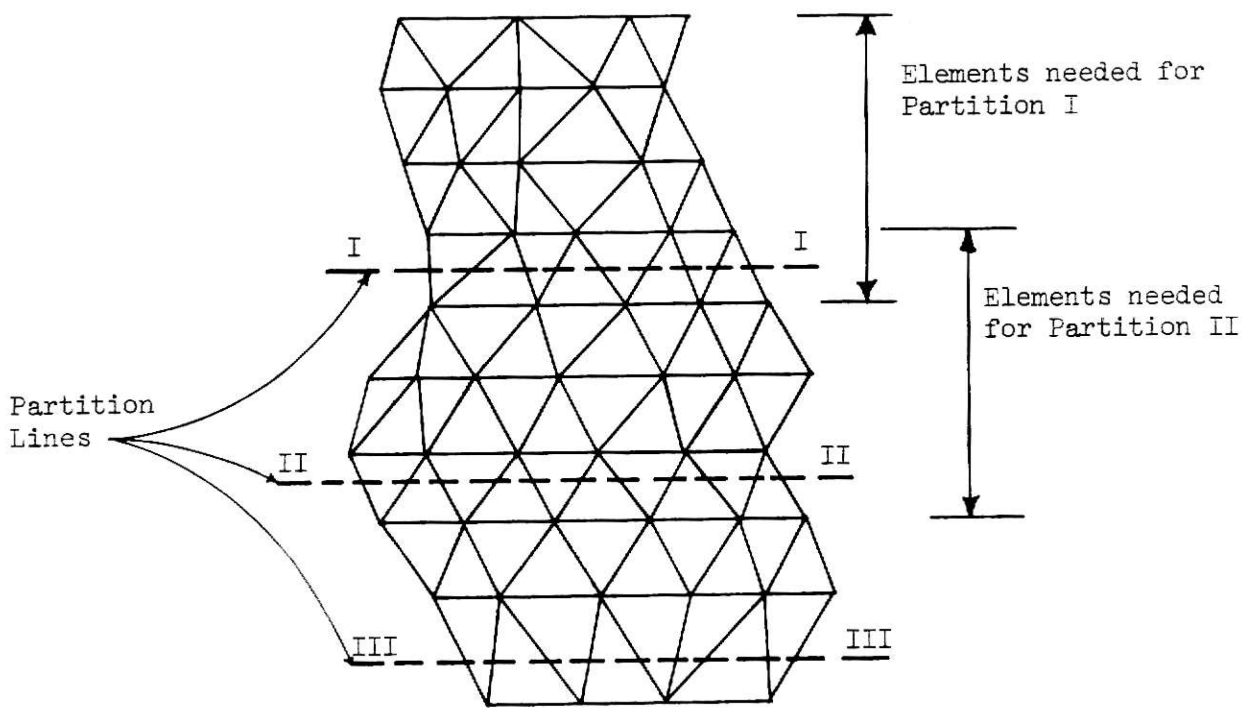


Fig. 2. Partitioning of a Structure.

The partitioning system allows the stiffness matrix to be written in the following tridiagonalized form:

$$\begin{bmatrix} K_I & C_I & 0 & 0 & . & . & 0 & 0 & 0 \\ C_I^T & K_{II} & C_{II} & 0 & . & . & 0 & 0 & 0 \\ 0 & C_{II}^T & K_{III} & C_{III} & . & . & 0 & 0 & 0 \\ . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . \\ 0 & 0 & 0 & 0 & . & . & K_{N-1} & C_{N-1} & \\ 0 & 0 & 0 & 0 & . & . & C_{N-1}^T & K_N & \end{bmatrix} \begin{Bmatrix} \delta_I \\ \delta_{II} \\ \delta_{III} \\ . \\ . \\ \delta_{N-1} \\ \delta_N \end{Bmatrix} = \begin{Bmatrix} P_I \\ P_{II} \\ P_{III} \\ . \\ . \\ P_{N-1} \\ P_N \end{Bmatrix} \tag{45}$$

This system of equations will be solved as follows: The first two matrix equations can be written as

$$\begin{aligned} \left[K_I\right]\left\{\delta_I\right\} + \left[C_I\right]\left\{\delta_{II}\right\} &= \left\{P_I\right\} \\ \left[C_I\right]^T\left\{\delta_I\right\} + \left[K_{II}\right]\left\{\delta_{II}\right\} + \left[C_{II}\right]\left\{\delta_{III}\right\} &= \left\{P_{II}\right\} \end{aligned} \tag{46}$$

The first equation will yield

$$\left\{\delta_I\right\} = \left[K_I\right]^{-1}\left\{P_I\right\} - \left[K_I\right]^{-1}\left[C_I\right]\left\{\delta_{II}\right\} \tag{47}$$

and substituting into the second yields

$$\left(\left[K_{II}\right] - \left[C_I\right]^T\left[K_I\right]^{-1}\left[C_I\right]\right)\left\{\delta_{II}\right\} + \left[C_{II}\right]\left\{\delta_{III}\right\} = \left\{P_{II}\right\} - \left[C_I\right]^T\left[K_I\right]^{-1}\left\{P_I\right\} \tag{48}$$

By defining new symbols,

$$[\bar{K}_{II}] = \left([K_{II}] - [C_I]^T[K_I]^{-1}[C_I]\right)$$

$$\{\bar{P}_{II}\} = \{P_{II}\} - [C_I]^T[K_I]^{-1}\{P_I\} \qquad (49)$$

equation (48) may be written as

$$[\bar{K}_{II}]\{\delta_{II}\} + [C_{II}]\{\delta_{III}\} = \{\bar{P}_{II}\} \qquad (50)$$

from which $\{\delta_{II}\}$ can be obtained as in equation (47) and substituting into the next row equation to give $[\bar{K}_{III}]$ and $\{\bar{P}_{III}\}$.

This process of substitution and elimination goes on until the last row is reached, that is,

$$[\bar{K}_N]\{\delta_N\} = \{\bar{P}_N\} \qquad (51)$$

where a direct inversion will yield $\{\delta_N\}$.

The process is then reversed and the known displacement values are back-substituted into equations in the form of equation (47), giving solutions for all of the unknowns.

To check the errors introduced in the solution of equation (45), the residuals are calculated as

$$\{R\} = \{P\} - [K]\{\delta\} \qquad (52)$$

FINELEM PROGRAM NOTATION

NPROB	number of problems to be done in one execution of program
NPART	total number of partitions
NPOIN	total number of nodal points
NELEM	total number of elements
NBOUN	total number of nodal points with prescribed displacements
NYM	total number of different elastic properties
NCOLN	total number of load vectors to be read in
NFREE	number of degrees of freedom per node
NP	NP = 0, plane strain case
	NP = 1, plane stress case
NCARD	number of cards read in for the previous set, used in checking
NCONC	number of points with concentrated loads
X	X,Y coordinates of the nodal points
NOD	the three nodal numbers defining a triangular element, counting anticlockwise
NEP	elastic property number relevant to the triangular element
AN	angle which the X-axis of orthotropy of element made with the global X-axis (in degrees)
THICK	thickness of each element
NF(1)	nodal point number 1 with prescribed displacements
NB	NB(1,1) = 0, displacement in X-direction is prescribed
	NB(1,2) = 0, displacement in Y-direction is prescribed
	NB(1,1) = 1, displacement in X-direction is not prescribed
	NB(1,2) = 1, displacement in Y-direction is not prescribed

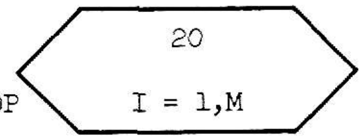
BV	BV(1,1) = prescribed value of displacement in X-direction
	BV(1,2) = prescribed value of displacement in Y-direction
EARTH	force per unit volume in X-direction
DENSIT	force per unit volume in Y-direction
NSTART	first element in each partition
NEND	last element in each partition
NFIRST	first nodal point in each partition
NLAST	last nodal point in each partition
U	loads in X- and Y-directions
E1	Young's modulus in X-direction
E2	Young's modulus in Y-direction
P1	Poisson's ratio in X-direction
P2	Poisson's ratio in Y-direction
GE	shear modulus

FLOW CHART SYMBOLS

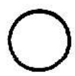
OPERATIONAL STATEMENT OR
STATEMENTS

INPUT OR OUTPUT STATEMENT

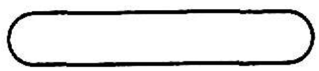
DO LOOP STATEMENT
20 = LAST STATEMENT OF DO LOOP
(I = 1,M) = RANGE OF VARIABLE IN DO LOOP



STATEMENT NUMBER



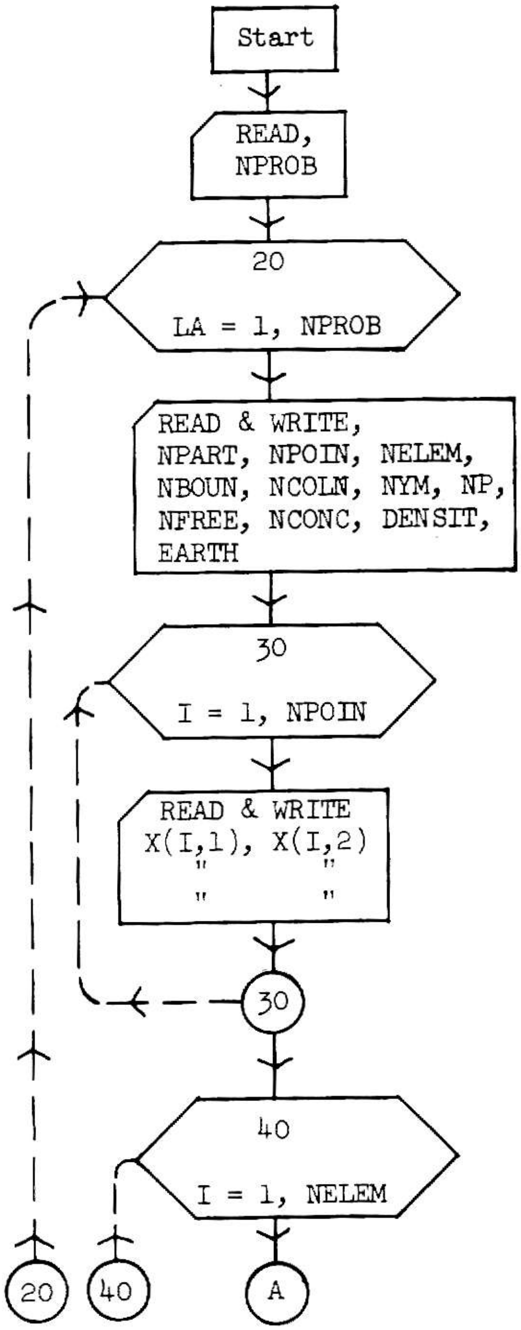
IF STATEMENT



FINELEM FLOW CHARTS

A detailed flow chart of the program FINELEM is shown on the left side of the page and an explanation of the adjacent flow chart operation is given on the right side of the page.

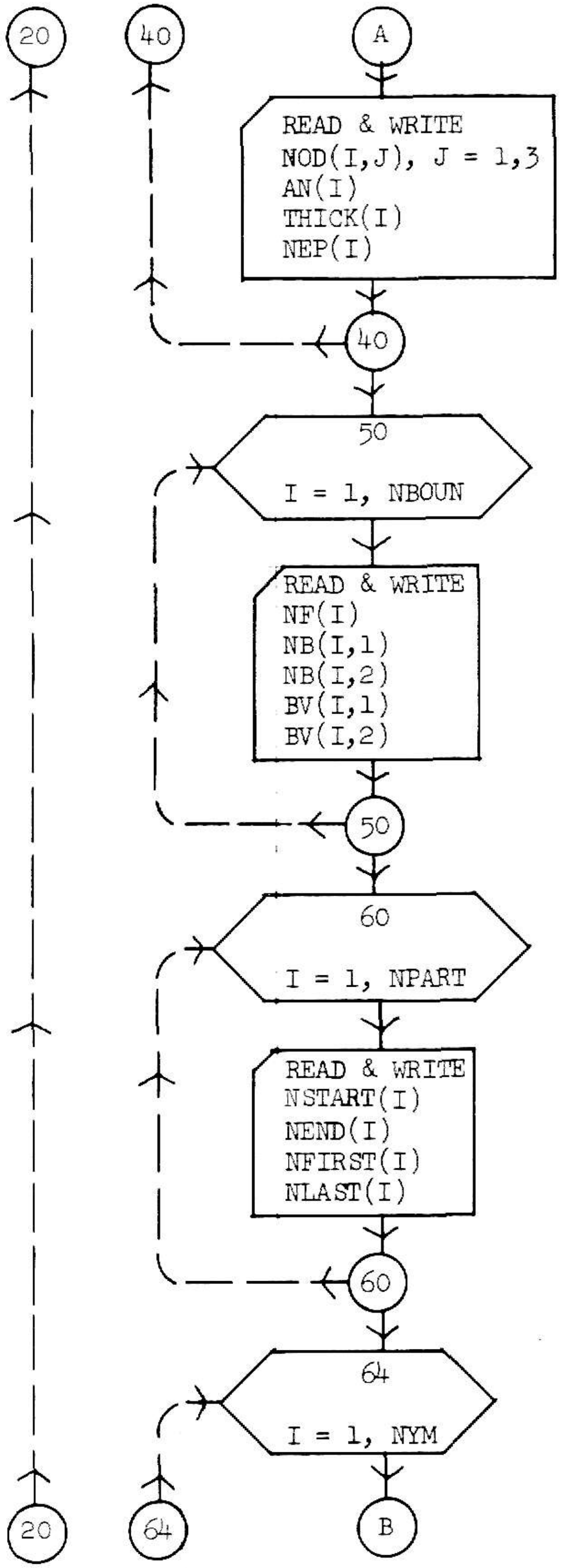
MAIN PROGRAM



Indicate number of problems to be worked.

Indicate parameters of a particular problem; no. partitions, no. elements, etc.

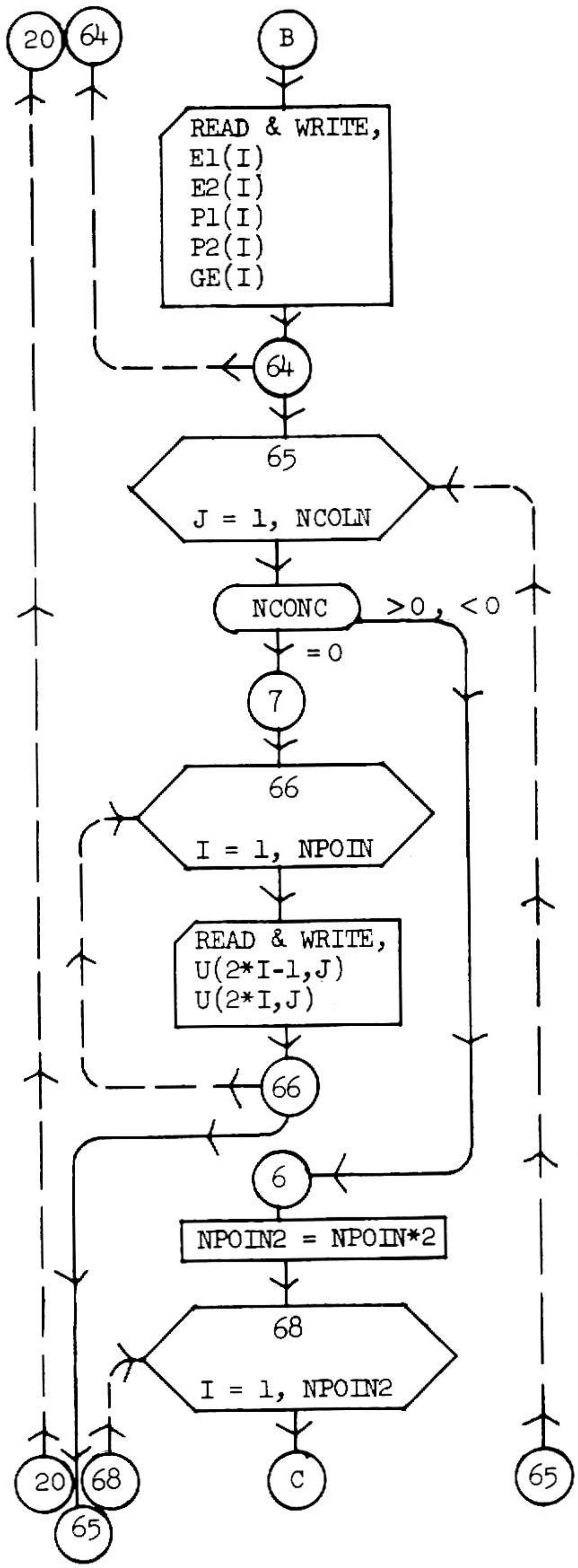
Indicate X and Y coordinates of each nodal point.



Indicate nodal points, angle of deviation, thickness and material property number for each element.

Indicate nodal points with prescribed displacements.

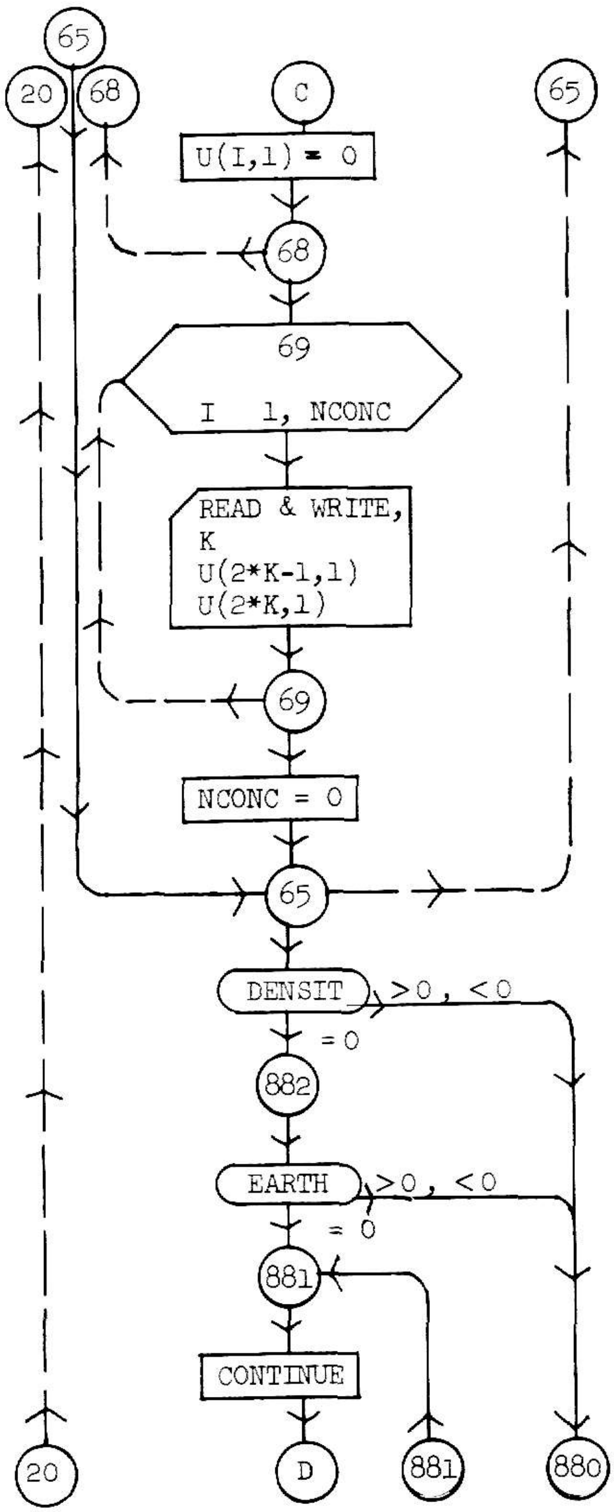
Indicate nodal points and elements in each partition in order.



Indicate different sets of elastic properties.

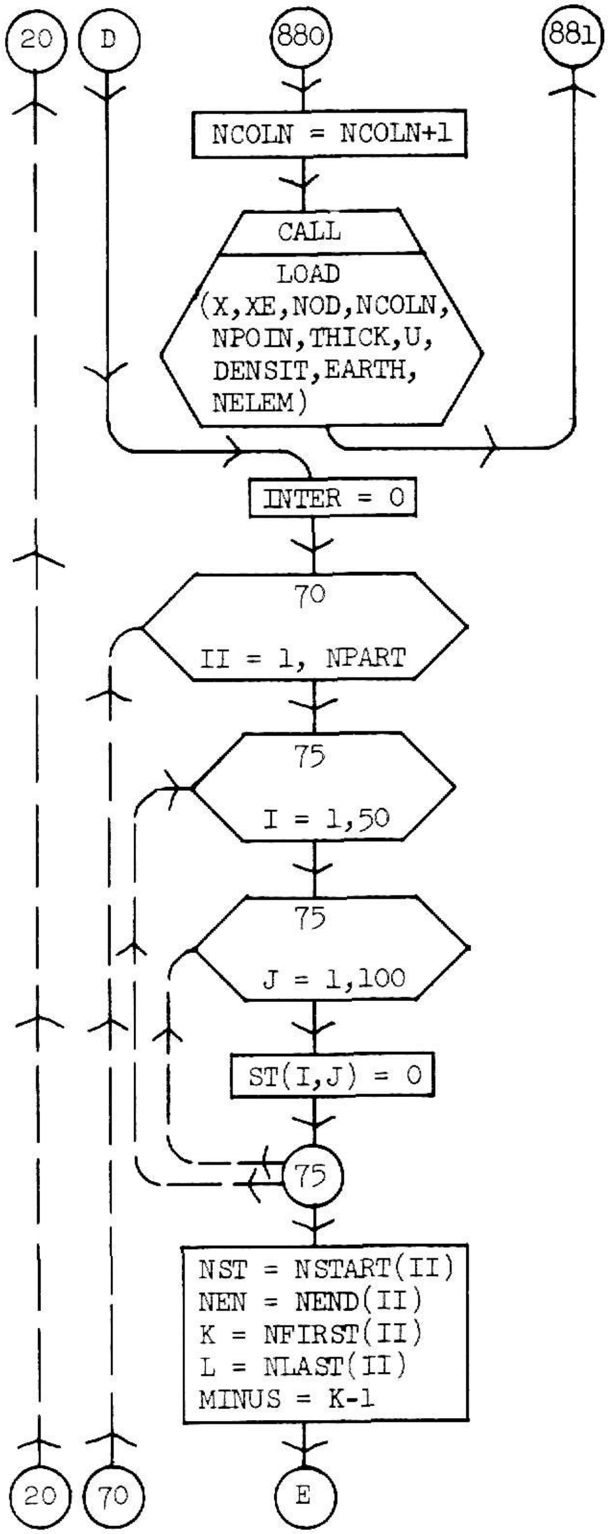
Indicate number of points with concentrated loads. The first option allows only load vectors at specific nodes to be read in.

The second option requires that the load vectors at all nodes be read in.



All data is now in the computer.

If uniform body loads are present, the subroutine LOAD is called to calculate the body forces due to these loads.

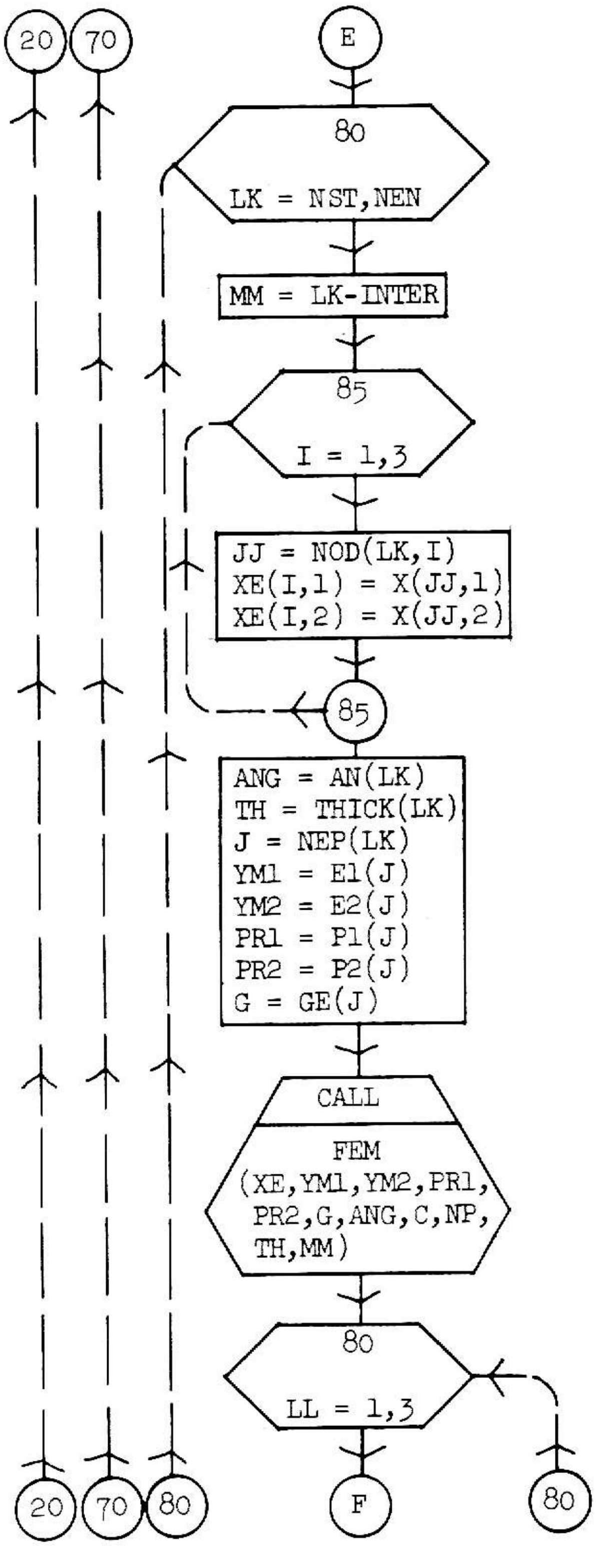


The subroutine LOAD is called.

The appropriate matrices are formed taking the partitions one at a time.

The overall stiffness matrix for a particular partition is initialized. ST(50,100)

The first and last nodes and elements in the partition are specified to be sure the proper partition is used.

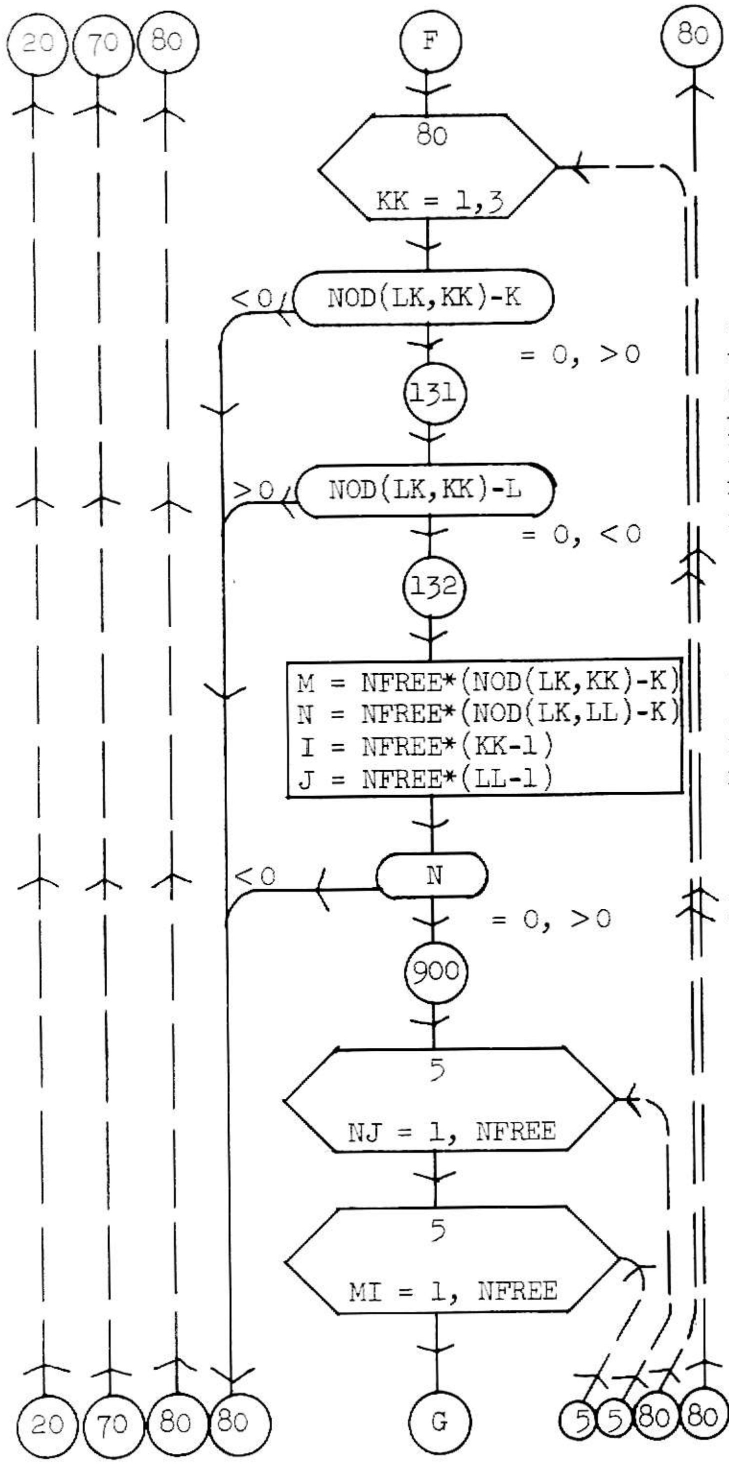


The appropriate matrices for the individual elements are formulated one at a time.

The X and Y components of the element being considered are retrieved.

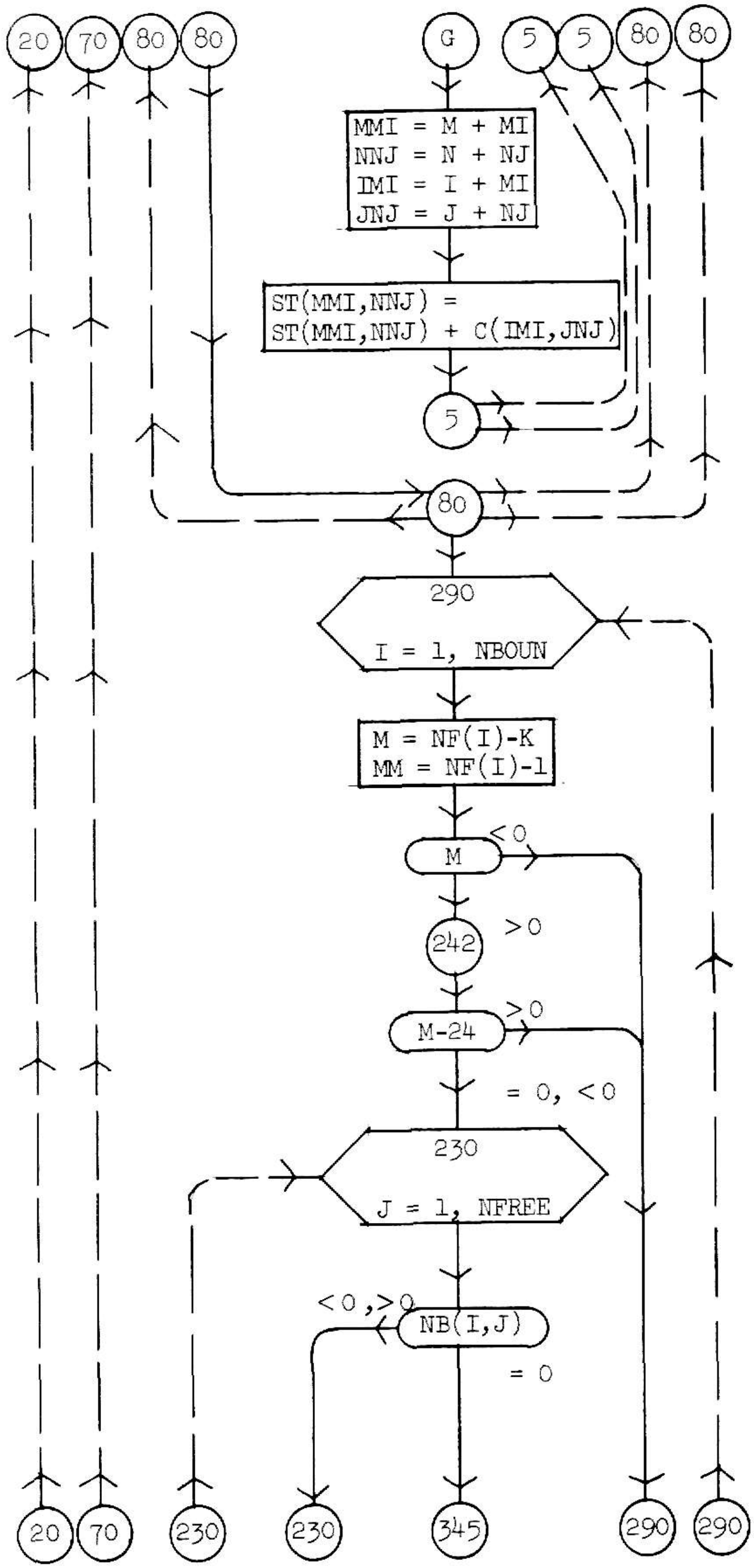
The properties of the element being considered are retrieved.

The subroutine FEM is called to formulate the stress and stiffness matrices for the particular element being considered.



Checks are made to determine which partition the nodal points of the element are in. Nodal points in the partition form the K terms of equation (45) and nodal points out of the partition form the C terms of equation (45).

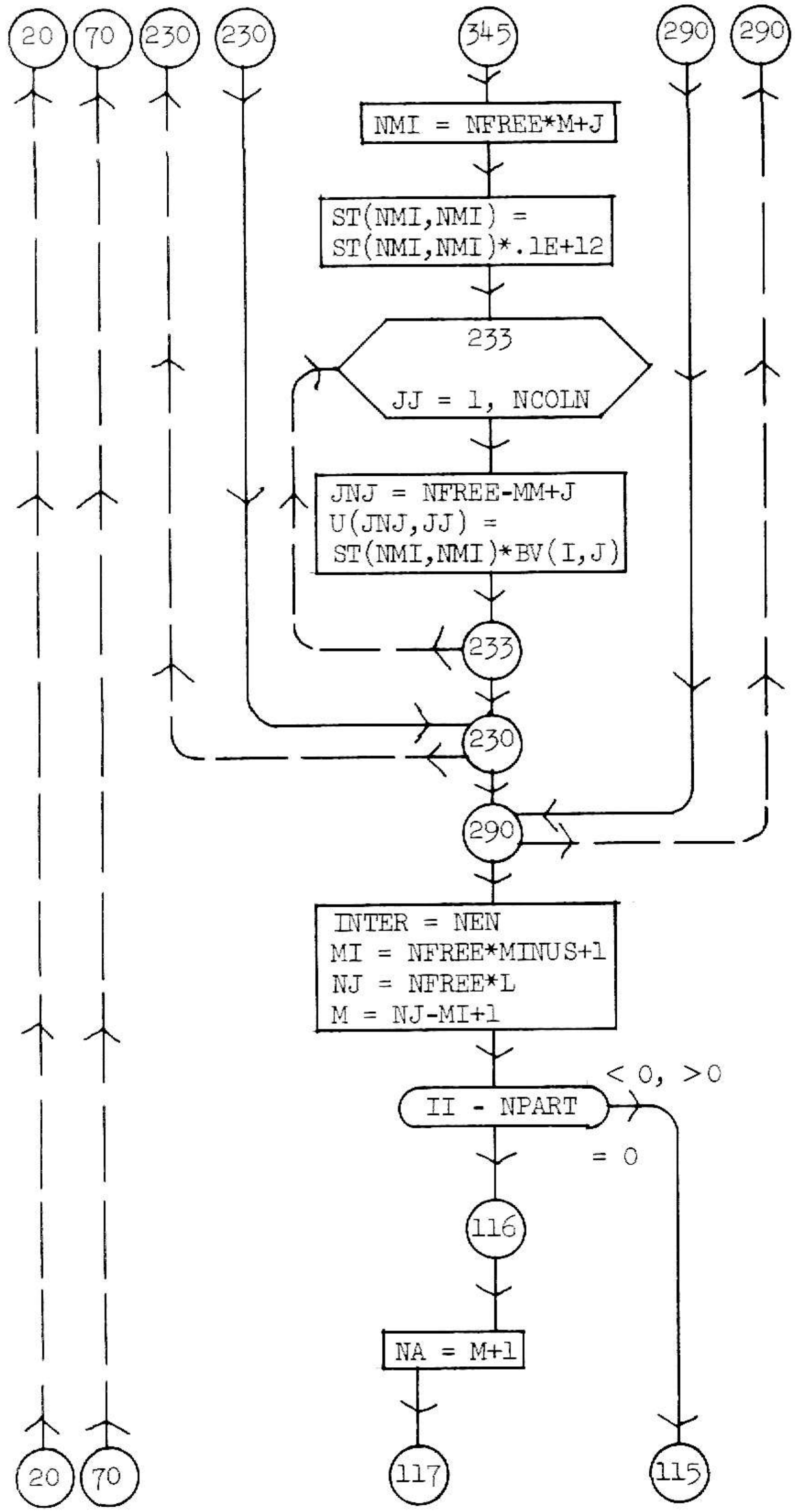
These coefficients specify the location of the element stiffness matrix in the overall partition matrix. The K and C terms of equation (45) are being formed. The subscript on the terms of equation (45) indicate the partition being considered.



The individual element stiffness is inserted in the overall partition matrix.

The prescribed displacements are introduced.

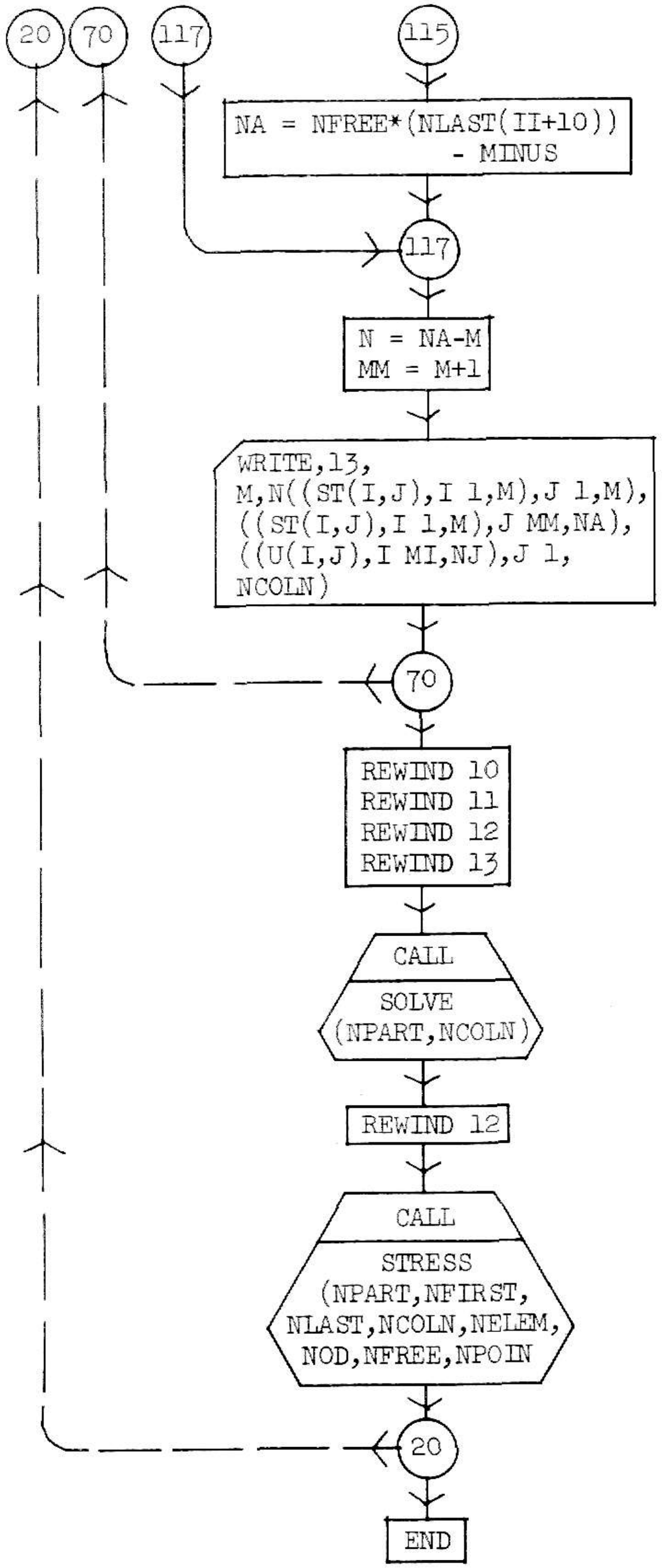
Only prescribed displacements at the nodal points in the partition being considered are introduced.



The prescribed displacements are multiplied by a large number.

The known displacements are inserted in the displacement matrix.

A check is made to see if the last partition was being considered.

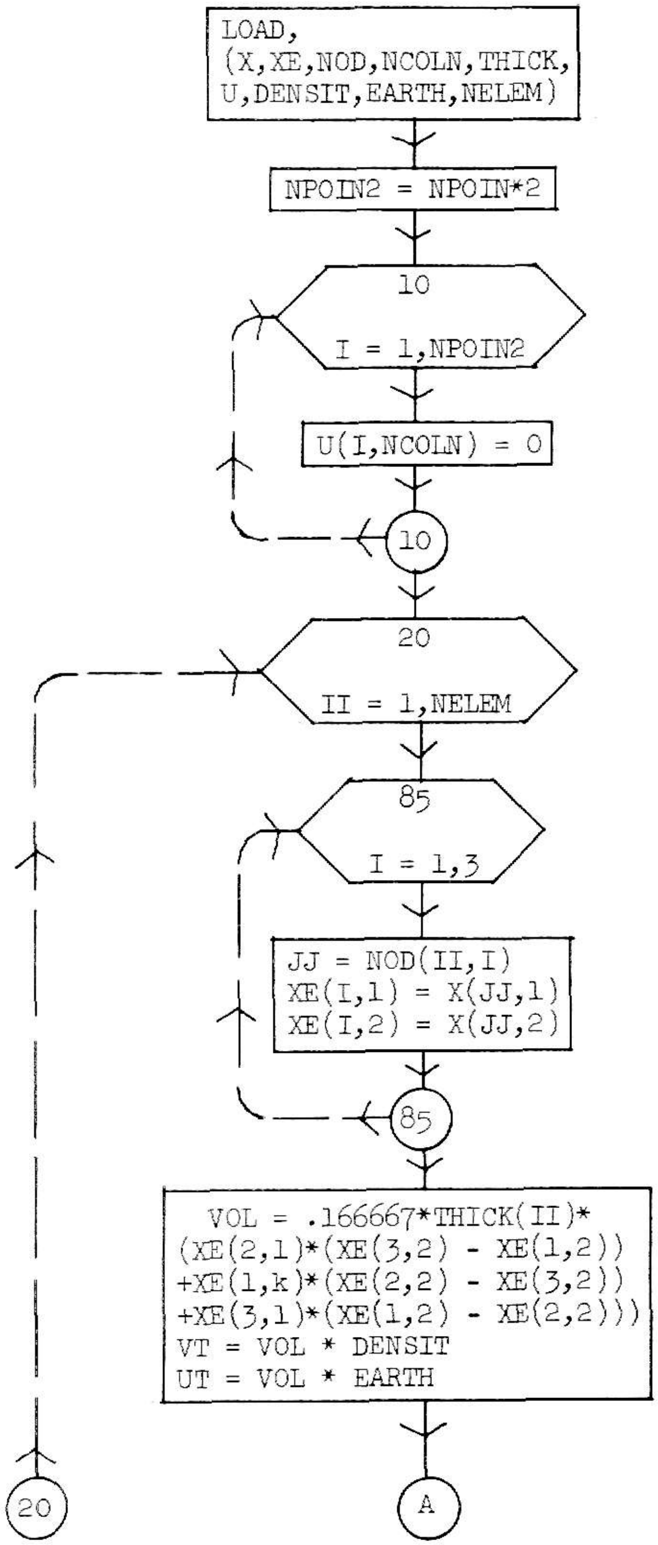


The [K], [C] and known displacement terms of the tridiagonalized stiffness matrix, equation (45), are stored for future use.

The subroutine SOLVE calculates the unknown displacements by following the theory given in equations (45) through (51). An error check is made according to equation (52). All of the terms of equation (41) are known; therefore, all terms are defined.

The stresses are calculated at the centroid of each element and are resolved into principal stresses and their angle of deviation from the original coordinate system.

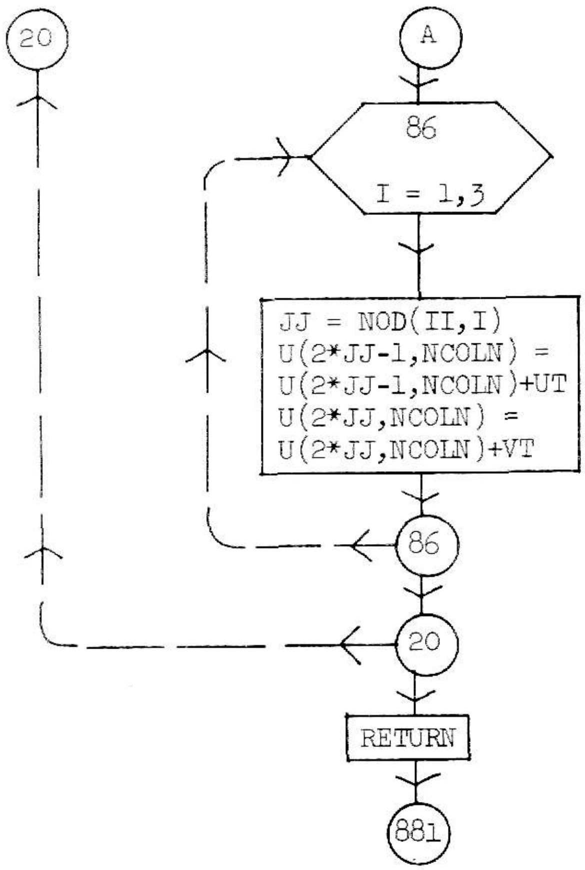
SUBROUTINE LOAD



The load vector due to the body forces is initialized.

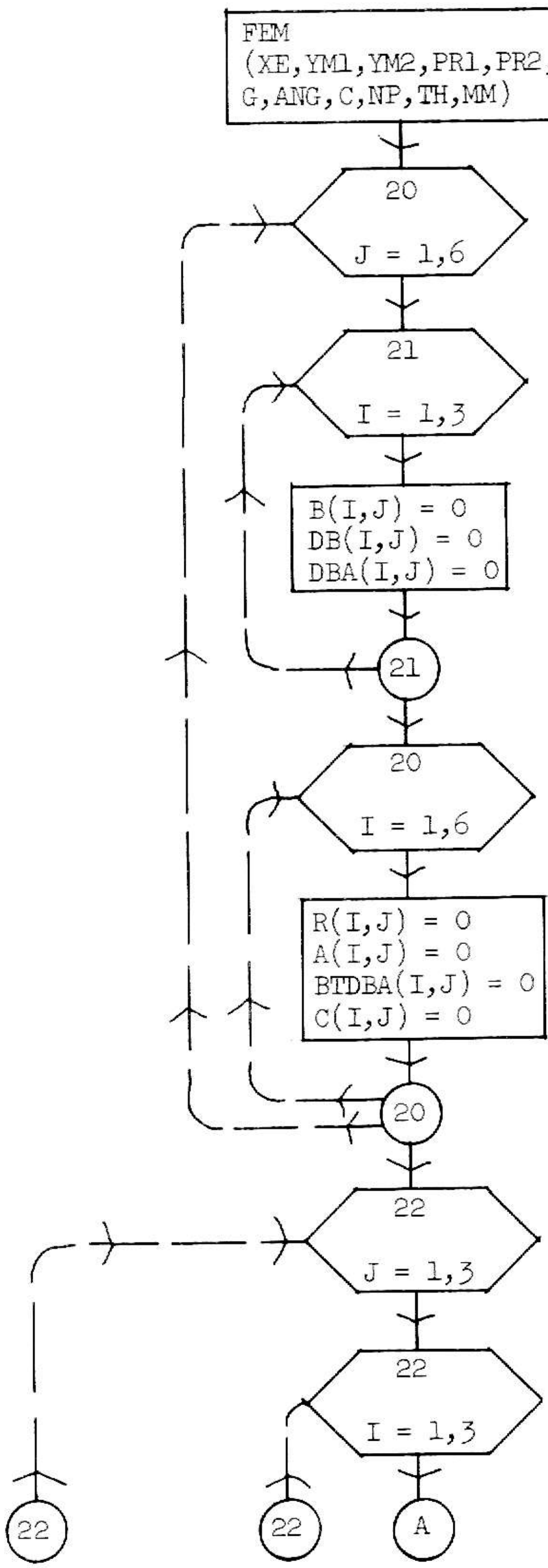
The nodal points of the element being considered are retrieved.

This operation is equation (11) times the element thickness divided by 6, which when multiplied by the appropriate body force per unit volume yields the terms that make up equation (35).



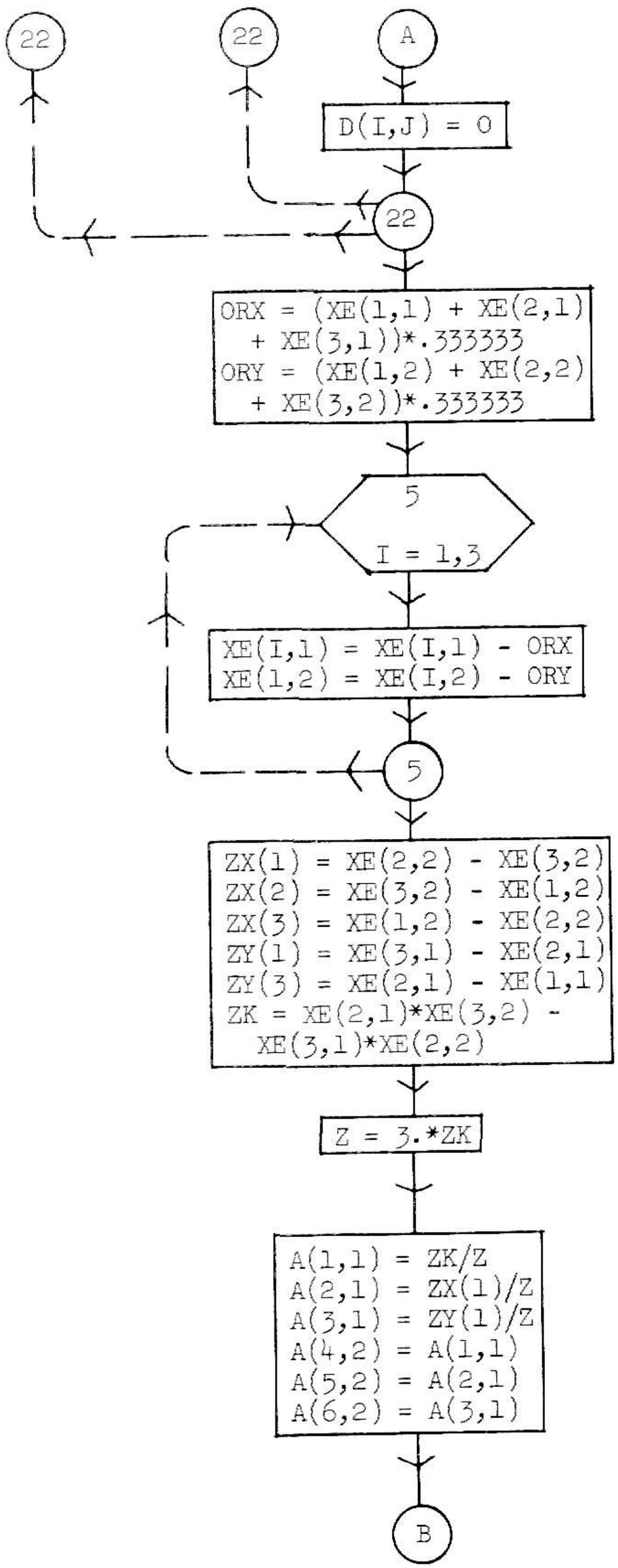
The terms that make up equation (35) are arranged in the appropriate places to yield equation (35).

SUBROUTINE FEM



Initialize matrices.

Initialize matrices.



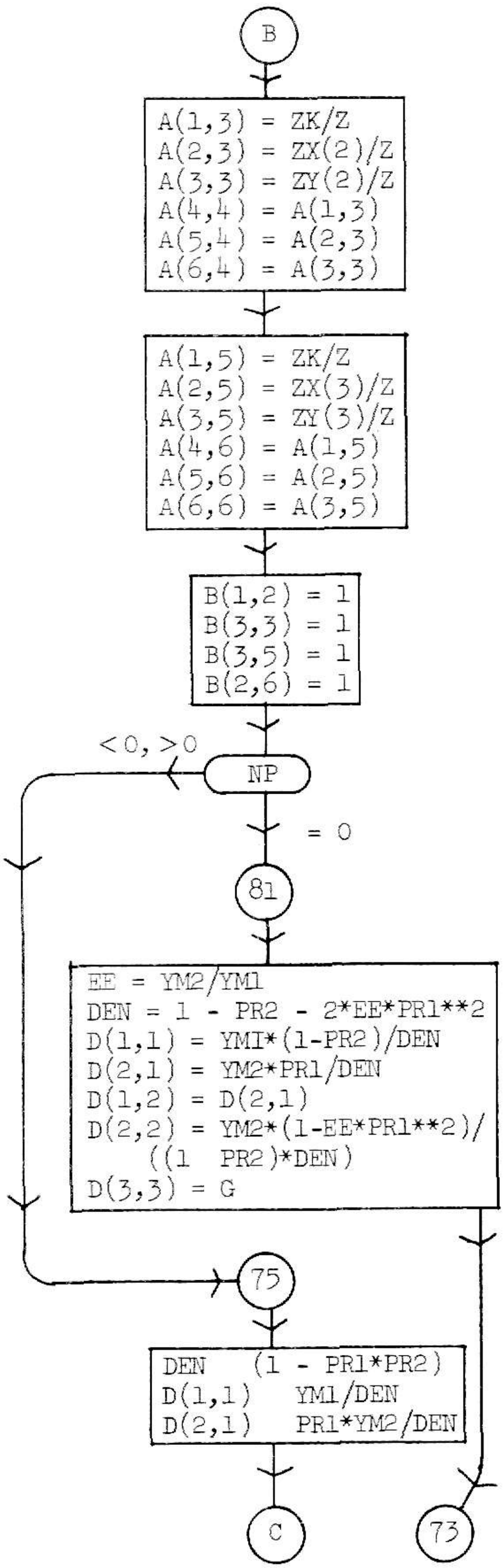
Locate the centroid of a particular element relative to the original X,Y coordinate system.

Locate nodal points relative to an X,Y coordinate system through the element centroid.

The terms of equation (10) are formed in the following order: $b_i, b_j, b_m, c_i, c_j, c_m, a_i, a_j$, and a_m where $a_i = a_j = a_m$.

The relationships of equation (15) are made use of

The term N_i' of equations (13) and (14) is formed.



The term N_j' of equations (13) and (14) is formed.

The term N_m' of equations (13) and (14) is formed.

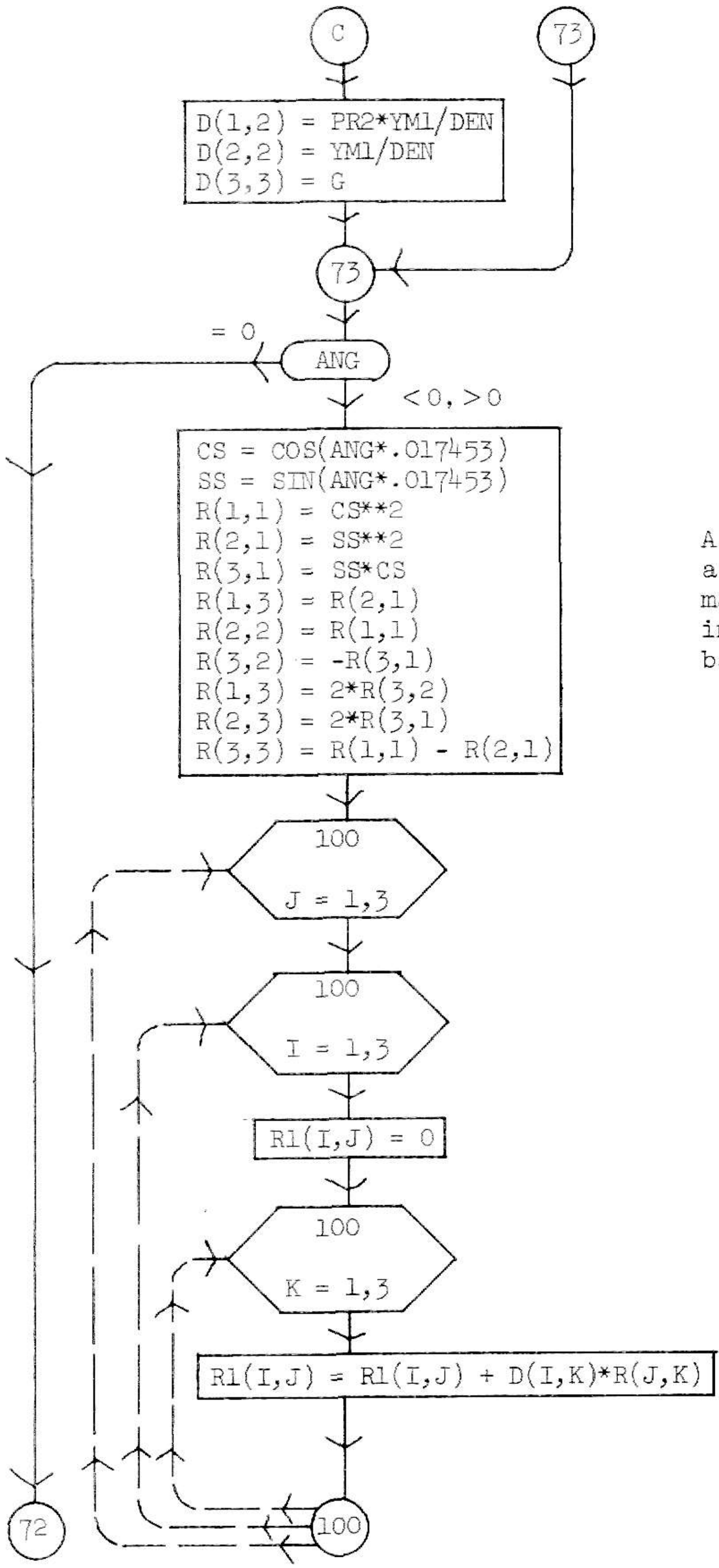
The relationships of equations (9) and (12) are formed.

This is an intermediate step in the formation of the matrix of equation (16).

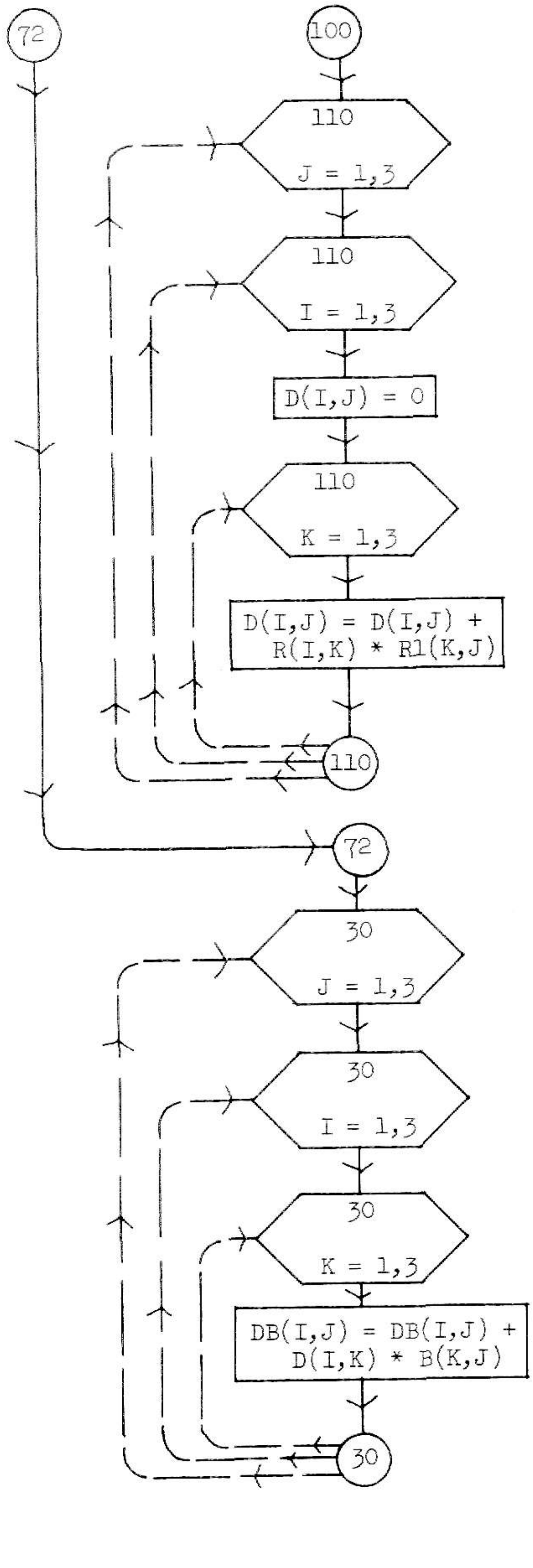
The formation of the plane stress or plane strain matrix is specified.

The elasticity matrix for the plane strain case is formed.

The elasticity matrix for the plane stress case is formed, equation (22)

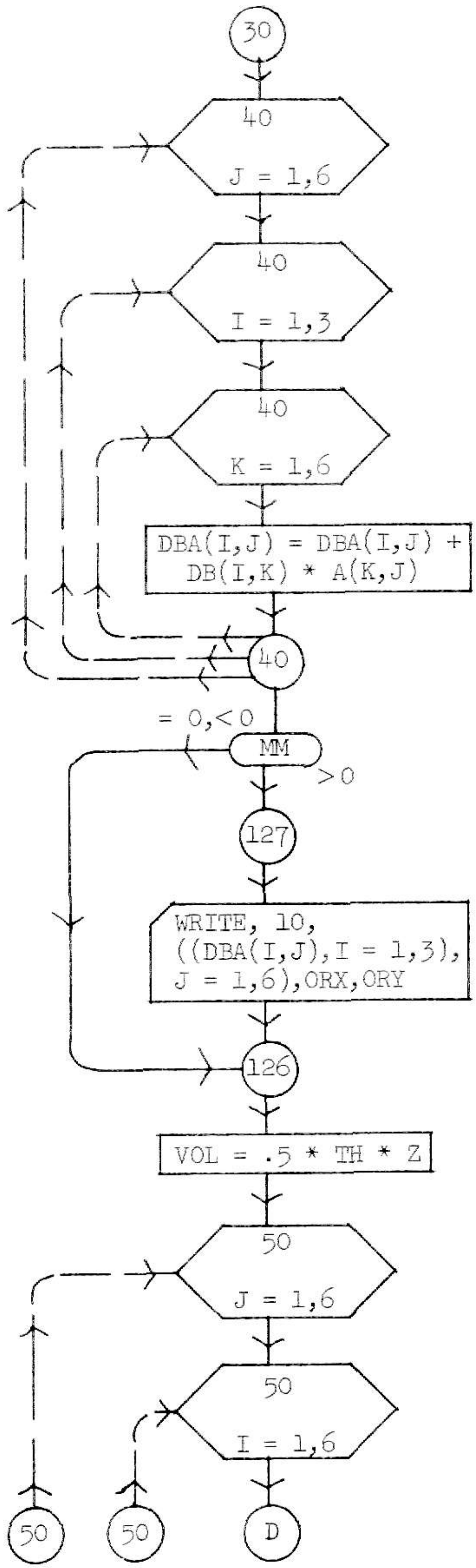


A matrix for transforming a transversely isotropic material from an axis inclined to the major axis back to the major is formed.



The axis transformation matrix is formed.

The [A] and [B] matrices are multiplied together as a step in the formation of the stress and stiffness matrices.



The [DBA] matrix is formed.

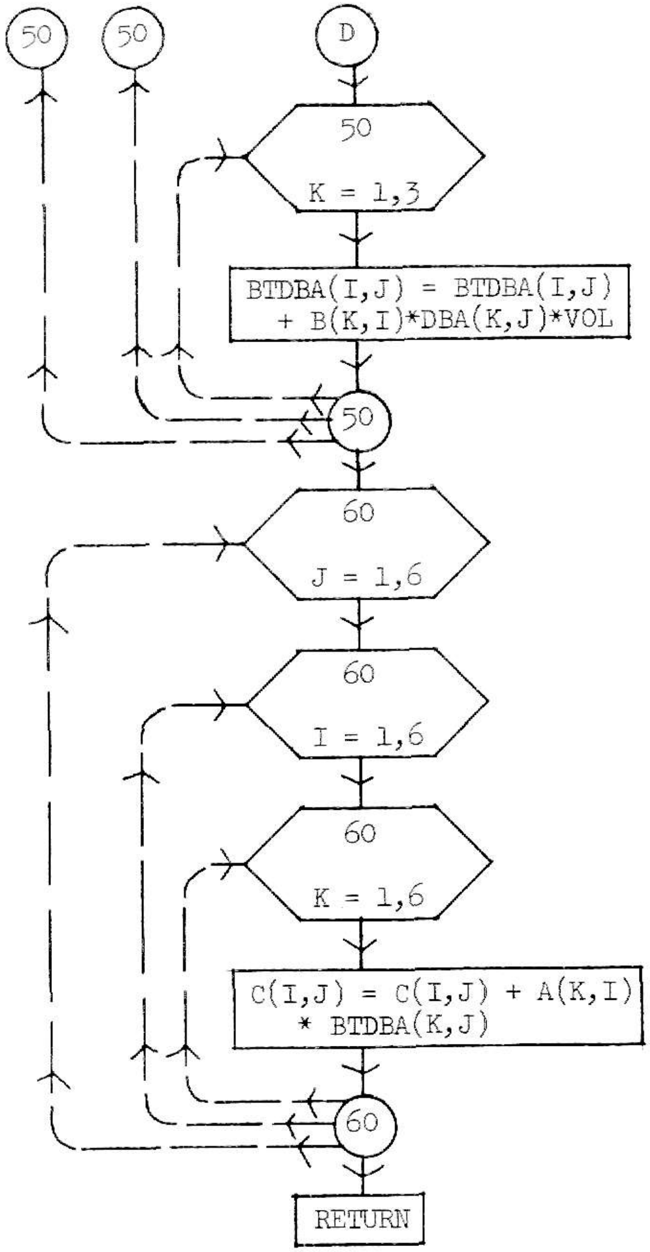
The [DBA] matrix in the program notation is the stress matrix of equation (44).

[D] in program notation is [D] in the report notation.

[B][A] in program notation is [B] in the report notation.

The element stress matrix is stored on a disc for use later in calculating the stresses at the centroid of the element.

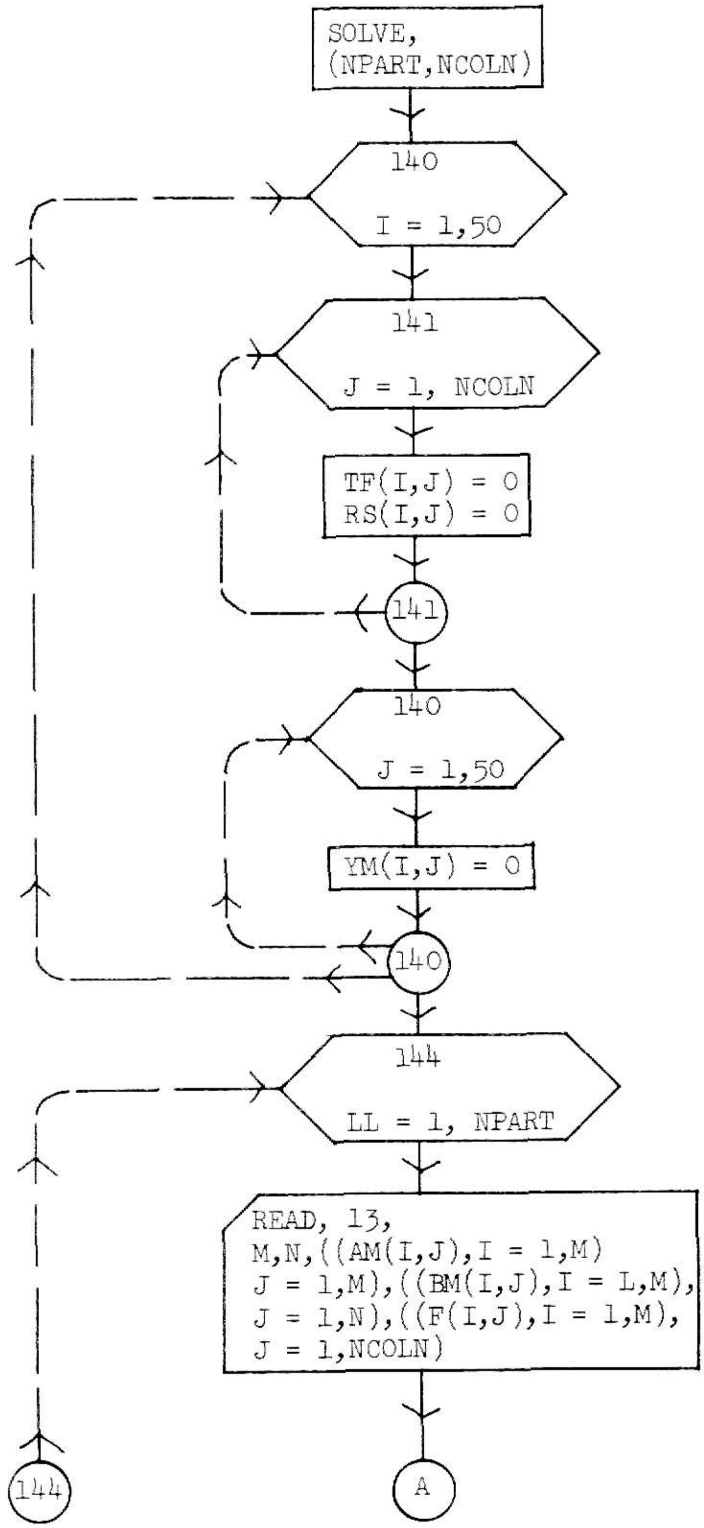
The Δ and t of equation (33) are formed.



This is a preliminary step in the formation of the element stiffness matrix.

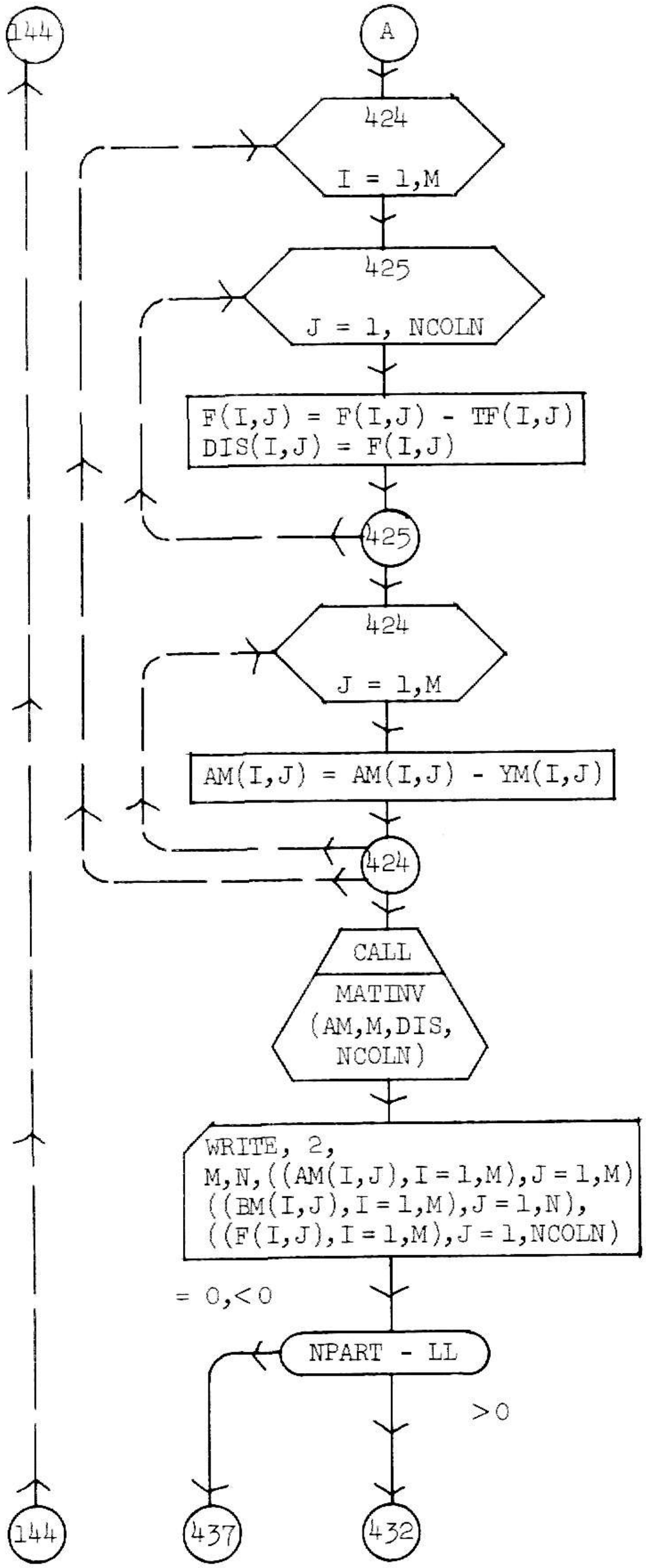
The element stiffness matrix, equation (33), is formed.

SUBROUTINE SOLVE



Initialize matrices.

The terms of the tridiagonalized stiffness matrix, equation (45), for each partition are read in one at a time. These terms are [K], [C], and [P] of equation (45).

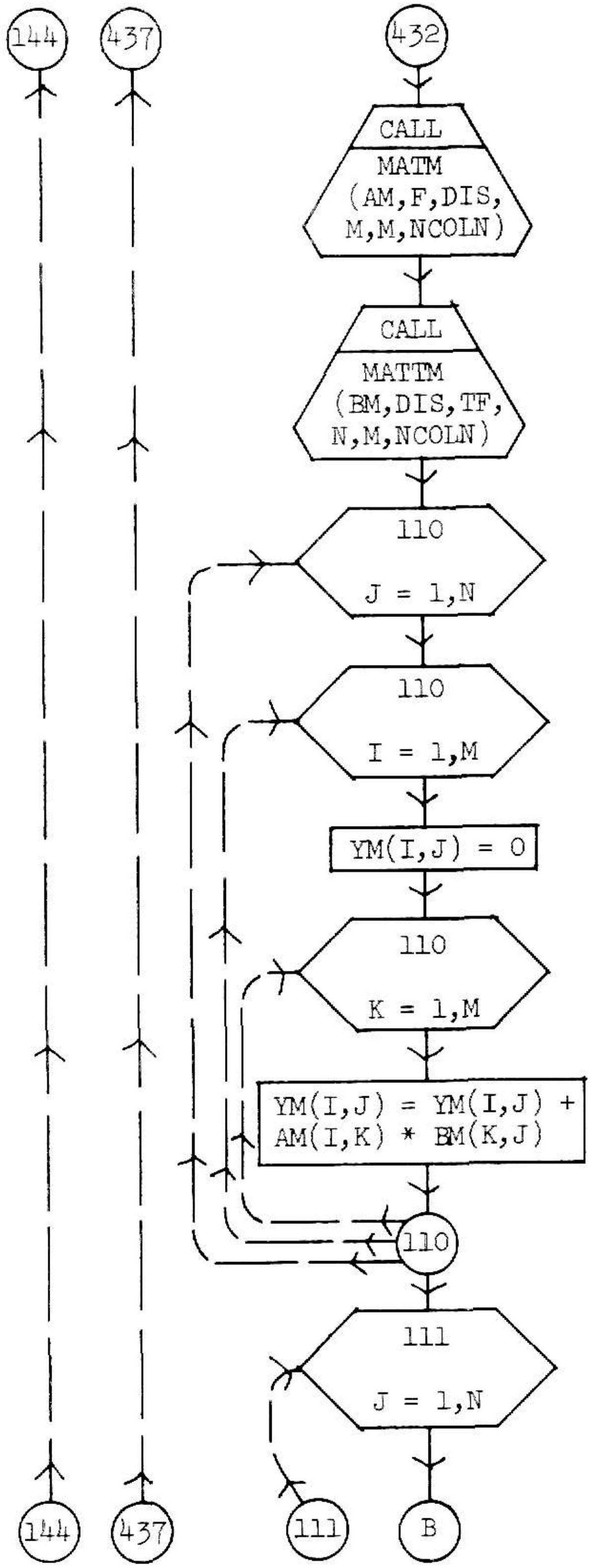


The [P] matrix of equation (46) is formed.

The [K] matrix of equation (46) is formed.

This subroutine inverts the [K] matrix and multiplies it by the [P] matrix to form the first term to the right of the equal sign in equation (47).

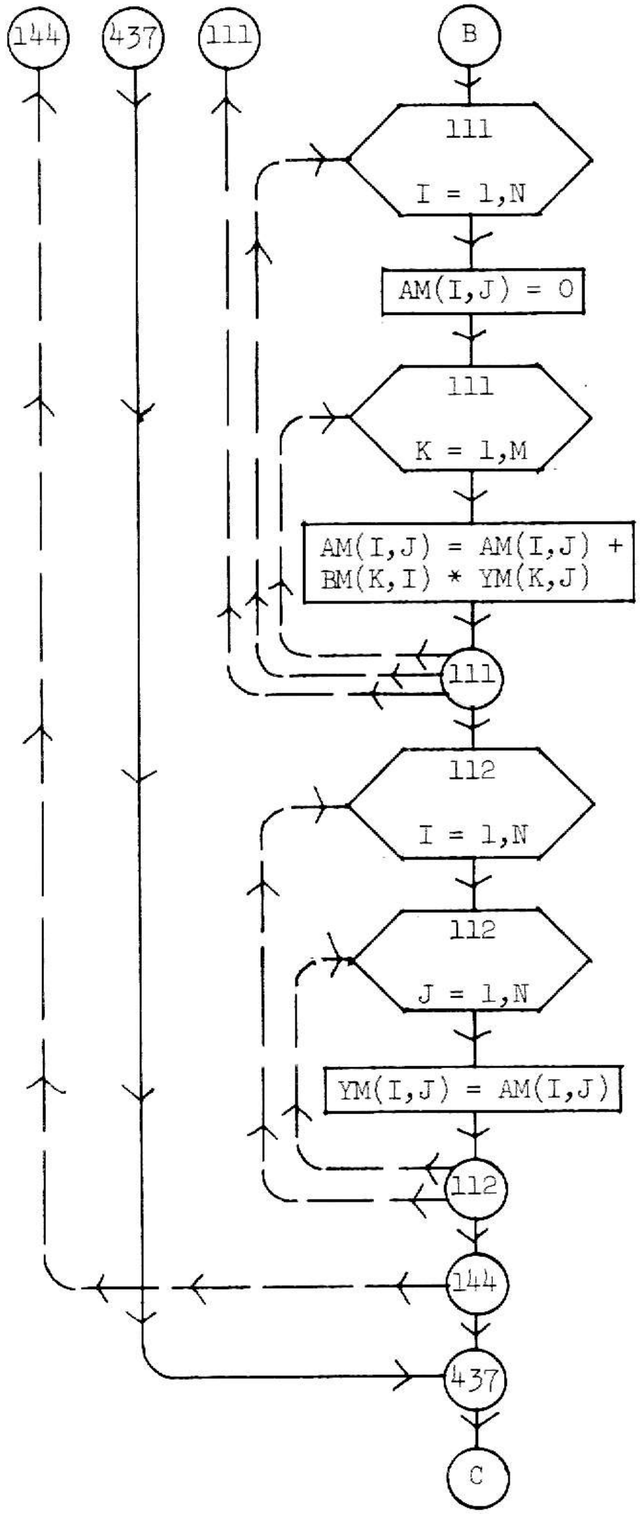
The term formed above is stored for future use.



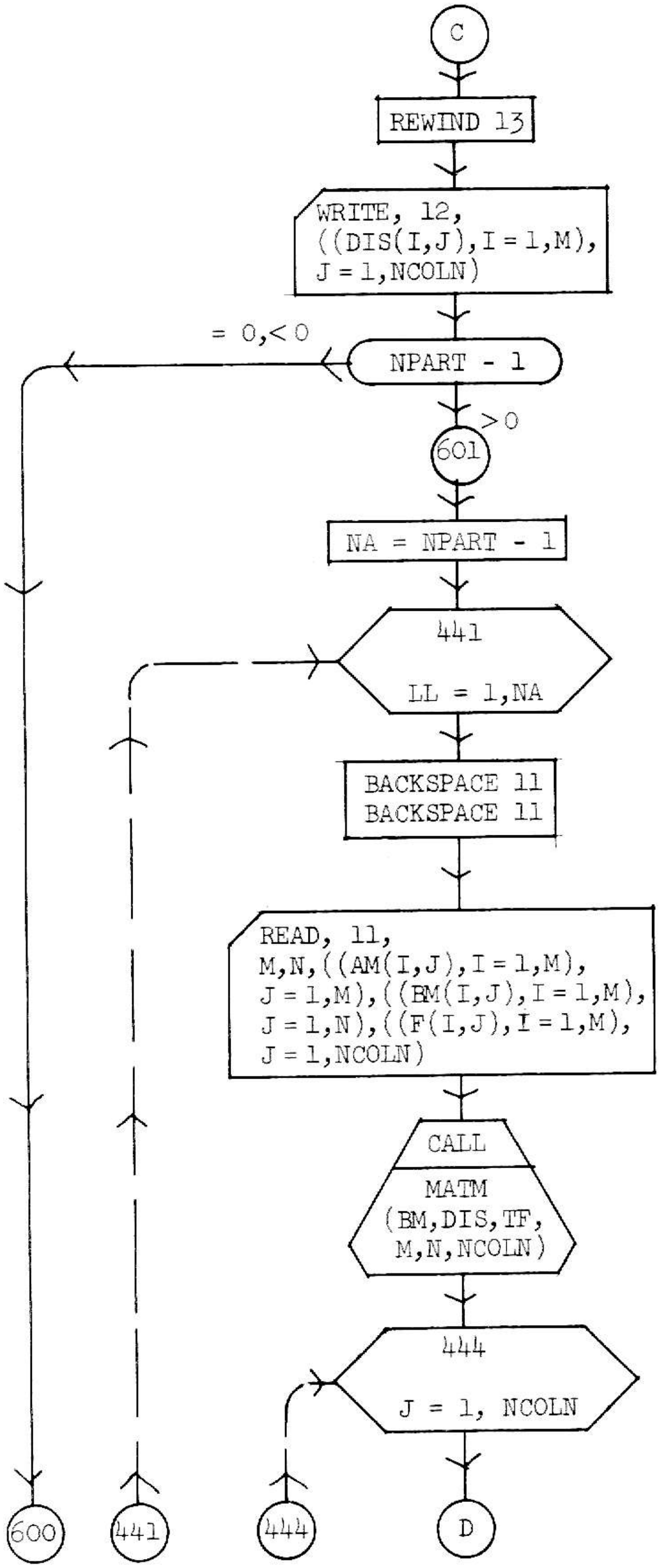
This subroutine multiplies the inverted [K] matrix by the [C] matrix to form part of the second term to the right of the equal sign in equation (47).

This subroutine transposes the [C] matrix of equation (46) and multiplies it by the first term to the right of the equal sign in equation (47) to form the second term to the right of the equal sign in equation (48).

The inverted [K] matrix is multiplied by the [C] matrix to form part of the second term of the first two terms enclosed in the first parenthesis of equation (48).



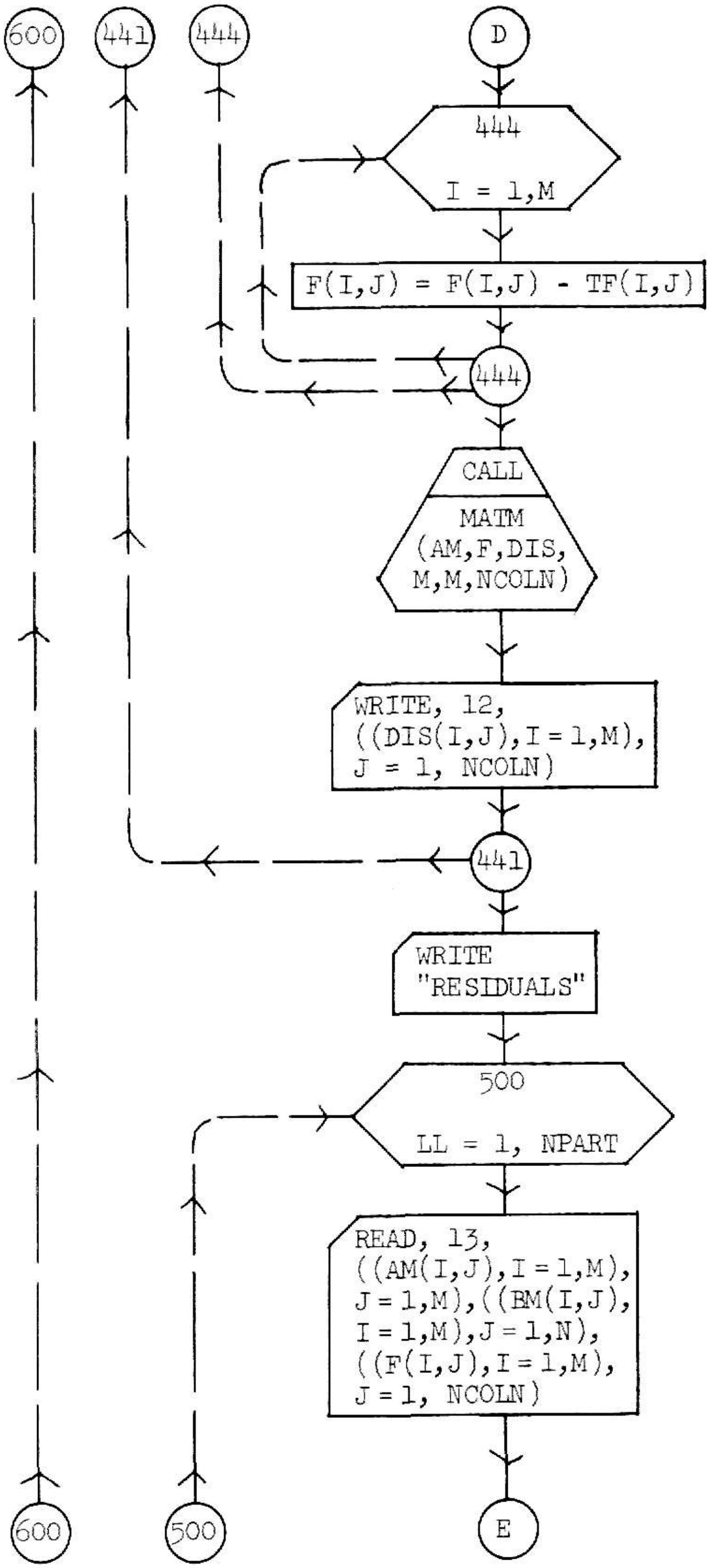
The term formed in the last operation is multiplied by the transposed [C] matrix to form the second term of the two terms enclosed in the first parenthesis of equation (48).



Store the inverted [K] matrix times the [P] matrix for future use.

Read the second line of equation (45) which includes some of the terms in equation (46).

This subroutine multiplies [C] times {δ} to form the second term of equation (46).

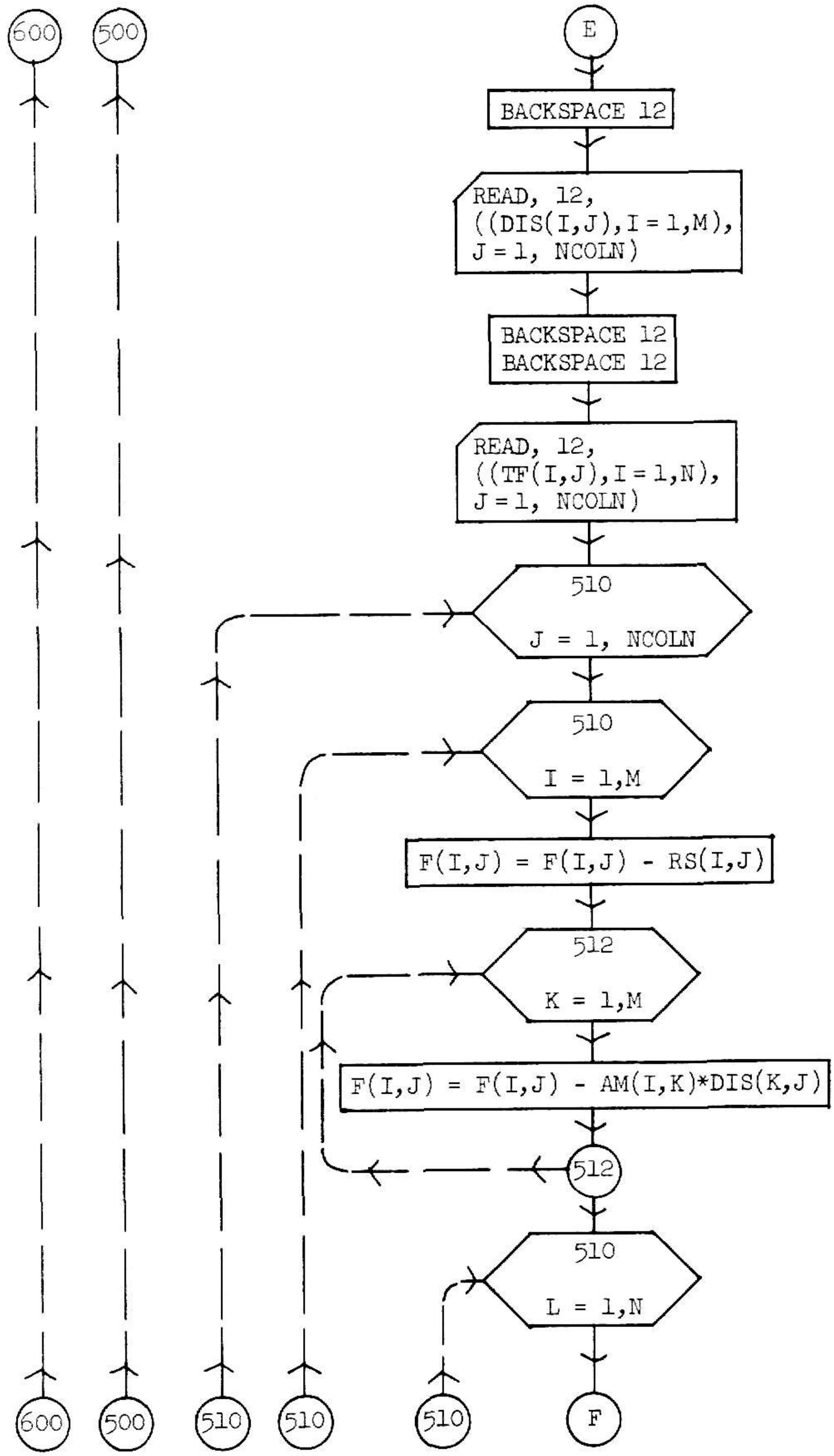


The second term of equation (46) is subtracted from the third term of equation (46) and set equal to the first term of equation (46).

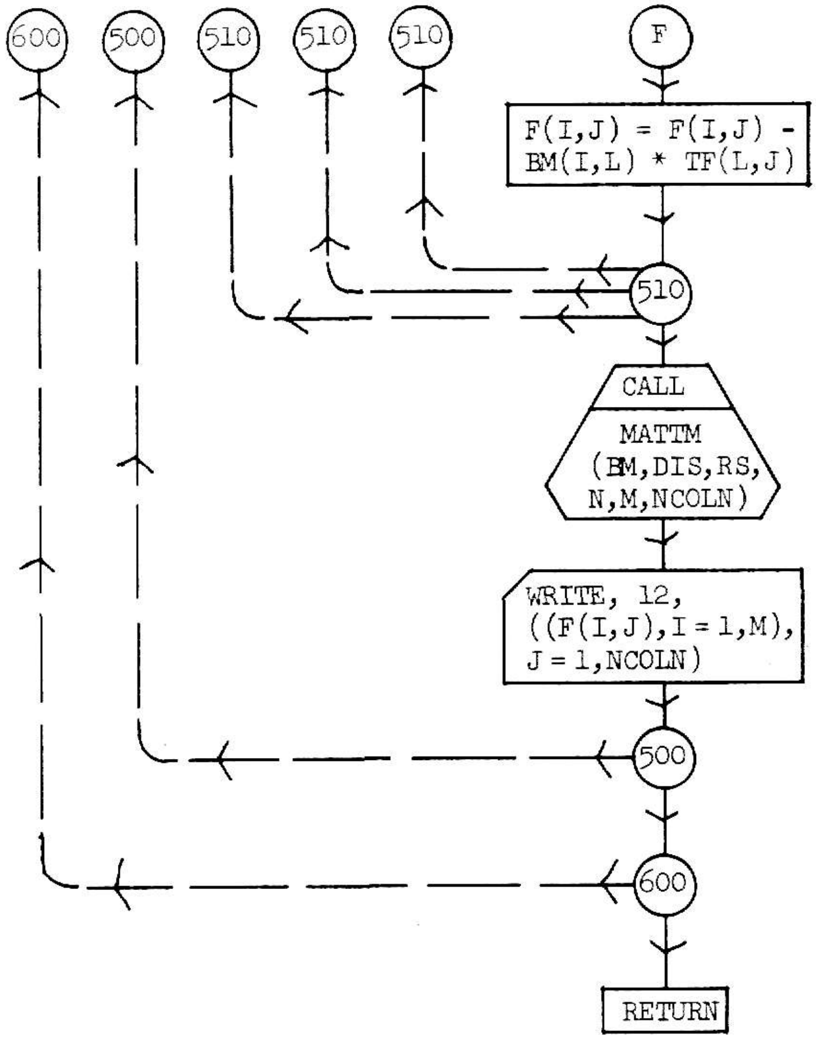
Multiply the term formed above by the inverted K matrix to form $\{\delta\}$. This process is repeated until $\{\delta_N\}$ of equation (51) is calculated.

All the displacements of equation (45) are stored.

The known $\{\delta\}$ are back substituted into equation (45) to make an order of error check.



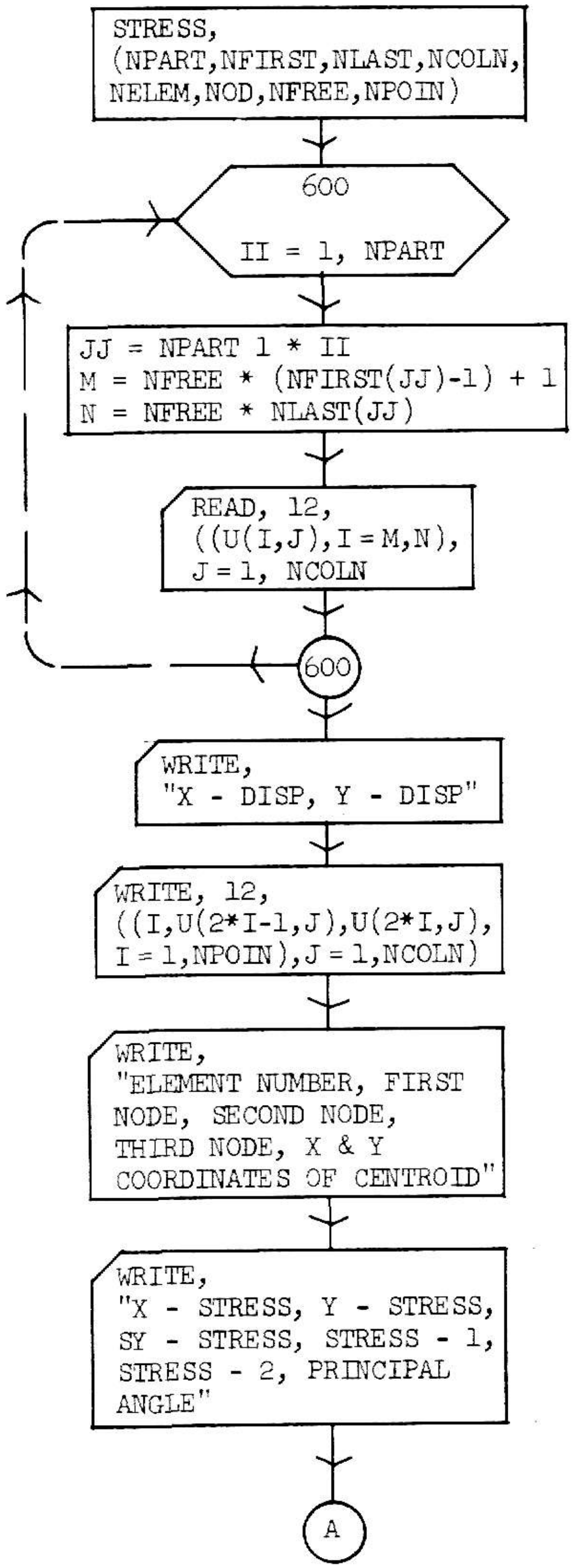
600
500
E
BACKSPACE 12
READ, 12, ((DIS(I,J),I=1,M), J=1, NCOLN)
BACKSPACE 12
BACKSPACE 12
READ, 12, ((TF(I,J),I=1,N), J=1, NCOLN)
510 J = 1, NCOLN
510 I = 1,M
F(I,J) = F(I,J) - RS(I,J)
512 K = 1,M
F(I,J) = F(I,J) - AM(I,K)*DIS(K,J)
512
510 L = 1,N
600
500
510
510
510
F



The R term of equation (52) is formed.

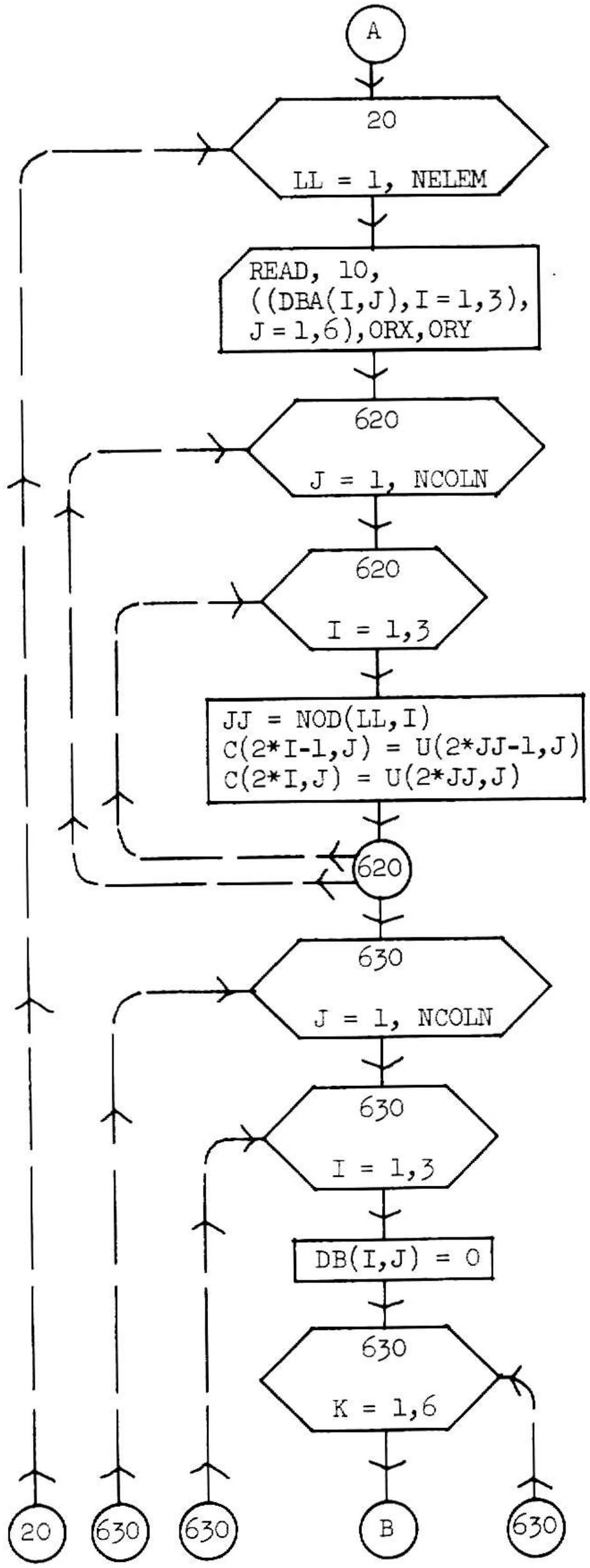
The residuals of equation (52) are printed out. If the magnitude of the residuals is too great they can be used as a load vector and the problem can be reworked.

SUBROUTINE STRESS

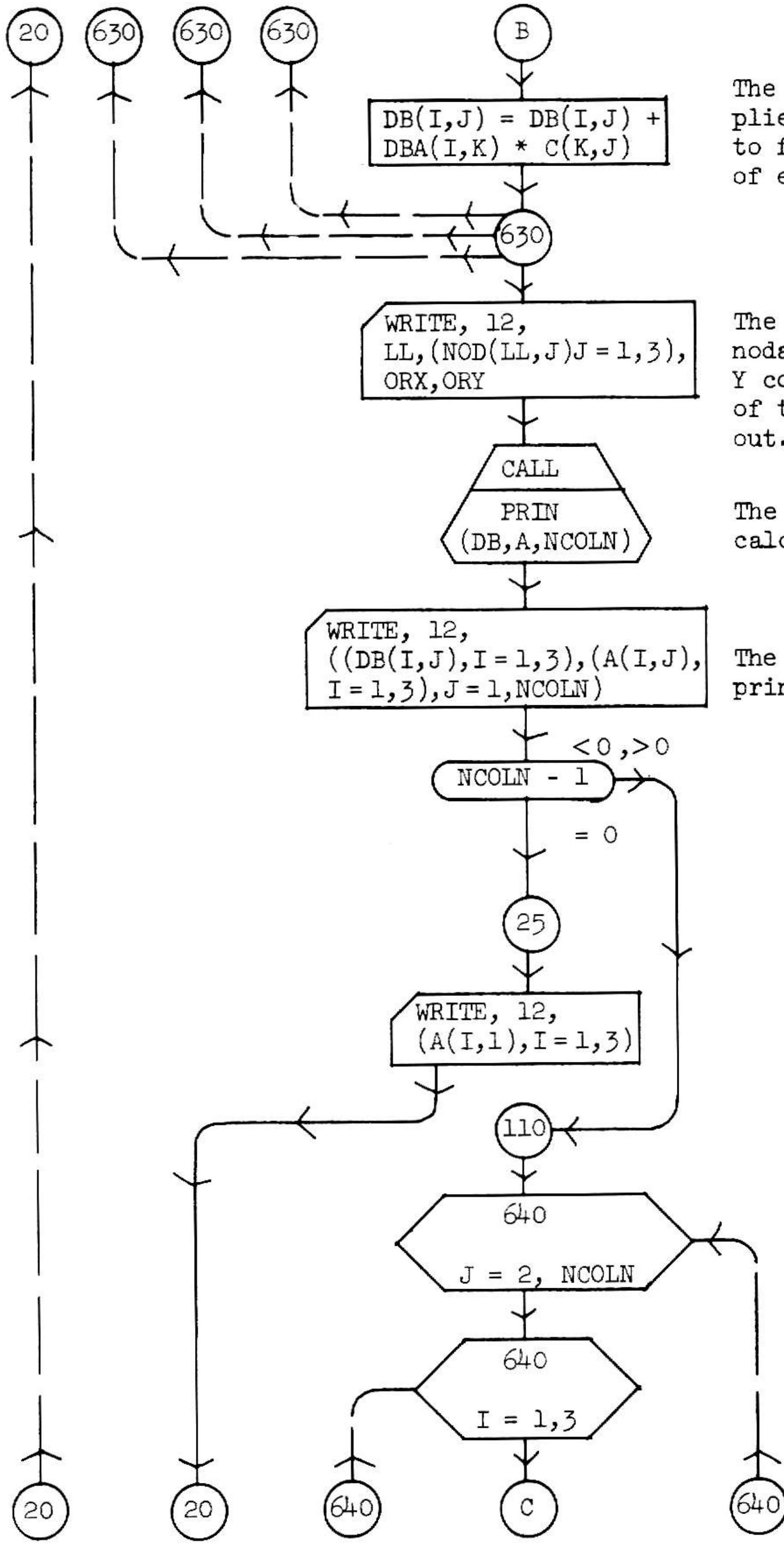


The nodal displacements are recalled from storage.

The node number and its X and Y displacements are printed out.



The element stress matrices are recalled from storage.

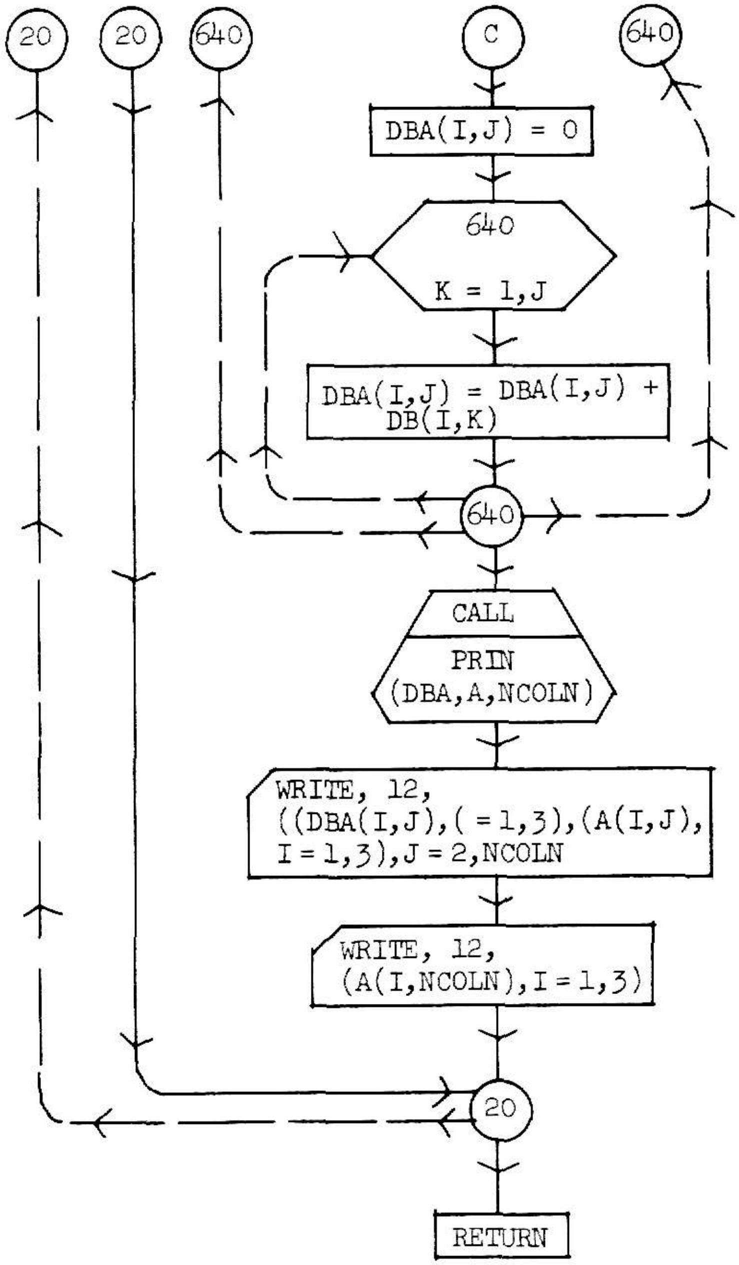


The stress matrix is multiplied by the displacement to form the stress matrix of equation (2).

The element number, its nodal points, and the X and Y coordinates of the centroid of the element are printed out.

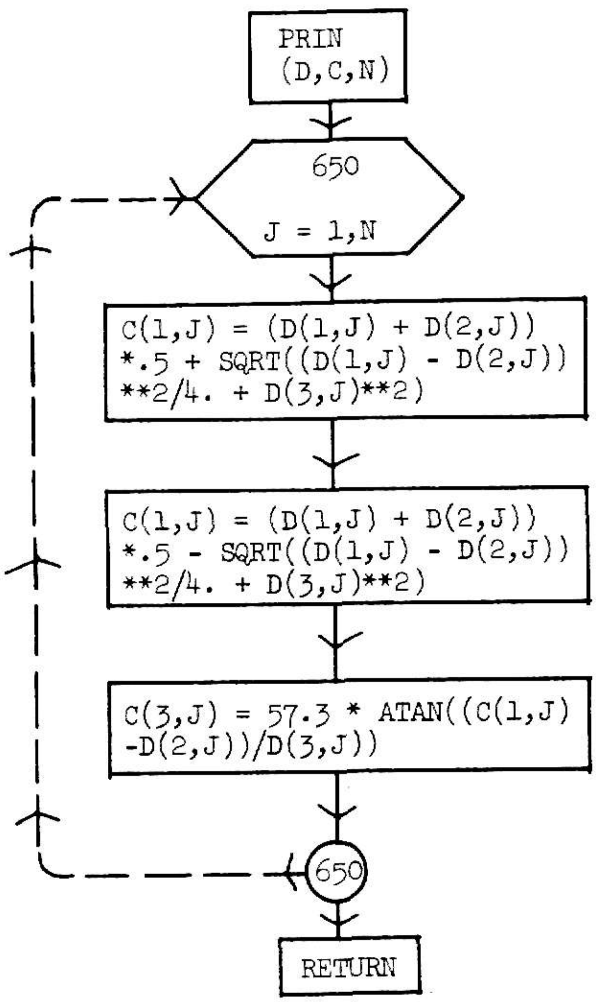
The principal stresses are calculated.

The principal stresses are printed out.



20
20
640
C
640
DBA(I,J) = 0
640
K = 1,J
DBA(I,J) = DBA(I,J) + DB(I,K)
640
CALL
PRIN (DBA,A,NCOLN)
WRITE, 12, ((DBA(I,J),(= 1,3),(A(I,J), I = 1,3),J = 2,NCOLN
WRITE, 12, (A(I,NCOLN),I = 1,3)
20
RETURN

SUBROUTINE PRIN



The maximum principal stress is calculated from σ_x = D(1,J), σ_y = D(2,J), and τ_{xy} = D(3,J) using Mohr's circle.

The minimum principal stress is calculated from σ_x, σ_y, and τ_{xy}.

The angle of deviation in (degrees) of the maximum principal stress from the X-axis is calculated.

SUBROUTINES MATTM, MATM, AND MATINV

SUBROUTINE MATTM (D,B,DB,L,M,N)

MATTM is a standard IBM subroutine which transposes the matrix D(L,M), multiplies it by the matrix B(M,N), and assigns the product to the matrix DB(L,N).

SUBROUTINE MATM (D,B,DB,L,M,N)

MATM is a standard IBM subroutine which multiplies the matrix D(L,M) by the matrix B(M,N) and assigns the product to the matrix DB(L,N).

SUBROUTINE MATINV (A,N,B,M)

MATINV is a standard IBM subroutine which inverts the matrix A(N,N), multiplies it by the matrix B(N,M), and assigns the product to the matrix B(N,M).

FINELEM PROGRAM LISTING

The control cards, main program, subroutines, and data location are shown in this section. The Fortran statements listed in this section in the order they are listed form the program FINELEM, which will run on the IBM 360 computer at Kansas State University.

```
 C       THESE ARE CONTROL CARDS

// FINELEM JOB  (OFK40260G001,10,2,,,2),'                    ',MSGLEVEL=1
//               EXEC FTGCLGKS,PARM.FORT='MAP',PARM.LKED='LIST,LET,MAP'
//FORT.SYSIN    DD    *

 C       MAIN PROGRAM

 C       THESE ARE CONTROL CARDS

//GO.FT12F001 DD DSNAME=&DSKSETC,UNIT=(SYSDA,SEP=FT11F001),                X
//               DCB=(RECFM=V,LRECL=293,BLKSIZE=297),SPACE=(CYL,(10,10))
//GO.FT13F001 DD DSNAME=&DSKSETD,UNIT=(SYSDA,SEP=FT12F001),                X
//               DCB=(RECFM=V,LRECL=293,BLKSIZE=297),SPACE=(CYL,(10,10))
//GO.SYSIN      DD    *

 C       DATA CARDS GO HERE
```

```
C     MAIN PROGRAM
      DIMENSION X(350,2),XE(3,2),NF(30),NB(30,2),BV(30,2),NOD(450,3),
     1NEP(450),AN(450),THICK(450),E1(10),E2(10),P1(10),P2(10),
     2GE(10),NSTART(15),NEND(15),NFIRST(15),NLAST(15)
      COMMON C(6,6),DBA(3,6),DB(3,6),A(6,6),B(3,6),ST(50,100),U(700,4)
      READ (1,10) NPROB
   10 FORMAT(8I4,2F16.8)
      DO 20 LA=1,NPROB
      REWIND 10
      REWIND 13
C     READING AND PRINTING OF DATA
      READ (1,10)NPART,NPOIN,NELEM,NBOUN,NCOLN,NYM,NP,NFREE,DENSIT,EARTH
      WRITE(3,10)NPART,NPOIN,NELEM,NBOUN,NCOLN,NYM,NP,NFREE,DENSIT,EARTH
      DO 30 I=1,NPOIN
      READ (1,35) X(I,1),X(I,2)
   30 WRITE(3,37)I,X(I,1),X(I,2)
   37 FORMAT(I4,4X,2F16.8)
   35 FORMAT(4F16.8,F8.4)
      READ (1,10) NCARD
      IF (NCARD-NPOIN) 110,111,110
  110 STOP
  111 CONTINUE
      DO 40 I=1,NELEM
      READ(1,46)NUM,(NOD(I,J),J=1,3),NEP(I),AN(I),THICK(I)
   40 WRITE(3,46)NUM,(NOD(I,J),J=1,3),NEP(I),AN(I),THICK(I)
   46 FORMAT(5I4,2F16.8)
   45 FORMAT(3I4,2F16.8,I4)
      READ (1,10) NCARD
      IF (NCARD-NELEM) 120,121,120
  120 STOP
  121 CONTINUE
      DO 50 I=1,NBOUN
      READ (1,45) NF(I),NB(I,1),NB(I,2),BV(I,1),BV(I,2)
   50 WRITE(3,45) NF(I),NB(I,1),NB(I,2),BV(I,1),BV(I,2)
      DO 60 I=1,NPART
      READ (1,10) NSTART(I),NEND(I),NFIRST(I),NLAST(I)
   60 WRITE(3,10) NSTART(I),NEND(I),NFIRST(I),NLAST(I)
      DO 64 I=1,NYM
      READ (1,36) E1(I),E2(I),P1(I),P2(I),GE(I)
   64 WRITE(3,36) E1(I),E2(I),P1(I),P2(I),GE(I)
   36 FORMAT(2F16.8,2F8.4,F16.8)
      READ(1,10)NCONC
      DO 65 J=1,NCOLN
      IF (NCONC) 6,7,6
    7 DO 66 I=1,NPOIN
```

```
      READ (1,35) U(2*I-1,J),U(2*I,J)
   66 WRITE (3,35) U(2*I-1,J),U(2*I,J)
      GO TO 65
    6 NPOIN2=NPOIN*2
      DO 68 I=1,NPOIN2
   68 U(I,1)=0.
      DO 69 I=1,NCONC
      READ (1,33) K,U(2*K-1,1),U(2*K,1)
   69 WRITE (3,33) K,U(2*K-1,1),U(2*K,1)
   33 FORMAT(I4,2E16.8)
      NCONC=0
   65 CONTINUE
C     CALCULATION OF LOADS DUE TO BODY FORCES
      IF (DENSIT) 880,882,880
  882 IF (EARTH) 880,881,880
  880 NCOLN=NCOLN+1
      CALL LOAD(X,XE,NOD,NCOLN,NPOIN,THICK,U,DENSIT,EARTH,NELEM)
  881 CONTINUE
C     FORMATION OF MATRICES
      INTER=0
      DO 70 II=1,NPART
      DO 75 I=1,50
      DO 75 J=1,100
   75 ST(I,J)=0.
      NST=NSTART(II)
      NEN=NEND(II)
      K=NFIRST(II)
      L=NLAST(II)
      MINUS=K-1
      DO 80 LK=NST,NEN
      MM=LK-INTER
      DO 85 I=1,3
      JJ=NOD(LK,I)
      XE(I,1)=X(JJ,1)
   85 XE(I,2)=X(JJ,2)
      ANG=AN(LK)
      TH=THICK(LK)
      J=NEP(LK)
      YM1=E1(J)
      YM2=E2(J)
      PR1=P1(J)
      PR2=P2(J)
      G=GE(J)
C     CALCULATION OF ELEMENT STIFFNESS AND STRESS MATRICES
      CALL FEM(XE,YM1,YM2,PR1,PR2,G,ANG,NP,TH,MM)
      DO 80 LL=1,3
      DO 80 KK=1,3
      IF (NOD(LK,KK)-K) 80,131,131
  131 IF(NOD(LK,KK)-L)132,132,80
  132 M=NFREE*(NOD(LK,KK)-K)
      N=NFREE*(NOD(LK,LL)-K)
```

```
      I=NFREE*(KK-1)
      J=NFREE*(LL-1)
      IF(N)80,900,900
  900 DO 5 NJ=1,NFREE
      DO 5 MI=1,NFREE
      MMI=M+MI
      NNJ=N+NJ
      IMI=I+MI
      JNJ=J+NJ
    5 ST(MMI,NNJ)=ST(MMI,NNJ)+C(IMI,JNJ)
   80 CONTINUE
C     INTRODUCTION OF PRESCRIBED DISPLACEMENTS
      DO 290 I=1,NBOUN
      M=NF(I)-K
      MM=NF(I)-1
      IF (M)290,242,242
  242 IF(M-24)243,243,290
  243 DO 230 J=1,NFREE
      IF(NB(I,J))230,345,230
  345 NMI=NFREE*M+J
      ST(NMI,NMI)=ST(NMI,NMI)*.1E+12
      DO 233 JJ=1,NCOLN
      JNJ=NFREE*MM+J
  233 U(JNJ,JJ)=ST(NMI,NMI)*BV(I,J)
  230 CONTINUE
  290 CONTINUE
      INTER=NEQ
      MI=NFREE*MINUS+1
      NJ=NFREE*L
      M=NJ-MI+1
      IF(II-NPART)115,116,115
  115 NA=NFREE*(NLAST(II+1)-MINUS)
      GO TO 117
  116 NA=M+1
  117 N=NA-M
      MM=M+1
   70 WRITE(13)M,N,((ST(I,J),I=1,M),J=1,M),((ST(I,J),I=1,M),J=MM,NA),
     1((U(I,J),I=MI,NJ),J=1,NCOLN)
      REWIND 10
      REWIND 11
      REWIND 12
      REWIND 13
C     SOLUTION OF TRIDIAGONAL MATRICES AND CALCULATION OF RESIDUALS
      CALL SOLVE(NPART,NCOLN)
      REWIND 12
C     CALCULATION OF STRESSES
      CALL STRESS (NPART,NFIRST,NLAST,NCOLN,NELEM,NOD,NFREE,NPOIN)
   20 CONTINUE
      STOP
      END
```

```
C     SUBROUTINE FOR CALCULATION OF LOADS DUE TO BODY FORCES
      SUBROUTINE LOAD(X,XE,NOD,NCOLN,NPOIN,THICK,U,DENSIT,EARTH,NELEM)
      DIMENSION X(350,2),XE(3,2),NOD(450,3),THICK(450),U(700,4)
      NPOIN2=NPOIN*2
      DO 10 I=1,NPOIN2
   10 U(I,NCOLN)=0.
      DO 20 II=1,NELEM
      DO 85 I=1,3
      JJ=NOD(II,I)
      XE(I,1)=X(JJ,1)
   85 XE(I,2)=X(JJ,2)
      VOL=.166667*THICK(II)*(XE(2,1)*(XE(3,2)-XE(1,2))+XE(1,1)*
     1(XE(2,2)-XE(3,2))+XE(3,1)*(XE(1,2)-XE(2,2)))
      VT=VOL*DENSIT
      UT=VOL*EARTH
      DO 86 I=1,3
      JJ=NOD(II,I)
      U(2*JJ-1,NCOLN)=U(2*JJ-1,NCOLN)+UT
   86 U(2*JJ,NCOLN)=U(2*JJ,NCOLN)+VT
   20 CONTINUE
      RETURN
      END
```

```
C     SUBROUTINE FOR FORMATION OF ELEMENT STIFFNESS AND STRESS MATRICES
      SUBROUTINE FEM(XE,YM1,YM2,PR1,PR2,G,ANG,NP,TH,MM)
      DIMENSION D(3,3),BTDBA(6,6),XE(3,2),R(3,3),ZX(3),ZY(3),R1(3,3)
      COMMON C(6,6),DBA(3,6),DB(3,6),A(6,6),B(3,6),ST(50,100),U(700,4)
      DO 20 J=1,6
      DO 21 I=1,3
      B(I,J)=0.
      DB(I,J)=0.
   21 DBA(I,J)=0.
      DO 20 I=1,6
      A(I,J)=0.
      BTDBA(I,J)=0.
   20 C(I,J)=0.
      DO 22 J=1,3
      DO 22 I=1,3
      R(I,J)=0.
   22 D(I,J)=0.
      ORX=(XE(1,1)+XE(2,1)+XE(3,1))*.333333
      ORY=(XE(1,2)+XE(2,2)+XE(3,2))*.333333
      DO 5 I=1,3
      XE(I,1)=XE(I,1)-ORX
    5 XE(I,2)=XE(I,2)-ORY
      ZX(1)=XE(2,2)-XE(3,2)
      ZX(2)=XE(3,2)-XE(1,2)
      ZX(3)=XE(1,2)-XE(2,2)
      ZY(1)=XE(3,1)-XE(2,1)
      ZY(2)=XE(1,1)-XE(3,1)
      ZY(3)=XE(2,1)-XE(1,1)
      ZK=XE(2,1)*XE(3,2)-XE(3,1)*XE(2,2)
      Z=3.*ZK
      A(1,1)=ZK/Z
      A(2,1)=ZX(1)/Z
      A(3,1)=ZY(1)/Z
      A(4,2)=A(1,1)
      A(5,2)=A(2,1)
      A(6,2)=A(3,1)
      A(1,3)=ZK/Z
      A(2,3)=ZX(2)/Z
      A(3,3)=ZY(2)/Z
      A(4,4)=A(1,3)
      A(5,4)=A(2,3)
      A(6,4)=A(3,3)
      A(1,5)=ZK/Z
      A(2,5)=ZX(3)/Z
      A(3,5)=ZY(3)/Z
      A(4,6)=A(1,5)
      A(5,6)=A(2,5)
      A(6,6)=A(3,5)
      B(1,2)=1.
      B(3,3)=1.
      B(3,5)=1.
```

```
      B(2,6)=1.
      IF (NP) 75,81,75
C     ELASTICITY MATRIX FOR PLANE STRAIN CASE
   81 EE=YM2/YM1
      DEN=1.-PR2-2.*EE*PR1**2
      D(1,1)=YM1*(1.-PR2)/DEN
      D(2,1)=YM2*PR1/DEN
      D(1,2)=D(2,1)
      D(2,2)=YM2*(1.-EE*PR1**2)/((1.+PR2)*DEN)
      D(3,3)=G
      GO TO 73
C     ELASTICITY MATRIX FOR PLANE STRESS CASE
   75 DEN=(1.-PR1*PR2)
      D(1,1)=YM1/DEN
      D(2,1)=PR1*YM2/DEN
      D(1,2)=D(2,1)
      D(2,2)=YM2/DEN
      D(3,3)=G
   73 IF (ANG)70,72,70
   70 CS=COS(ANG*.017453)
      SS=SIN(ANG*.017453)
      R(1,1)=CS**2
      R(2,1)=SS**2
      R(3,1)=SS*CS
      R(1,2)=R(2,1)
      R(2,2)=R(1,1)
      R(3,2)=-R(3,1)
      R(1,3)=2.*R(3,2)
      R(2,3)=2.*R(3,1)
      R(3,3)=R(1,1)-R(2,1)
      DO 100 J=1,3
      DO 100 I=1,3
      R1(I,J)=0.
      DO 100 K=1,3
  100 R1(I,J)=R1(I,J)+D(I,K)*R(J,K)
      DO 110 J=1,3
      DO 110 I=1,3
      D(I,J)=0.
      DO 110 K=1,3
  110 D(I,J)=D(I,J)+R(I,K)*R1(K,J)
   72 DO 30 J=1,6
      DO 30 I=1,3
      DO 30 K=1,3
   30 DB(I,J)=DB(I,J)+D(I,K)*B(K,J)
      DO 40 J=1,6
      DO 40 I=1,3
      DO 40 K=1,6
   40 DBA(I,J)=DBA(I,J)+DB(I,K)*A(K,J)
C     STRESS MATRIX IS FORMED
      IF (MM) 126,126,127
  127 WRITE(10)((DBA(I,J),I=1,3),J=1,6),ORX,ORY
```

```
  126 CONTINUE
      VOL=.5*TH*Z
      DO 50 J=1,6
      DO 50 I=1,6
      DO 50 K=1,3
   50 BTDBA(I,J)=BTDBA(I,J)+B(K,I)*DBA(K,J)*VOL
      DO 60 J=1,6
      DO 60 I=1,6
      DO 60 K=1,6
   60 C(I,J)=C(I,J)+A(K,I)*BTDBA(K,J)
C     STIFFNESS MATRIX C IS FORMED
      RETURN
      END
```

```
C     SUBROUTINE FOR SOLUTION OF EQUATIONS.CALCULATION AND PRINTING OF RESID
      SUBROUTINE SOLVE(NPART,NCOLN)
      DIMENSION AM(50,50),BM(50,50),YM(50,50),TF(50,4),RS(50,4),F(50,4),
     1DIS(50,4)
      COMMON C(6,6),DBA(3,6),DB(3,6),A(6,6),B(3,6),ST(50,100),U(700,4)
      EQUIVALENCE(AM(1,1),ST(1,1)),(BM(1,1),ST(1,51)),(TF(1,1),U(1,1)),
     1(DIS(1,1),U(1,2)),(RS(1,1),U(1,3)),(F(1,1),U(1,4))
      DO 140 I=1,50
      DO 141 J=1,NCOLN
      TF(I,J)=0.
  141 RS(I,J)=0.
      DO 140 J=1,50
  140 YM(I,J)=0.
      DO 144 LL=1,NPART
      READ(13)M,N,((AM(I,J),I=1,M),J=1,M),((BM(I,J),I=1,M),J=1,N),
     1((F(I,J),I=1,M),J=1,NCOLN)
  150 DO 424 I=1,M
      DO 425 J=1,NCOLN
      F(I,J)=F(I,J)-TF(I,J)
  425 DIS(I,J)=F(I,J)
      DO 424 J=1,M
  424 AM(I,J)=AM(I,J)-YM(I,J)
      CALL MATINV(AM,M,DIS,NCOLN)
C     MATINV ---------- STANDARD IBM INVERSION PROGRAM
      WRITE(11)M,N,((AM(I,J),I=1,M),J=1,M),((BM(I,J),I=1,M),J=1,N),
     1((F(I,J),I=1,M),J=1,NCOLN)
      IF(NPART-LL)437,437,432
  432 CALL MATM(AM,F,DIS,M,M,NCOLN)
      CALL MATTM(BM,DIS,TF,N,M,NCOLN)
      DO 110 J=1,N
      DO 110 I=1,M
      YM(I,J)=0.
      DO 110 K=1,M
  110 YM(I,J)=YM(I,J)+AM(I,K)*BM(K,J)
      DO 111 J=1,N
      DO 111 I=1,N
      AM(I,J)=0.
      DO 111 K=1,M
  111 AM(I,J)=AM(I,J)+BM(K,I)*YM(K,J)
      DO 112 I=1,N
      DO 112 J=1,N
  112 YM(I,J)=AM(I,J)
  144 CONTINUE
  437 REWIND 13
      WRITE (12)((DIS(I,J),I=1,M),J=1,NCOLN)
      IF(NPART-1)600,600,601
  601 NA=NPART-1
      DO 441 LL=1,NA
      BACKSPACE 11
      BACKSPACE 11
```

```
      READ(11)M,N,((AM(I,J),I=1,M),J=1,M),((BM(I,J),I=1,M),J=1,N),
     1((F(I,J),I=1,M),J=1,NCOLN)
      CALL MATM(BM,DIS,TF,M,N,NCOLN)
      DO 444 J=1,NCOLN
      DO 444 I=1,M
  444 F(I,J)=F(I,J)-TF(I,J)
      CALL MATM(AM,F,DIS,M,M,NCOLN)
  441 WRITE (12)((DIS(I,J),I=1,M),J=1,NCOLN)
      WRITE (3,515)
  515 FORMAT(10H RESIDUALS)
      DO 500 LL=1,NPART
      READ (13)M,N,((AM(I,J),I=1,M),J=1,M),((BM(I,J),I=1,M),J=1,N),
     1((F(I,J),I=1,M),J=1,NCOLN)
      BACKSPACE 12
      READ (12)((DIS(I,J),I=1,M),J=1,NCOLN)
      BACKSPACE 12
      BACKSPACE 12
      READ (12)((TF(I,J),I=1,N),J=1,NCOLN)
      DO 510 J=1,NCOLN
      DO 510 I=1,M
      F(I,J)=F(I,J)-RS(I,J)
      DO 512 K=1,M
  512 F(I,J)=F(I,J)-AM(I,K)*DIS(K,J)
      DO 510 L=1,N
  510 F(I,J)=F(I,J)-BM(I,L)*TF(L,J)
      CALL MATTM(BM,DIS,RS,N,M,NCOLN)
  500 WRITE (3,31) ((F(I,J),I=1,M),J=1,NCOLN)
   31 FORMAT(1H ,12E9.2)
  600 CONTINUE
      RETURN
      END
```

```
C     SUBROUTINE FOR CALCULATION OF STRESSES
      SUBROUTINE STRESS(NPART,NFIRST,NLAST,NCOLN,NELEM,NOD,NFREE,NPOIN)
      DIMENSION NOD(450,3),NFIRST(15),NLAST(15)
      COMMON C(6,6),DBA(3,6),DB(3,6),A(6,6),B(3,6),ST(50,100),U(700,4)

      DO 600 II=1,NPART
      JJ=NPART+1-II
      M=NFREE*(NFIRST(JJ)-1)+1
      N=NFREE*NLAST(JJ)
  600 READ (12)((U(I,J),I=M,N),J=1,NCOLN)
      WRITE (3,615)
  615 FORMAT(5H NODE,16H X-DISPLACEMENTS,16H Y-DISPLACEMENTS)
      WRITE (3,32) ((I,U(2*I-1,J),U(2*I,J),I=1,NPOIN),J=1,NCOLN)
   32 FORMAT(1H ,I4,2E16.8)
      WRITE(3,625)
  625 FORMAT(16H ELEMENT NUMBER ,16H FIRST NODE      ,16H SECOND NODE
     1,16H THIRD NODE      ,36H X AND Y CO-ORDINATES OF CENTROID    )
      WRITE (3,635)
C     PRINCIPLE ANGLE IS THE ANGLE BETWEEN Y AXIS AND STRESS-1
  635 FORMAT(16H    X-STRESS      ,16HY-STRESS          ,
     116H  XY-STRESS      ,16H  STRESS-1        ,16H  STRESS-2
     216H PRINCIPLE ANGLE)
      DO 20 LL=1,NELEM
      READ (10) ((DBA(I,J),I=1,3),J=1,6),ORX,ORY
      DO 620 J=1,NCOLN
      DO 620 I=1,3
      JJ=NOD(LL,I)
      C(2*I-1,J)=U(2*JJ-1,J)
  620 C(2*I,J)=U(2*JJ,J)
      DO 630 J=1,NCOLN
      DO 630 I=1,3
      DB(I,J)=0.
      DO 630 K=1,6
  630 DB(I,J)=DB(I,J)+DBA(I,K)*C(K,J)
      WRITE (3,10) LL,(NOD(LL,J),J=1,3),ORX,ORY
      CALL PRIN(DB,A,NCOLN)
      WRITE (3,31) ((DB(I,J),I=1,3),(A(I,J),I=1,3),J=1,NCOLN)
      IF (NCOLN-1)110,25,110
   25 WRITE(3,33) (A(I,1),I=1,3)
      GO TO 20
  110 DO 640 J=2,NCOLN
      DO 640 I=1,3
      DBA(I,J)=0.
      DO 640 K=1,J
  640 DBA(I,J)=DBA(I,J)+DB(I,K)
      CALL PRIN(DBA,A,NCOLN)
      WRITE (3,31) ((DBA(I,J),I=1,3),(A(I,J),I=1,3),J=2,NCOLN)
      WRITE (3,33) (A(I,NCOLN),I=1,3)
```

```
20 CONTINUE
31 FORMAT(1H ,5E16.8,F16.8)
33 FORMAT(1H0,5E12.5)
10 FORMAT(1H ,4I4,2F16.8)
   RETURN
   END
```

```
      SUBROUTINE PRIN(D,C,N)
      DIMENSION D(3,6),C(6,6)
      DO 650 J=1,N
      C(1,J) = (D(1,J)+D(2,J))*.5 + SQRT((D(1,J)-D(2,J))**2/4.
     1 + D(3,J)**2)
      C(2,J) = (D(1,J)+D(2,J))*.5 - SQRT((D(1,J)-D(2,J))**2/4.
     1 + D(3,J)**2)
  650 C(3,J) = 57.3*ATAN((C(1,J)-D(2,J))/D(3,J))
      RETURN
      END
```

```
      SUBROUTINE MATTM (D,B,DB,L,M,N)
      DIMENSION D(50,50),B(50,4),DB(50,4)
      DO 110 J=1,N
      DO 110 I=1,L
      DB(I,J)=0.
      DO 110 K=1,M
  110 DB(I,J)=DB(I,J)+D(K,I)*B(K,J)
      RETURN
      END
```

```
      SUBROUTINE MATM (D,B,DB,L,M,N)
      DIMENSION D(50,50),B(50,4),DB(50,4)
      DO 110 J=1,N
      DO 110 I=1,L
      DB(I,J)=0.
      DO 110 K=1,M
  110 DB(I,J)=DB(I,J)+D(I,K)*B(K,J)
      RETURN
      END
```

```
      SUBROUTINE MATINV(A,N,B,M)
C     MATRIX INVERSION WITH ACCOMPANYING SOLUTION OF LINEAR EQUATIONS
C     INITIALIZATION
      DIMENSION IPIVOT(50),A(50,50),B(50,4),INDEX(50,2),PIVOT(50)
   15 DO 20 J=1,N
   20 IPIVOT(J)=0
   30 DO 550 I=1,N
C     SEARCH FOR PIVOT ELEMENT
   40 AMAX=0.0
   45 DO 105 J=1,N
   50 IF (IPIVOT(J)-1) 60, 105, 60
   60 DO 100 K=1,N
   70 IF (IPIVOT(K)-1) 80,100,740
   80 IF ( ABS(AMAX)- ABS(A(J,K))) 85, 100, 100
   85 IROW=J
   90 ICOLUM=K
   95 AMAX=A(J,K)
  100 CONTINUE
  105 CONTINUE
  110 IPIVOT(ICOLUM)=IPIVOT(ICOLUM)+1
C     INTERCHANGE ROWS TO PUT PIVOT ELEMENT ON DIAGONAL
  130 IF (IROW-ICOLUM) 150, 260, 150
  150 DO 200 L=1,N
  160 SWAP=A(IROW,L)
  170 A(IROW,L)=A(ICOLUM,L)
  200 A(ICOLUM,L)=SWAP
  205 IF(M) 260, 260, 210
  210 DO 250 L=1, M
  220 SWAP=B(IROW,L)
  230 B(IROW,L)=B(ICOLUM,L)
  250 B(ICOLUM,L)=SWAP
  260 INDEX(I,1)=IROW
  270 INDEX(I,2)=ICOLUM
  310 PIVOT(I)=A(ICOLUM,ICOLUM)
C     DIVIDE PIVOT ROW BY PIVOT ELEMENT
  330 A(ICOLUM,ICOLUM)=1.0
  340 DO 350 L=1,N
  350 A(ICOLUM,L)=A(ICOLUM,L)/PIVOT(I)
  355 IF(M) 380, 380, 360
  360 DO 370 L=1,M
  370 B(ICOLUM,L)=B(ICOLUM,L)/PIVOT(I)
C     REDUCE NON-PIVOT ROWS
  380 DO 550 L1=1,N
  390 IF(L1-ICOLUM) 400, 550, 400
  400 T=A(L1,ICOLUM)
  420 A(L1,ICOLUM)=0.0
  430 DO 450 L=1,N
  450 A(L1,L)=A(L1,L)-A(ICOLUM,L)*T
  455 IF(M) 550, 550, 460
```

```
  460 DO 500 L=1,M
  500 B(L1,L)=B(L1,L)-B(ICOLUM,L)*T
  550 CONTINUE
C     INTERCHANGE COLUMNS
  600 DO 710 I=1,N
  610 L=N+1-I
  620 IF (INDEX(L,1)-INDEX(L,2)) 630, 710, 630
  630 JROW=INDEX(L,1)
  640 JCOLUM=INDEX(L,2)
  650 DO 705 K=1,N
  660 SWAP=A(K,JROW)
  670 A(K,JROW)=A(K,JCOLUM)
  700 A(K,JCOLUM)=SWAP
  705 CONTINUE
  710 CONTINUE
  740 RETURN
      END
```

DATA PREPARATION FOR FINELEM

		Format
1. 1 Card		
Columns		
1 - 4	Number of problems to be run in one execution of program	I4
2. 1 Card		
Columns		
1 - 4	Number of partitions ($\leq$ 15)	I4
5 - 8	Number of nodal points ($\leq$ 350)	I4
9 - 12	Number of elements ($\leq$ 450)	I4
13 - 16	Number of nodal points with prescribed displacements ($\leq$ 45)	I4
17 - 20	Number of load vectors ($\leq$ 4)	I4
21 - 24	Number of different elastic properties ($\leq$ 10)	I4
25 - 28	0: plane strain 1: plane stress	I4
29 - 32	Number of degrees of freedom per node	I4
33 - 48	Force per unit volume in y-direction	F 16.8
49 - 64	Force per unit volume in x-direction	F 16.8
3. 1 Card for each nodal point (in ascending order)		
Columns		
1 - 16	x-coordinate of nodal point	F 16.8
17 - 32	y-coordinate of nodal point	F 16.8
4. 1 Card		
Columns		
1 - 4	Number of nodal point cards to be read in	I4

		Format
5.	1 Card for each element (in ascending order)	
Columns		
1 - 4	Element number	I4
5 - 8	Nodal points in anticlockwise rotation	I4
9 - 12	Nodal points in anticlockwise rotation	I4
13 - 16	Nodal points in anticlockwise rotation	I4
17 - 20	Elastic property number	I4
21 - 36	Angle which the x-axis of orthotropy makes with the global x-axis	F 16.8
37 - 52	Thickness of element	F 16.8
6.	1 Card	
Columns		
1 - 4	Number of element cards to be read in	I4
7.	1 Card for each nodal point with prescribed displacement	
Columns		
1 - 4	Nodal point number	I4
5 - 8	Displacement in x-direction 0: fixed 1: free	I4
9 - 12	Displacement in y-direction 0: fixed 1: free	I4
13 - 28	Prescribed value of displacement in x-direction	F 16.8
29 - 44	Prescribed value of displacement in y-direction	F 16.8
8.	1 Card for each partition (in ascending order)	
Columns		
1 - 4	First element in partition	I4
5 - 8	Last element in partition	I4

Columns		Format
9 - 12	First nodal point in partition	I4
13 - 16	Last nodal point in partition	I4

NOTE: A partition cannot contain more than 24 nodal points numbered in consecutive order.

9. 1 Card for each elastic property

Columns		
1 - 16	Young's modulus in x-direction	F 16.8
17 - 32	Young's modulus in y-direction	F 16.8
33 - 40	Poisson's ratio in x-direction	F 8.4
41 - 48	Poisson's ratio in y-direction	F 8.4
49 - 64	Shear modulus	F 16.8

10. 1 Card

Columns		
1 - 4	Number of nodal points with concentrated loads	I4

11. 1 Card for each nodal point with concentrated load

Columns		
1 - 4	Nodal point number	I4
5 - 20	Load in x-direction	F 16.8
21 - 36	Load in y-direction	F 16.8

NOTE: If there are no points with concentrated loads, omit Set 11 cards. A blank card (or card with a zero punch in column 4) must still be included (Set 10).

If points with concentrated loads are present, they together form one load vector (regardless of the number of points) which must be included in the count in columns 17 - 20 of the second data card. (Set 2.)

		Format
12. 1 Card for every point (in ascending order)		
Columns		
1 - 16	Load in x-direction	F 16.8
17 - 32	Load in y-direction	F 16.8

NOTE: One card must be included for every point even if the load is zero. If only concentrated load exists, however, omit Set 12 completely.

Repeat Set 12 for every separate load vector.

Set 11 and Set 12 cards are alternatives. If only a single load vector of a relatively small number of arbitrarily specified loads is to be dealt with, use Set 11. If more than one load vector of arbitrarily specified loads is to be dealt with, then Set 12 should be used and one card must be included for every nodal point, even if the load is zero.

For a combined loading, arbitrarily specified loads, and computer output, the cards for the nodes with combined loads should be abstracted from the output deck and replaced by cards with the total load.

NUMERICAL EXAMPLES

EXAMPLE 1: DEFLECTION AND STRESSES, SIMPLY SUPPORTED BEAM

Determine the centerline deflection, the flexural stresses at sections A and B, and the horizontal shear stresses at section A of the simply supported beam shown in Fig. 3(a) on page 76. Calculate the deflection and stresses using "classical methods" of analysis and then the computer program, FINELEM. For this example, $\mu = 0.3$ and $E = 30 \times 10^3$ ksi.

Solution:

The centerline deflection or maximum vertical deflection of a simply supported beam with a concentrated load at midspan is calculated using the following formula from "classical" beam theory,

$$\Delta_{max} = \frac{PL^3}{48EI} \tag{53}$$

in which Δ_{max} represents the deflection, P represents the concentrated load, L represents the beam length, E represents Young's modulus, and I represents the moment of inertia of the section.

The moment of inertia for this section is

$$I = \frac{bh^3}{12} = \frac{5(10)^3}{12} = 416.7 \text{ in}^4.$$

Substituting the appropriate values into equation (53) gives the following:

$$\Delta_{max} = \frac{10(60)^3}{48(30 \times 10^3)416.7} = 0.0036 \text{ in.}$$

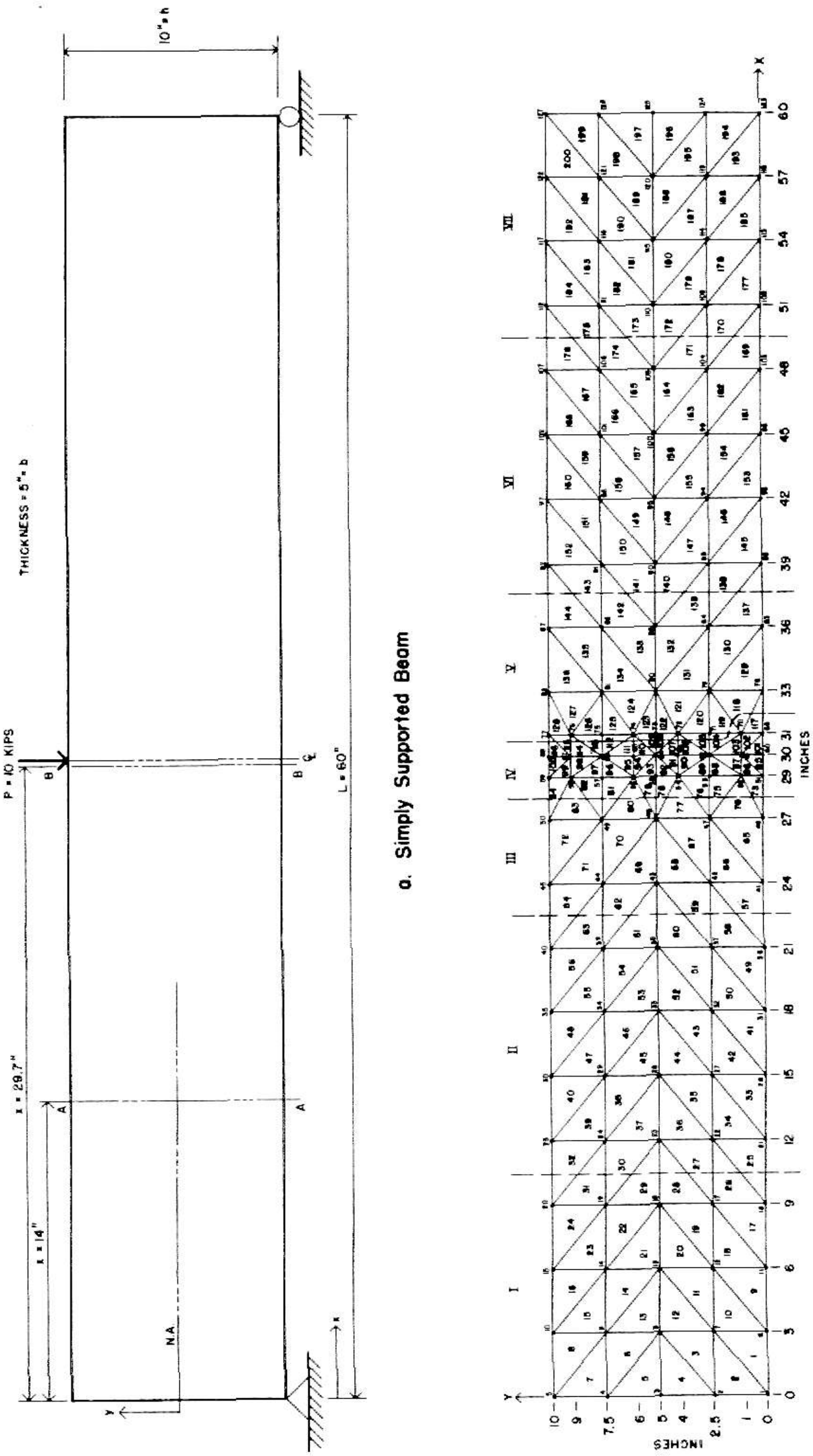


Fig. 3. Example 1: Flexural Stresses, Simply Supported Beam

Fig. 3. Example 1: Flexural Stresses, Simply Supported Beam

The centerline deflection calculated by FINELEM is found in Appendix A as the y-displacement of nodal point 68 and equals the following:

$$\Delta_{max} = 0.0034 \text{ in.}$$

The FINELEM deflection is smaller than the "classical method" deflection by approximately 5.5 percent.

The "classical method" for calculating the flexural stresses at a given point along the beam makes use of the flexural formula

$$\sigma_x = \frac{M_x y}{I} \tag{54}$$

in which σ_x represents the flexural stress in the x-direction, M_x represents the moment at the point where the stress is to be determined, y represents the distance from the neutral axis of the section, and I represents the moment of inertia of the beam.

At section A,

$$x = 14 \text{ in.}$$

and

$$M_x = \frac{P}{2} x = \frac{(10)}{2} 14 = 70 \text{ in-kips}$$

Similarly, at section B,

$$x = 29.7 \text{ in.}$$

and

$$M_x = \frac{P}{2} x = \frac{(10)}{2} 29.7 = 148.5 \text{ in-kips}$$

The flexural stress distributions for sections A and B are linear and vary from a maximum value in compression on the top of the beam to the same maximum value in tension on the bottom of the beam and are calculated using equation (54) in which y varies from 0 inches at the neutral axis to ± 5 inches at the outer fiber of the beam.

The maximum flexural stress at section A is

$$\sigma_{14} = \frac{M_{14}y}{I} = \frac{70(5)}{416.7} = \pm 0.84 \text{ kip/in}^2$$

The maximum flexural stress at section B is

$$\sigma_{29.7} = \frac{M_{29.7}y}{I} = \frac{148.5(5)}{416.7} = \pm 1.78 \text{ kip/in}^2$$

The "classical method" flexural stress distributions for sections A and B are shown in Fig. 4(a) and Fig. 4(b), respectively.

The "classical method" used for calculating the horizontal shear stresses at a given point along the beam makes use of the horizontal shear formula

$$\tau_{xy} = \frac{VQ}{Ib} \qquad (55)$$

in which τ_{xy} represents the horizontal shear stress, V represents the shear force at the point where the stress is to be determined, Q represents the area above the point where the stress is to be determined multiplied by the distance from the centroid of the area to the neutral axis, I represents the moment of inertia of the beam, and b represents the width of the beam where the stress is being calculated.

Using equation (55), the horizontal shear stresses are calculated at the neutral axis and 2.5 inches above the neutral axis. These points are assumed to be enough to show the general shape of the shear distribution curve.

The horizontal shear stress at the neutral axis is

$$\tau_{n.a.} = \frac{5(5)5(2.5)}{416.7(5)} = 0.15 \text{ kip/in}^2$$

The horizontal shear stress 2.5 inches above the neutral axis is

$$\tau_{2.5} = \frac{5(5)2.5(3.75)}{416.7(5)} = 0.1125 \text{ kip/in}^2$$

The "classical method" horizontal shear stresses are shown in Fig. 5. The shear distribution curve is drawn through these points.

To solve the problem using the computer program, FINELEM, the beam was divided into 200 triangular elements with 127 nodal points as shown in Fig. 3(b). Smaller triangular elements were used near the center of the beam in order to place the centroids of some of the elements near the outer edge of the beam, where the flexural stresses are largest. The triangular elements were numbered with larger numerals than the nodal points in Fig. 3(b) in order to distinguish between the two. The elements and nodal points were numbered consecutively and in an orderly manner. An order similar to this should always be used in numbering the elements and nodal points for a problem.

There are only two nodal points with prescribed displacements: nodal point 1, which was fixed against displacement in the X- and Y-directions, and nodal point 123, which was fixed against displacement in the Y-direction. These displacements correspond to a hinge at nodal point 1 and a roller at nodal point 123. In order to fix a nodal point, a displacement of 0.0 inches is assigned in the direction required.

The plane stress case is specified, which causes the strain in the Z-direction to be eliminated from the calculations.

The concentrated load of 10 kips was divided into three concentrated loads of 3.33 kips, 3.34 kips, and 3.33 kips, and applied in the negative Y-direction at nodal points 59, 68, and 77, respectively, in an attempt to distribute the concentrated load and minimize the compression effect of a point concentrated load.

The nodal points were assigned consecutively to seven partitions with no more than 24 consecutive nodal points in one partition. The partitions of the partitioning scheme were indicated in Fig. 3(b) by Roman numerals.

The form of the data required for use in the program is shown in the section entitled "Data Preparation for FINELEM" starting on page 71.

The input data and significant parts of the output information for Example 1 were included in Appendix A for reference. All of the output information used to construct the graphs of Figs. 4 and 5 has been underlined in Appendix A.

The flexural stresses for the elements are found under the heading "X-STRESS" in Appendix A. The flexural stresses at section A, x = 14 in., were output as the X-stresses at the centroids of elements 33, 35, 38, and 40. The flexural stresses at section B, x = 29.7 in., were output as the X-stresses at the centroids of elements 85, 87, 90, 91, 94, 95, 98, and 100. These stresses are shown in Fig. 4(a) and Fig. 4(b) along with the "classical method" stresses.

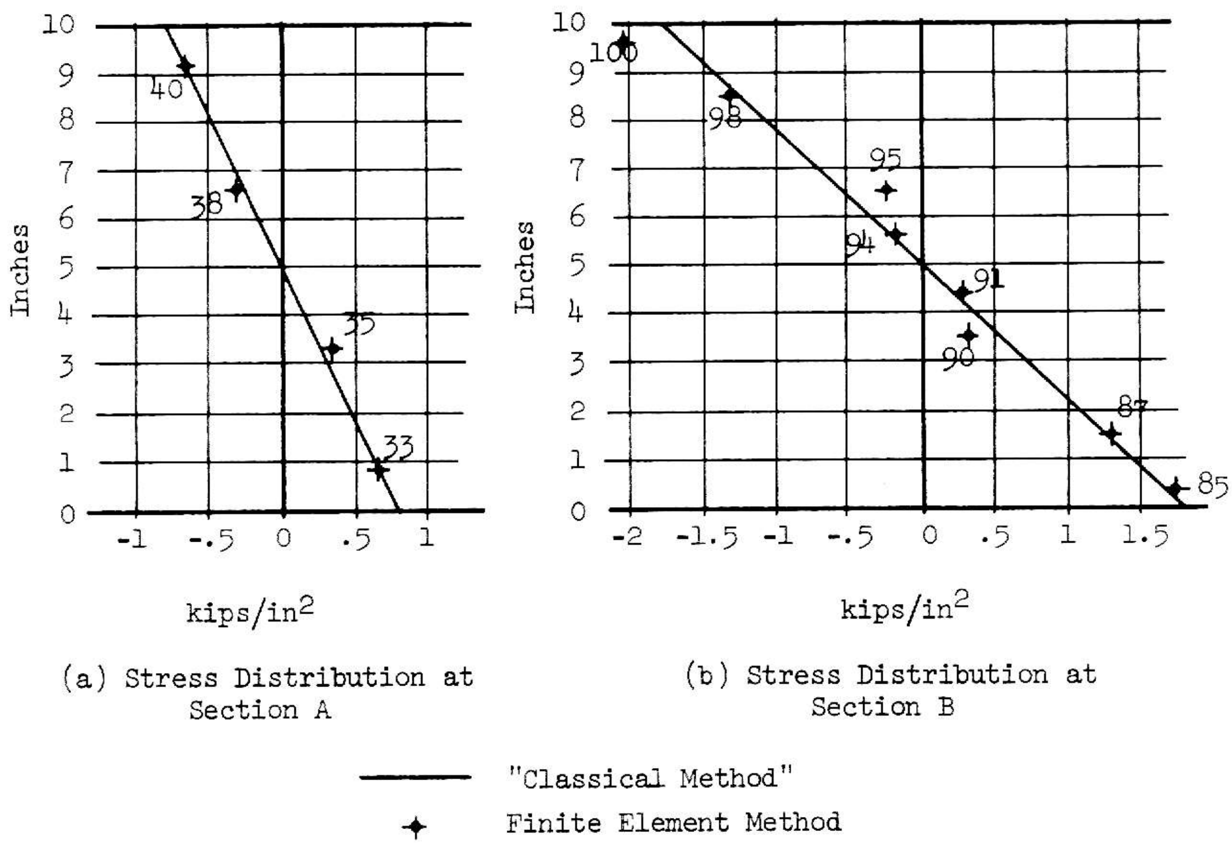


Fig. 4. Flexural Stress Distributions for Example 1.

In Fig. 4(a) the stresses calculated for section A using the finite element method approximate the "classical method" stresses very well. However, in Fig. 4(b) the stresses calculated for section B using the finite element method show a deviation of more than 20 percent from the "classical method" stresses near the top of the beam. This difference is attributed to the fact that the axial compression deformation due to the concentrated loading is ignored in the "classical method," but not in the finite element method. Dividing the concentrated load into three smaller loads had some effect in reducing the difference between the two methods, but the axial compression effect will always be present in the finite element method making it a more "realistic" method than the "classical method."

The horizontal shear stresses, which are also equal to the vertical shear stresses, for the elements should be found under the heading "XY-STRESS" in Appendix A. However, it was discovered that these shear stresses do not necessarily equal the expected shear stress calculated by equation (55).

For example, the FINELEM shear stress from Appendix A for element 33, whose centroid is on section A, is 0.141 ksi. The horizonal shear stress calculated using equation (55) is

$$\tau_{4.167} = \frac{VQ}{Ib} = \frac{5(5)0.833(4.583)}{416.7(5)}$$

$$\tau_{4.167} = 0.046 \text{ ksi}$$

The FINELEM shear stress is greater than the calculated horizontal shear stress by over 200 percent; therefore, this is an incorrect interpretation of the meaning of the FINELEM shear stress.

Since the "classical method" horizontal shear stress is constant at sections where V, the shear force, is constant, it was assumed that the correct interpretation of the "XY-STRESS" could be found by averaging the stresses at adjacent elements. For example, the FINELEM shear stress for element 34, which is adjacent to element 33, is 0.007 ksi. The average of the stresses of elements 33 and 34 is

$$\tau_{ave.} = \frac{0.141 + 0.007}{2} = 0.072 \text{ ksi.}$$

The horizontal shear stress calculated using equation (55) for a point midway between the centroids of elements 33 and 34 is

$$\tau_{4.75} = \frac{VQ}{Ib} = \frac{5(5)1.25(5.38)}{416.7(5)}$$

$$\tau_{4.75} = 0.080 \text{ ksi}$$

The FINELEM shear stress is smaller than the calculated shear stress by about 10 percent; therefore, this is a more correct interpretation of the meaning of the "XY-STRESS." The FINELEM shear stresses for the elements on section A, 33, 35, 38, and 40, and the elements adjacent to section A, have been shown in Fig. 5. The curve of the average of adjacent elements approximates the "classical method" shear distribution curve.

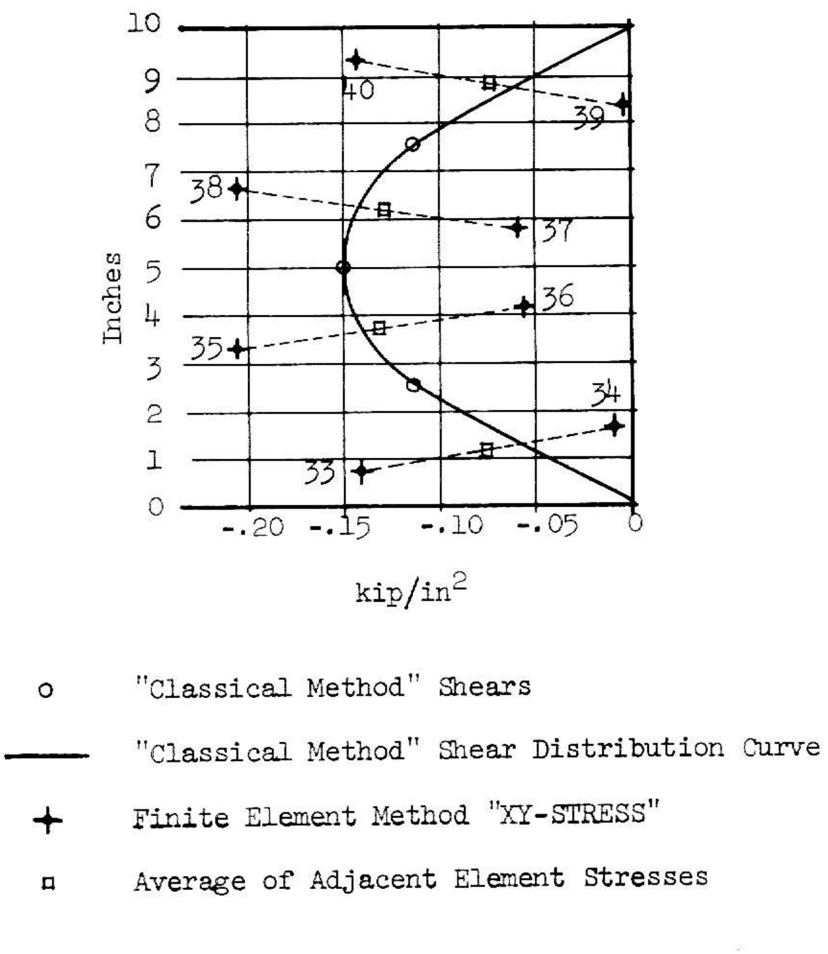


Fig. 5. Horizontal Shear Distributions Near Section A.

The total shear force was calculated by multiplying the average shear force of adjacent elements by the height of the elements by their width and then adding the results as follows:

Adjacent elements	FINELEM stress kip/in^2	Average stress kip/in^2		Area of element in^2		Shear force kips
33 34	0.141 0.006	0.074	×	2.5(5)	=	0.93
35 36	0.204 0.053	0.129	×	2.5(5)	=	1.61
37 38	0.057 0.206	0.132	×	2.5(5)	=	1.65
39 40	0.001 0.142	0.072	×	2.5(5)	=	0.90
				Total shear force	=	5.09 kips

This total shear is within less than 2 percent of the "classical method" total shear, 5 kips.

EXAMPLE 2: STRESSES NEAR RECTANGULAR HOLE, SIMPLY SUPPORTED BEAM

Determine the stresses near the rectangular hole in the simply supported 12WF45 beam, shown in Fig. 6, using the computer program, FINELEM. For this example $\mu = 0.3$ and $E = 30 \times 10^3$ ksi.

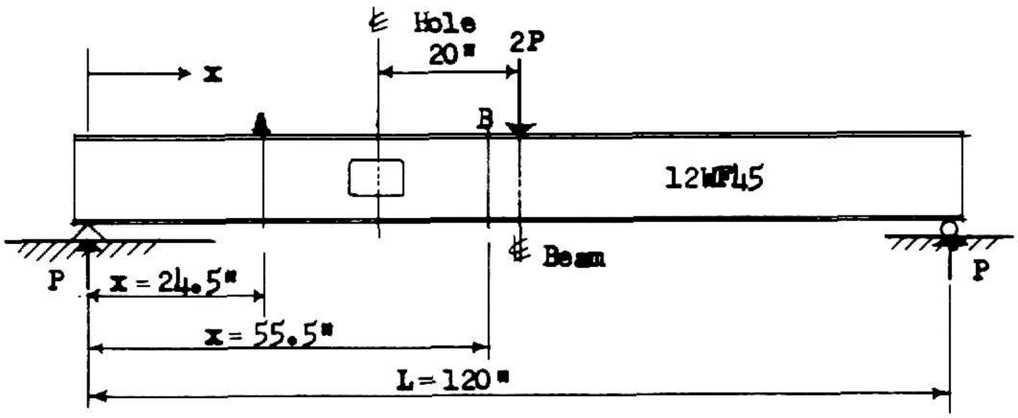
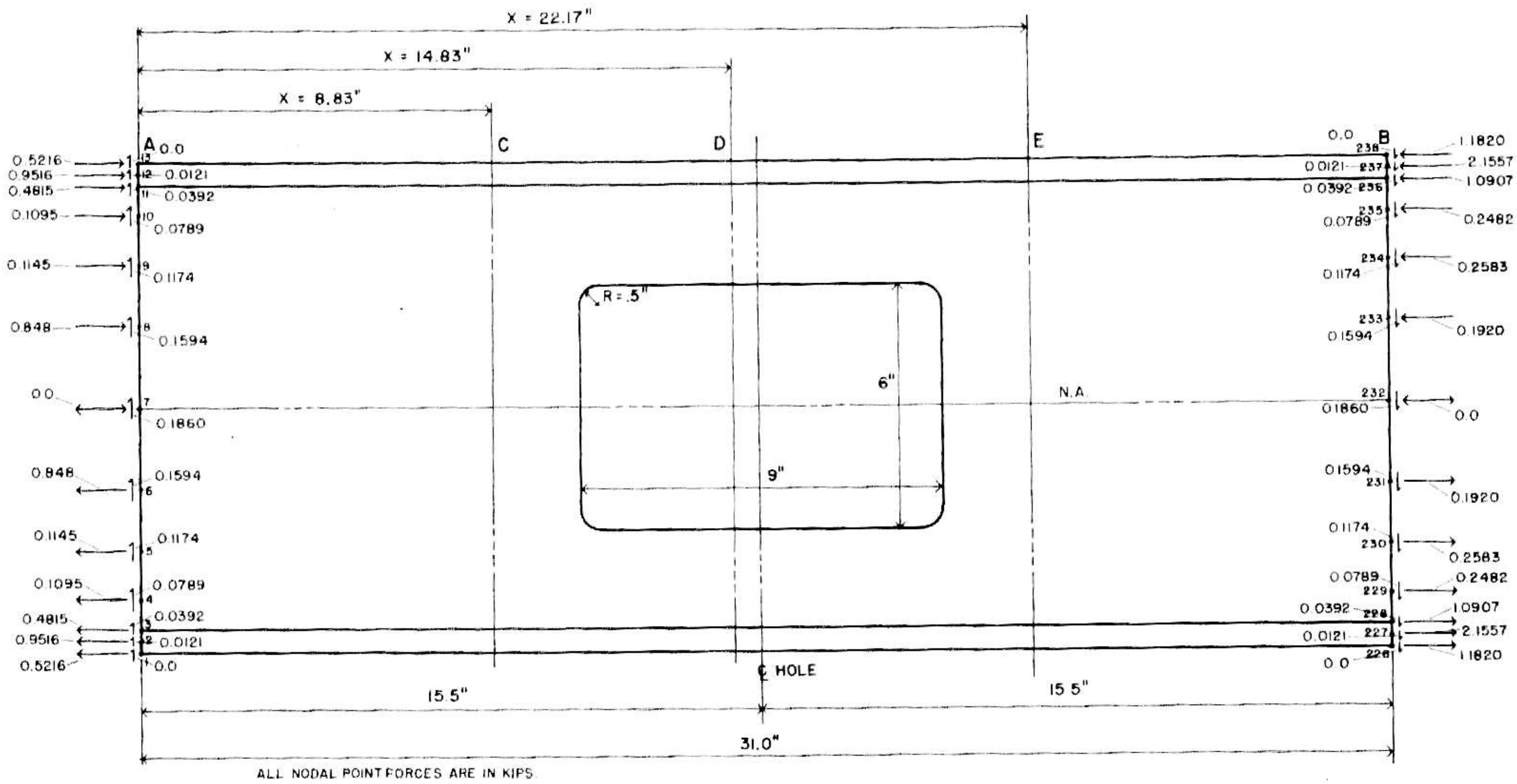


Fig. 6. Simply Supported Beam.

Solution:

A section A-B was cut out of the beam as shown in Fig. 7 with a constant cross section as shown in Fig. 8 in order to make a more accurate analysis of the section around the area of the rectangular hole. This procedure allowed a finer element mesh to be used in the area of the beam, where "classical methods" for claculating flexural and horizontal shear stresses were questionable. Section A-B was assumed to extend far enough past the hole on either side that the actual stress condition in the section as it existed in the beam would be approximated by applying the end moments and shears to the section as a free body.



M_A = 24.5 in-kip
V_A = 1 kip

M_B = 55.5 in-kip
V_B = 1 kip

Fig. 7. Portion of Beam Used for Finite Element Method Analysis

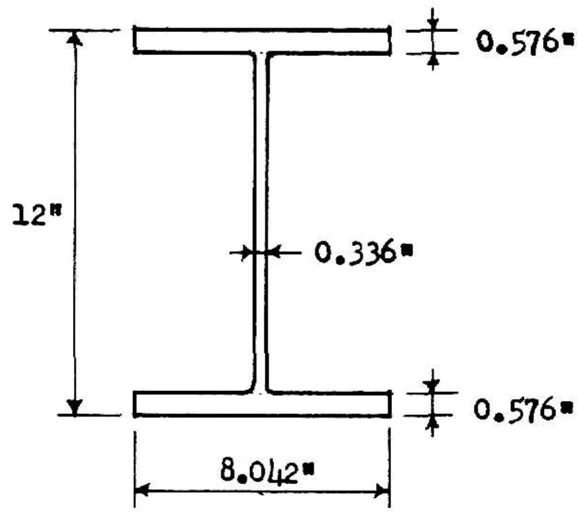


Fig. 8. Section Through 12WF45 Beam.

Section A-B shown in Fig. 9 was divided into a finite element mesh using 394 triangular elements and 238 nodal points. Smaller triangular elements were used near the perimeter of the hole in order to give a better picture of the stresses near the hole. Small triangular elements were used along both flanges in order to try to reduce the adverse effect, which might be caused by the great difference in thickness between the elements in the flange and in the web. The triangular elements were numbered with larger numerals than the nodal points in Fig. 9 in order to distinguish between the two. The elements and nodal points were again numbered consecutively and in an orderly manner as in Example 1.

The nodal points were assigned, consecutively, to 12 partitions with no more than 24 consecutive nodal points in one partition. The partitions of the partitioning scheme were indicated in Fig. 9 by Roman numerals and dashed lines, which indicate the nodal points and elements in each partition.

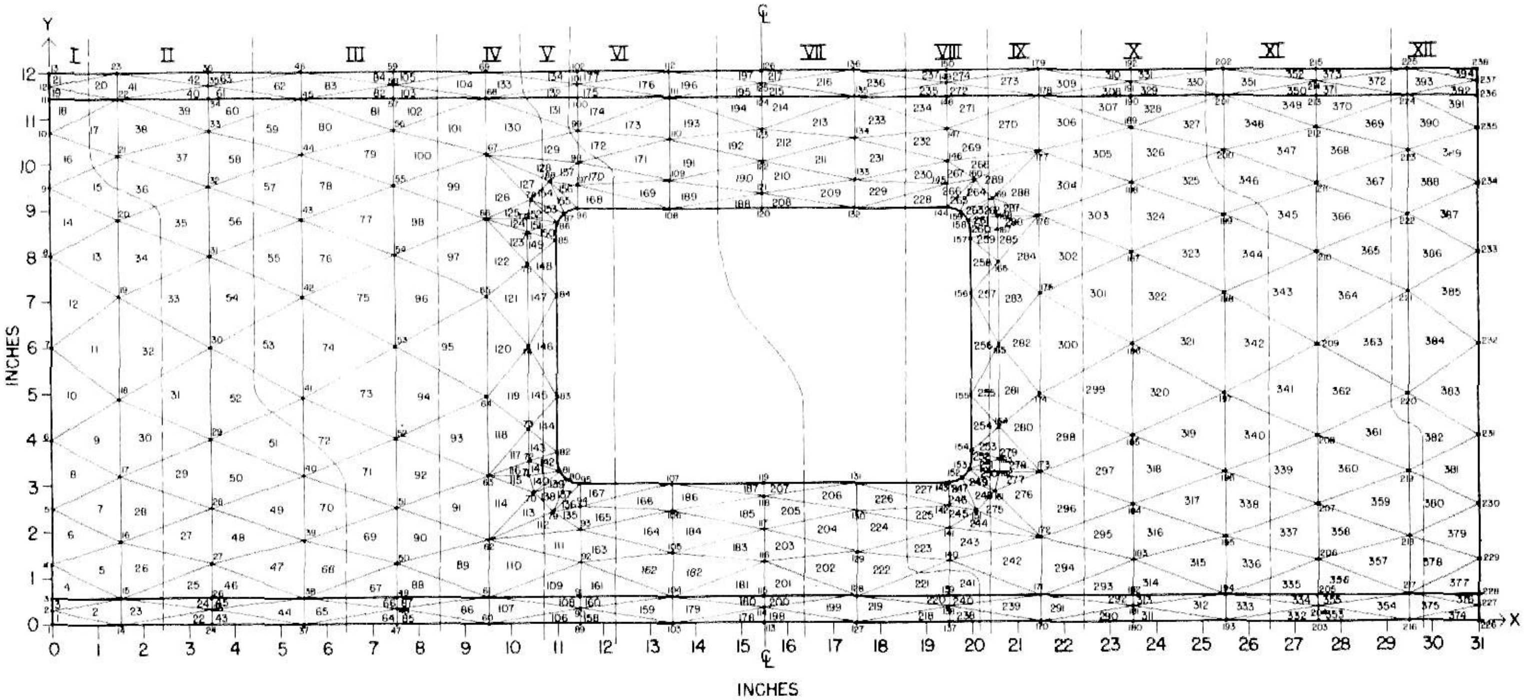


Fig. 8. Element Layout

The plane stress case was specified, which caused the strain in the Z-direction to be eliminated from the calculations. The effect of the strain in the Z-direction was not introduced into the solution of the problem because it is normally ignored in "classical method" calculations.

The moments and shears forces on the free body, section A-B, cannot be used as such. These moments and forces must be put into the form of concentrated loads to be used in the finite element method analysis.

The moments and shears on the free body, section A-B, were approximated by a series of concentrated loads applied at the nodal points on either end of the section. The series of concentrated loads were to approximate the actual stress conditions at sections A and B as closely as possible. In order to do this the flexural stress and horizontal shear stress distributions at sections A and B were calculated with P assumed to be 1 kip.

The maximum flexural stress at section A, calculated by equation (54), is

$$\sigma_{24.5} = \frac{M_{24.5}y}{I} = \frac{1(24.5)6}{350.8}$$

$$\sigma_{24.5} = \pm 0.4190 \text{ kip/in}^2$$

and the flexural stress distribution for section A is shown in Fig. 10.

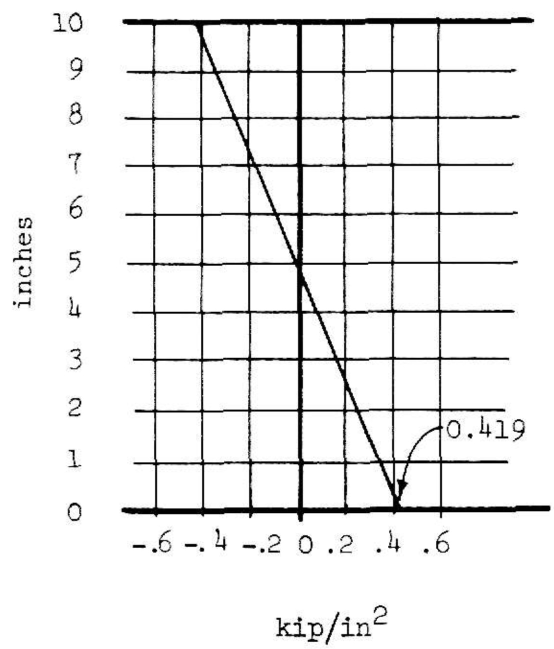


Fig. 10. Flexural Stress Distribution, Section A.

This stress distribution was resolved into a series of x-direction concentrated loads by multiplying the stress at a nodal point by the sum of half the distance between the adjacent nodal points and then multiplying this value by the flange or web thickness at the nodal point. The sum of the moments produced by these concentrated forces applied at nodal points about the neutral axis was checked to see if it equaled the statical moment at the section, which was 24.5 in-kip. The small difference between the sum of the moments and the statical moment was proportionately resolved into a series of small concentrated loads, which were then added to the previous concentrated loads making the sum of the moments produced by the concentrated loads equal to the statical moment, 24.5 in-kip. These concentrated loads are shown in Fig. 7.

The maximum flexural stress at section A calculated by equation (54) is

$$\sigma_{55.5} = \frac{M_{55.5}y}{I} = \frac{1(55.5)6}{350.8}$$

$$\sigma_{55.5} = \pm 0.9493 \text{ kip/in}^2$$

The stress distribution at section B was resolved into a series of concentrated loads by the same method used in section A. The resultant concentrated loads are shown in Fig. 7.

The horizontal shear stress distributions at sections A and B, and the stress distributions above and below the neutral axis of the sections were identical, respectively; therefore, the horizontal stresses at nodal points 1 through 7 calculated using equation (55) were used to plot the horizontal stress distribution. The horizontal shear stress for nodal point 7 on the neutral axis, using equation (55) and referring to Fig. 11, was calculated as follows:

The distance, $\bar{y}$, from the neutral axis to the centroid of the section in Fig. 11 is

$$\bar{y} = \frac{\Sigma Ay}{\Sigma A} = \frac{8.042(0.576)5.712 + 0.336(5.424)2.712}{8.042(0.576) + 0.336(5.424)} = \frac{31.402}{6.455}$$

$$\bar{y} = 4.865 \text{ in.}$$

$$\tau_{n.a.} = \frac{V(\Sigma A)\bar{y}}{Ib} = \frac{1(6.455)4.865}{350.8(0.336)}$$

$$\tau_{n.a.} = 0.2664 \text{ kip/in}^2$$

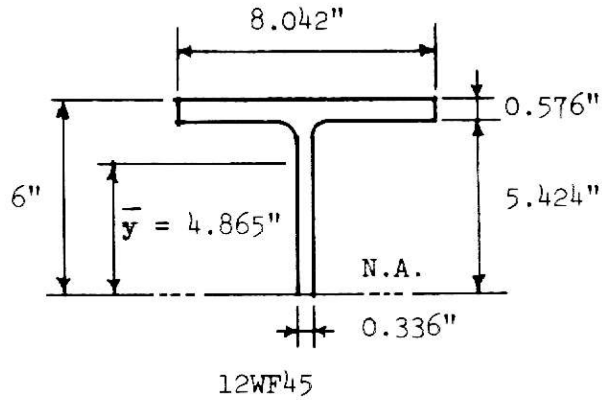
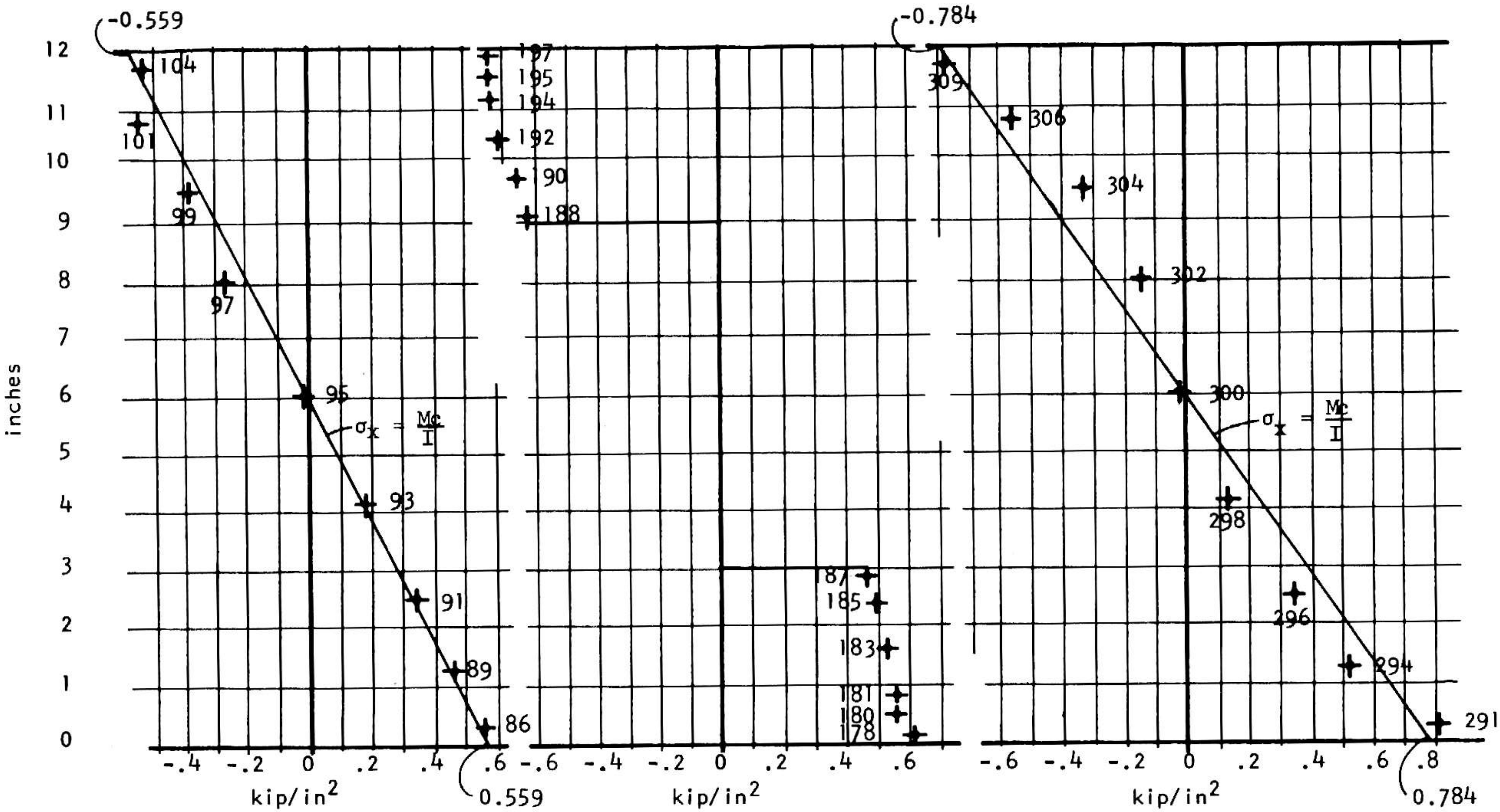


Fig. 11. Section for Calculating Horizontal Shear Stress at the Neutral Axis.

The horizontal shear stress for nodal points 1 through 6 were calculated by the same method used for nodal point 7. The horizontal shear stresses at the nodal points were resolved into a series of concentrated loads in the y-direction by multiplying them by the sum of half the distance between adjacent nodal points and then multiplying this value by the flange or web thickness at the nodal point. The small difference between the sum of the concentrated loads at section A and the shear force at section A, 1 kip, was proportionately resolved into a series of small concentrated loads which were added to the previous concentrated loads, making the sum of the new concentrated loads equal to the shear force, 1 kip. These concentrated loads are shown in Fig. 7 in the appropriate directions.

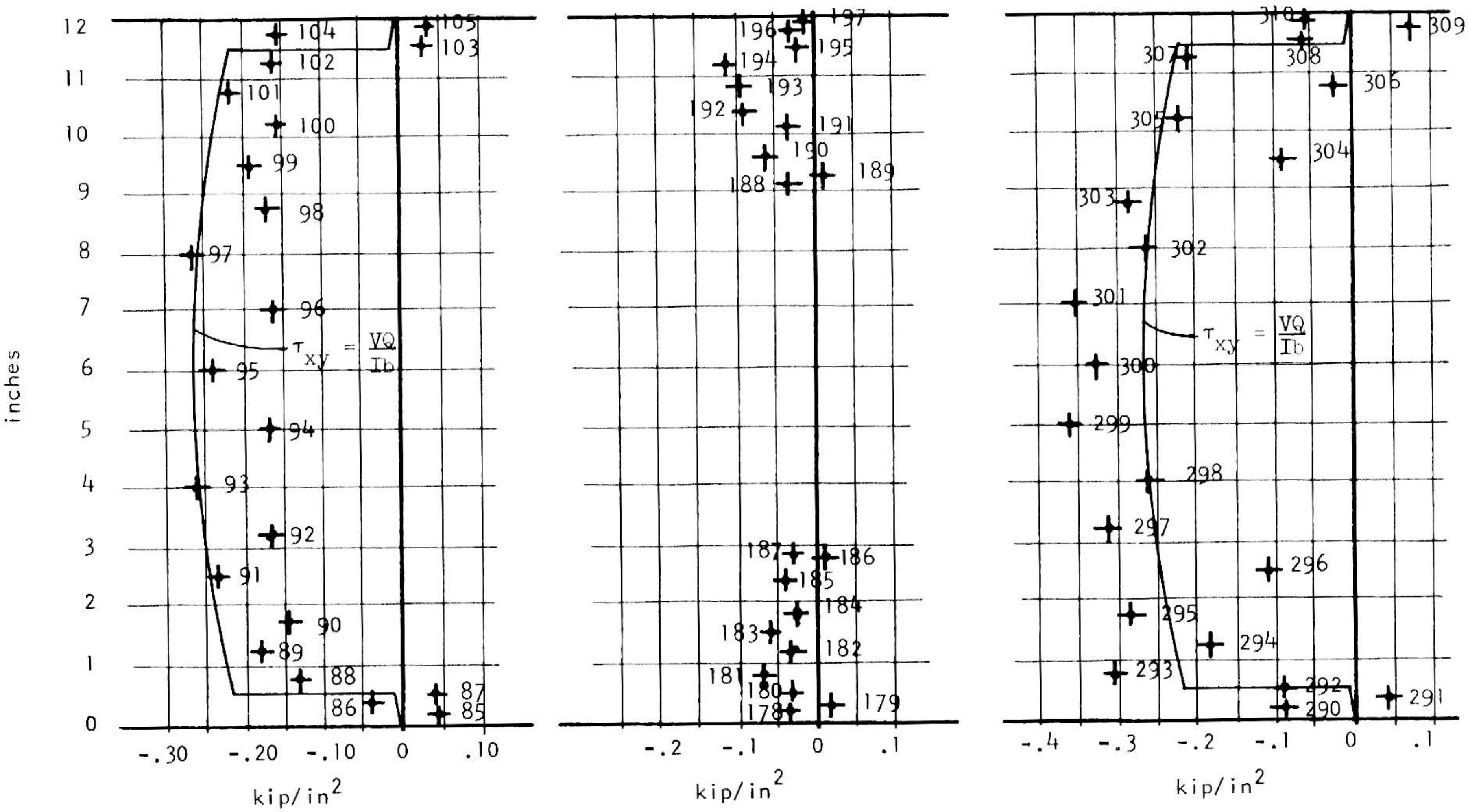
The input data and significant parts of the output information for Example 2 were included in Appendix B for reference.

The flexural and horizontal shear stresses at sections C, D, and E in Fig. 7 are shown in Figs. 12 and 13 as a sampling of the stresses in section A-B.



a. Section C, x = 8.83 in b. Section D, x = 14.83 in c. Section E, x = 22.17 in

Fig. 12. Flexural Stress Distributions, Example 2



a. Section C, x = 8.83 in   b. Section D, x = 14.83 in   c. Section E, x = 22.17 in

Fig. 10. Horizontal Stress Distributions, Example 2

All of the output information used to construct the graphs of Figs. 12 and 13 were underlined in Appendix B.

The flexural stresses for the elements are found under the heading "X-STRESS" in Appendix B. The flexural stresses at section C, $x = 8.83$ in., were output as the X-stresses at the centroids of elements 86, 89, 91, 93, 95, 97, 99, 101, and 104. The flexural stresses at section D, $x = 14.83$ in., were output as the X-stresses at the centroids of elements 178, 180, 181, 183, 185, 187, 188, 190, 192, 194, 195, and 197. The flexural stresses at section E, $x = 22.17$ in., were output as the X-stresses at the centroids of elements 291, 294, 296, 298, 300, 302, 304, 306, and 309. The flexural stresses were shown in Fig. 12.

The maximum flexural stress on section C, $x = 33.33$ in., calculated using equation (54) is

$$\sigma_{33.33} = \frac{1(33.33)6}{350.8}$$

$$\sigma_{33.33} = \pm 0.559 \text{ kip/in}^2$$

The maximum flexural stress on section E, $x = 46.67$ in., calculated using equation (54) is

$$\sigma_{46.67} = \frac{1(46.67)6}{350.8}$$

$$\sigma_{46.67} = \pm 0.784 \text{ kip/in}^2$$

The FINELEM stresses at sections C and E vary from the stresses calculated above by less than 3 percent.

The horizontal shear stresses for the elements are found under the heading "XY-STRESS" in Appendix B. Shear stresses of elements adjacent to the elements, whose centroids are on the required section, were used to graph the horizontal shear distributions at sections C. D, and E. The shear stresses at section C were output as the XY-stresses of elements 85 through 105. The shear stresses at section D were output as the XY-stresses of elements 178 through 197. The shear stresses at section E were output as the XY-stresses of elements 290 through 310. The horizontal shear stresses were shown in Fig. 13.

CONCLUSIONS

The computer program, FINELEM, can be used as listed in the section titled "FINELEM Program Listing" on the IBM 360-50 Computer at Kansas State University. An important point to note in using the program is that control cards providing additional temporary disc storage must be used. These control cards are shown on page 56.

REFERENCES

1. The Finite Element Method in Structural and Continuum Mechanics, O. C. Zienkiewicz and Y. K. Cheung, McGraw-Hill Publishing Company Limited, Berkshire, England, 1967.

2. Elementary Structural Analysis, C. H. Norris and J. B. Wilbur, McGraw-Hill Book Company, New York, 1960.

3. Theory of Elasticity, S. Timoshenko and J. H. Goodier, McGraw-Hill Book Company, New York, 1951 (2nd ed.).

4. Computer Methods in Solid Mechanics, J. J. Gennaro, Macmillan Company, 1965.

APPENDIX B - EXAMPLE 2, DATA AND OUTPUT

DATA

```
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  0.00          7.5
  0.00          10.
  3.00          0.0
  3.00          2.5
  3.00          5.0
  3.00          7.5
  3.00          10.
  6.00          0.0
  6.00          2.5
  6.00          5.0
  6.00          7.5
  6.00          10.
  9.00          0.0
  9.00          2.5
  9.00          5.0
  9.00          7.5
  9.00          10.
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  12.0          5.0
  12.0          7.5
  12.0          10.
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  15.0          2.5
  15.0          5.0
  15.0          7.5
  15.0          10.
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  18.0          5.0
  18.0          7.5
  18.0          10.
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  21.0          5.0
  21.0          7.5
  21.0          10.
  24.0          0.0
  24.0          2.5
  24.0          5.0
  24.0          7.5
  24.0          10.
  27.0          0.0
  27.0          2.5
  27.0          5.0
  27.0          7.5
  27.0          10.
  29.0          0.0
  29.0          1.0
  29.0          2.5
  29.0          4.0
  29.0          5.0
  29.0          6.0
  29.0          7.5
  29.0          9.0
```

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30.0	2.5
30.0	4.0
30.0	5.0
30.0	6.0
30.0	7.5
30.0	9.0
30.0	10.
31.0	0.0
31.0	1.0
31.0	2.5
31.0	4.0
31.0	5.0
31.0	6.0
31.0	7.5
31.0	9.0
31.0	10.
33.0	0.0
33.0	2.5
33.0	5.0
33.0	7.5
33.0	10.
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36.0	5.0
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36.0	10.
39.0	0.0
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39.0	5.0
39.0	7.5
39.0	10.
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42.0	5.0
42.0	7.5
42.0	10.
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45.0	2.5
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45.0	7.5
45.0	10.
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48.0	7.5
48.0	10.
51.0	0.0
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51.0	5.0
51.0	7.5
51.0	10.
54.0	0.0
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54.0	5.0
54.0	7.5
54.0	10.
57.0	0.0

57.0	2.5
57.0	5.0
57.0	7.5
57.0	10.
60.0	0.0
60.0	2.5
60.0	5.0
60.0	7.5
60.0	10.

127

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3	2	7	8	1	.	5.
4	2	8	3	1	.	5.
5	3	8	4	1	.	5.
6	8	9	4	1	.	5.
7	4	9	5	1	.	5.
8	9	10	5	1	.	5.
9	6	11	12	1	.	5.
10	6	12	7	1	.	5.
11	12	13	7	1	.	5.
12	7	13	8	1	.	5.
13	8	13	9	1	.	5.
14	9	13	14	1	.	5.
15	10	9	14	1	.	5.
16	10	14	15	1	.	5.
17	11	16	17	1	.	5.
18	12	11	17	1	.	5.
19	12	17	18	1	.	5.
20	12	18	13	1	.	5.
21	13	18	14	1	.	5.
22	14	18	19	1	.	5.
23	14	19	15	1	.	5.
24	19	20	15	1	.	5.
25	16	21	22	1	.	5.
26	17	16	22	1	.	5.
27	17	22	23	1	.	5.
28	18	17	23	1	.	5.
29	19	18	23	1	.	5.
30	19	23	24	1	.	5.
31	20	19	24	1	.	5.
32	20	24	25	1	.	5.
33	21	26	27	1	.	5.
34	22	21	27	1	.	5.
35	22	27	28	1	.	5.
36	23	22	28	1	.	5.
37	24	23	28	1	.	5.
38	24	28	29	1	.	5.
39	25	24	29	1	.	5.
40	25	29	30	1	.	5.
41	26	31	32	1	.	5.
42	26	32	27	1	.	5.
43	27	32	33	1	.	5.
44	28	27	33	1	.	5.
45	29	33	28	1	.	5.
46	29	33	34	1	.	5.
47	30	29	34	1	.	5.
48	30	34	35	1	.	5.
49	31	36	37	1	.	5.
50	32	31	37	1	.	5.

51	32	37	38	1	.	5.
52	33	32	38	1	.	5.
53	34	33	38	1	.	5.
54	34	38	39	1	.	5.
55	35	34	39	1	.	5.
56	35	39	40	1	.	5.
57	36	41	42	1	.	5.
58	37	36	42	1	.	5.
59	37	42	43	1	.	5.
60	38	37	43	1	.	5.
61	38	43	39	1	.	5.
62	39	43	44	1	.	5.
63	40	39	44	1	.	5.
64	40	44	45	1	.	5.
65	41	46	47	1	.	5.
66	42	41	47	1	.	5.
67	42	47	48	1	.	5.
68	43	42	48	1	.	5.
69	44	43	48	1	.	5.
70	44	48	49	1	.	5.
71	45	44	49	1	.	5.
72	45	49	50	1	.	5.
73	46	51	52	1	.	5.
74	47	46	52	1	.	5.
75	47	52	53	1	.	5.
76	47	53	54	1	.	5.
77	48	47	54	1	.	5.
78	48	54	55	1	.	5.
79	48	55	56	1	.	5.
80	49	48	56	1	.	5.
81	49	56	57	1	.	5.
82	49	57	58	1	.	5.
83	50	49	58	1	.	5.
84	50	58	59	1	.	5.
85	51	60	61	1	.	5.
86	52	51	61	1	.	5.
87	52	61	62	1	.	5.
88	53	52	62	1	.	5.
89	54	53	62	1	.	5.
90	54	62	63	1	.	5.
91	54	63	64	1	.	5.
92	55	54	64	1	.	5.
93	56	55	64	1	.	5.
94	56	64	65	1	.	5.
95	56	65	66	1	.	5.
96	56	66	57	1	.	5.
97	58	57	66	1	.	5.
98	58	66	67	1	.	5.
99	59	58	67	1	.	5.
100	59	67	68	1	.	5.
101	61	60	69	1	.	5.
102	61	69	70	1	.	5.
103	62	61	70	1	.	5.
104	62	70	71	1	.	5.
105	62	71	72	1	.	5.
106	63	62	72	1	.	5.
107	64	63	72	1	.	5.
108	64	72	73	1	.	5.
109	64	73	74	1	.	5.
110	65	64	74	1	.	5.

111	66	65	74	1	.	5.
112	66	74	75	1	.	5.
113	76	66	75	1	.	5.
114	67	66	76	1	.	5.
115	67	76	77	1	.	5.
116	68	67	77	1	.	5.
117	70	69	78	1	.	5.
118	70	78	79	1	.	5.
119	71	70	79	1	.	5.
120	72	71	79	1	.	5.
121	72	79	80	1	.	5.
122	73	72	80	1	.	5.
123	74	73	80	1	.	5.
124	74	80	81	1	.	5.
125	75	74	81	1	.	5.
126	76	75	81	1	.	5.
127	76	81	82	1	.	5.
128	77	76	82	1	.	5.
129	78	83	79	1	.	5.
130	79	83	84	1	.	5.
131	80	79	84	1	.	5.
132	80	84	85	1	.	5.
133	80	85	86	1	.	5.
134	81	80	86	1	.	5.
135	81	86	87	1	.	5.
136	82	81	87	1	.	5.
137	83	88	84	1	.	5.
138	84	88	89	1	.	5.
139	85	84	89	1	.	5.
140	85	89	90	1	.	5.
141	85	90	91	1	.	5.
142	86	85	91	1	.	5.
143	86	91	92	1	.	5.
144	87	86	92	1	.	5.
145	89	88	93	1	.	5.
146	89	93	94	1	.	5.
147	90	89	94	1	.	5.
148	90	94	95	1	.	5.
149	90	95	96	1	.	5.
150	91	90	96	1	.	5.
151	91	96	97	1	.	5.
152	92	91	97	1	.	5.
153	94	93	98	1	.	5.
154	94	98	99	1	.	5.
155	95	94	99	1	.	5.
156	95	99	100	1	.	5.
157	95	100	101	1	.	5.
158	96	95	101	1	.	5.
159	96	101	102	1	.	5.
160	97	96	102	1	.	5.
161	98	103	99	1	.	5.
162	99	103	104	1	.	5.
163	100	99	104	1	.	5.
164	100	104	105	1	.	5.
165	100	105	106	1	.	5.
166	101	100	106	1	.	5.
167	101	106	107	1	.	5.
168	102	101	107	1	.	5.
169	103	108	104	1	.	5.
170	104	108	109	1	.	5.

```
171 105 104 109    1              .                  5.
172 105 109 110    1              .                  5.
173 105 110 111    1              .                  5.
174 106 105 111    1              .                  5.
175 106 111 112    1              .                  5.
176 107 106 112    1              .                  5.
177 109 108 113    1              .                  5.
178 109 113 114    1              .                  5.
179 110 109 114    1              .                  5.
180 110 114 115    1              .                  5.
181 110 115 116    1              .                  5.
182 111 110 116    1              .                  5.
183 111 116 117    1              .                  5.
184 112 111 117    1              .                  5.
185 114 113 118    1              .                  5.
186 114 118 119    1              .                  5.
187 115 114 119    1              .                  5.
188 115 119 120    1              .                  5.
189 115 120 121    1              .                  5.
190 116 115 121    1              .                  5.
191 116 121 122    1              .                  5.
192 117 116 122    1              .                  5.
193 119 118 123    1              .                  5.
194 119 123 124    1              .                  5.
195 120 119 124    1              .                  5.
196 120 124 125    1              .                  5.
197 120 125 126    1              .                  5.
198 121 120 126    1              .                  5.
199 121 126 127    1              .                  5.
200 122 121 127    1              .                  5.
200
  1   0   0       0.0              0.0
123   1   0       0.0              0.0
  1  32   1  20
 25  64  21  40
 57  34  41  50
 73 119  51  70
104 144  71  87
137 176  88 107
169 200 108 127
 30000.          30000.          .3        .3        12000.
  3
 59       0.0             -3.33
 68       0.0             -3.34
 77       0.0             -3.33
```

OUTPUT

```
  7 127 200   2   1   1   1   2        0.0                  0.0
  1             0.0               0.0
  2             0.0               2.50000000
  3             0.0               5.00000000
  4             0.0               7.50000000
  5             0.0              10.00000000
                 .
                 .
                 .
```

X and Y coordinates for nodal points 6 through 124 have been eliminated.

```
                 .
                 .
                 .
125            60.00000000       5.00000000
126            60.00000000       7.50000000
127            60.00000000      10.00000000
  1   1   6   7   1        0.0               5.00000000
  2   1   7   2   1        0.0               5.00000000
  3   2   7   8   1        0.0               5.00000000
  4   2   8   3   1        0.0               5.00000000
                 .
                 .
                 .
```

Information for elements 5 through 196 has been eliminated.

```
                 .
                 .
                 .
197 120 125 126   1        0.0               5.00000000
198 121 120 126   1        0.0               5.00000000
199 121 126 127   1        0.0               5.00000000
200 122 121 127   1        0.0               5.00000000
  1   0   0          0.0          0.0
123   1   0          0.0          0.0
  1  32   1  20
 25  64  21  40
 57  84  41  50
 73 119  51  70
104 144  71  87
137 176  88 107
169 200 108 127
 30000.00000000   30000.00000000  0.3000  0.3000  12000.00000000
 59  0.0              -0.33299999E 01
 68  0.0              -0.33399992E 01
 77  0.0              -0.33299999E 01
RESIDUALS
 0.46E-04-0.12E-03-0.29E-03-0.61E-04-0.32E-03 0.21E-03-0.81E-03 0.46E-04-0.13E-02 0.93E-04 0.31E-04-0.46E-04
 0.26E-03-0.40E-03 0.58E-03-0.44E-03 0.79E-03-0.63E-03-0.31E-04 0.53E-03-0.76E-04 0.11E-02 0.41E-03-0.63E-03
 0.39E-04-0.78E-03 0.17E-02 0.46E-04-0.34E-03 0.70E-03-0.27E-03 0.29E-03 0.20E-03-0.95E-03 0.81E-03-0.69E-03
 0.10E-02-0.14E-02 0.55E-03 0.70E-03
 0.14E-03 0.98E-03 0.43E-03-0.14E-03 0.62E-03-0.14E-03 0.16E-02-0.49E-03-0.41E-03 0.18E-02 0.31E-04 0.62E-03
 0.31E-04-0.11E-02 0.40E-03-0.19E-02 0.75E-03-0.14E-02 0.47E-03 0.12E-02 0.15E-04 0.16E-02 0.74E-03-0.11E-02
-0.18E-03-0.19E-02 0.14E-02-0.16E-02 0.11E-03 0.22E-02-0.17E-03 0.13E-02 0.11E-02-0.26E-02 0.33E-03-0.73E-03
 0.13E-02-0.29E-02 0.37E-03 0.16E-02
 0.26E-03 0.96E-03 0.90E-03-0.14E-02 0.26E-03-0.43E-03-0.11E-03-0.13E-02 0.15E-03 0.11E-02 0.12E-03 0.60E-03
 0.56E-03-0.32E-03 0.79E-03-0.25E-02 0.16E-02-0.20E-03 0.26E-03 0.92E-03
 0.76E-04 0.25E-02 0.52E-03-0.34E-02-0.57E-03-0.20E-02 0.92E-04-0.99E-03 0.59E-03-0.29E-02 0.50E-03-0.44E-03
 0.11E-02-0.34E-02-0.35E-03-0.31E-02 0.21E-03 0.36E-02 0.40E-03 0.15E-02 0.60E-03-0.22E-02 0.25E-02-0.26E-03
 0.15E-02-0.28E-02 0.76E-03-0.18E-02 0.14E-02-0.25E-02 0.76E-03-0.11E-02 0.21E-02-0.27E-02 0.46E-04 0.21E-02
-0.14E-03 0.33E-02 0.15E-02-0.67E-02
-0.18E-03 0.15E-02 0.58E-03-0.72E-03 0.54E-03-0.19E-02-0.24E-03 0.10E-02 0.49E-03-0.75E-03 0.23E-03-0.22E-02
-0.63E-03 0.28E-02-0.58E-03 0.20E-02 0.14E-02-0.12E-02 0.23E-03-0.29E-02-0.44E-03-0.99E-03 0.27E-03 0.26E-02
 0.50E-03 0.12E-02-0.46E-03-0.30E-02 0.15E-02-0.18E-02 0.17E-02-0.28E-02-0.17E-03 0.18E-02
```

```
 0.12E-03 0.20E-02 0.76E-03-0.16E-02 0.12E-02-0.79E-03 0.32E-03-0.11E-02-0.29E-03 0.28E-02 0.92E-04 0.53E-03
 0.72E-03-0.19E-02 0.27E-03-0.14E-02 0.37E-03-0.19E-02-0.46E-04 0.15E-02 0.17E-03 0.22E-02 0.20E-02-0.35E-03
 0.38E-03-0.17E-02-0.58E-03-0.76E-03-0.61E-04 0.22E-02 0.18E-03 0.13E-02 0.92E-04-0.14E-02 0.72E-03-0.10E-02
 0.12E-02-0.24E-02-0.27E-03 0.17E-02
-0.31E-04 0.13E-02 0.41E-03-0.11E-02 0.11E-02-0.34E-03 0.15E-03-0.86E-04-0.31E-04 0.11E-02 0.45E-03 0.52E-03
 0.93E-03-0.58E-03-0.21E-03-0.41E-03 0.35E-03-0.67E-03-0.26E-04 0.69E-03 0.55E-03 0.53E-03 0.73E-03-0.34E-03
 0.96E-03-0.90E-03-0.78E-04 0.61E-04 0.60E-04 0.34E-03-0.78E-03 0.17E-03-0.57E-03-0.46E-04-0.58E-03 0.17E-03
-0.23E-03-0.13E-03 0.0      -0.76E-05
NODE X-DISPLACEMENTS Y-DISPLACEMENTS
   1 -0.29423807E-17 -0.40228157E-15
   2  0.38915873E-03 -0.40890009E-04
   3  0.75649587E-03 -0.65743472E-04
   4  0.11234044E-02 -0.78853351E-04
   5  0.14938426E-02 -0.81002509E-04
   6  0.79227611E-05 -0.51768473E-03
   7  0.39947708E-03 -0.52281516E-03
   8  0.76343887E-03 -0.52951532E-03
   9  0.11214777E-02 -0.53323270E-03
  10  0.14894083E-02 -0.53292233E-03
  11  0.36253070E-04 -0.98608062E-03
  12  0.40745432E-03 -0.99141337E-03
  13  0.76251477E-03 -0.99169044E-03
  14  0.11116681E-02 -0.99108624E-03
  15  0.14720948E-02 -0.98744640E-03
  16  0.75456119E-04 -0.14298004E-02
  17  0.42416831E-03 -0.14371402E-02
  18  0.76040486E-03 -0.14379008E-02
  19  0.10939997E-02 -0.14357055E-02
  20  0.14387334E-02 -0.14289075E-02
  21  0.12681015E-03 -0.18463540E-02
  22  0.44873706E-03 -0.18561389E-02
  23  0.75924327E-03 -0.18581909E-02
  24  0.10689320E-02 -0.18552223E-02
  25  0.13896511E-02 -0.18455309E-02
  26  0.19161095E-03 -0.22284635E-02
  27  0.48071798E-03 -0.22408471E-02
  28  0.75872126E-03 -0.22440248E-02
  29  0.10366326E-02 -0.22402806E-02
  30  0.13255933E-02 -0.22277902E-02
  31  0.27056853E-03 -0.25677332E-02
  32  0.51993341E-03 -0.25827934E-02
  33  0.75838901E-03 -0.25869242E-02
  34  0.99706301E-03 -0.25822627E-02
  35  0.12470975E-02 -0.25669569E-02
  36  0.36423653E-03 -0.28551186E-02
  37  0.56637265E-03 -0.28731928E-02
  38  0.75795478E-03 -0.28784184E-02
  39  0.95004006E-03 -0.28727890E-02
  40  0.11545876E-02 -0.28544946E-02
  41  0.47364179E-03 -0.30794898E-02
  42  0.62060030E-03 -0.31027193E-02
  43  0.75730938E-03 -0.31105822E-02
  44  0.89497189E-03 -0.31041235E-02
  45  0.10484471E-02 -0.30818814E-02
  46  0.60015148E-03 -0.32225181E-02
  47  0.68734726E-03 -0.32591512E-02
  48  0.75668679E-03 -0.32797894E-02
  49  0.82869013E-03 -0.32699381E-02
  50  0.92841033E-03 -0.32392645E-02
  51  0.70449454E-03 -0.32795703E-02
```

52	0.71977079E-03	-0.32956556E-02
53	0.73754089E-03	-0.33070145E-02
54	0.75236871E-03	-0.33244595E-02
55	0.76076877E-03	-0.33277860E-02
56	0.76785497E-03	-0.33350314E-02
57	0.78532519E-03	-0.33336496E-02
58	0.80334162E-03	-0.33406354E-02
59	0.82792062E-03	-0.33384394E-02
60	0.76327100E-03	-0.32820541E-02
61	0.76330337E-03	-0.33005660E-02
62	0.76334830E-03	-0.33198239E-02
63	0.76339766E-03	-0.33276263E-02
64	0.76342956E-03	-0.33356836E-02
65	0.76346309E-03	-0.33392250E-02
66	0.76351454E-03	-0.33502160E-02
67	0.76356856E-03	-0.33530316E-02
68	0.76361327E-03	-0.33498728E-02
69	0.82204840E-03	-0.32796431E-02
70	0.80683688E-03	-0.32957294E-02
71	0.78917085E-03	-0.33071043E-02
72	0.77443244E-03	-0.33245529E-02
73	0.76609617E-03	-0.33278826E-02
74	0.75907679E-03	-0.33351318E-02
75	0.74170437E-03	-0.33337504E-02
76	0.72379992E-03	-0.33407323E-02
77	0.69930777E-03	-0.33385316E-02
78	0.92642475E-03	-0.32227489E-02
79	0.83938730E-03	-0.32593932E-02
80	0.76999492E-03	-0.32800462E-02
81	0.69834618E-03	-0.32701979E-02
82	0.59879967E-03	-0.32395299E-02
83	0.10529992E-02	-0.30799245E-02
84	0.90618501E-03	-0.31031708E-02
85	0.76960004E-03	-0.31110465E-02
86	0.63207094E-03	-0.31045934E-02
87	0.47875103E-03	-0.30823539E-02
88	0.11625036E-02	-0.28557405E-02
89	0.96047367E-03	-0.28738372E-02
90	0.76859026E-03	-0.28790797E-02
91	0.57700579E-03	-0.28734577E-02
92	0.37258049E-03	-0.28551598E-02
93	0.12562915E-02	-0.25684710E-02
94	0.10069925E-02	-0.25835617E-02
95	0.76859817E-03	-0.25877140E-02
96	0.52998122E-03	-0.25830567E-02
97	0.28002611E-03	-0.25677413E-02
98	0.13353925E-02	-0.22292808E-02
99	0.10462988E-02	-0.22416930E-02
100	0.76830806E-03	-0.22448883E-02
101	0.49040955E-03	-0.22411472E-02
102	0.20147146E-03	-0.22286526E-02
103	0.14003566E-02	-0.18471573E-02
104	0.10783856E-02	-0.18569769E-02
105	0.76782960E-03	-0.18590461E-02
106	0.45809755E-03	-0.18560791E-02
107	0.13735513E-03	-0.18463787E-02
108	0.14518937E-02	-0.14305378E-02
109	0.11030668E-02	-0.14379127E-02
110	0.76671923E-03	-0.14386906E-02
111	0.43302565E-03	-0.14364989E-02

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112  0.88206260E-04 -0.14296926E-02
113  0.14912945E-02 -0.98666037E-03
114  0.11198989E-02 -0.99203829E-03
115  0.76466077E-03 -0.99232700E-03
116  0.41535380E-03 -0.99172001E-03
117  0.54789009E-04 -0.98807411E-03
118  0.15198698E-02 -0.51803584E-03
119  0.11279932E-02 -0.52321656E-03
120  0.76376903E-03 -0.52991253E-03
121  0.40554511E-03 -0.53363340E-03
122  0.37436606E-04 -0.53332257E-03
123  0.15281320E-02 -0.40215790E-15
124  0.11383833E-02 -0.40898434E-04
125  0.77075697E-03 -0.65812492E-04
126  0.40362729E-03 -0.78972298E-04
127  0.32997923E-04 -0.81136051E-04
ELEMENT NUMBER  FIRST NODE        SECOND NODE      THIRD NODE       X AND Y CO-ORDINATES OF CENTROID
  X-STRESS       Y-STRESS              XY-STRESS         STRESS-1          STRESS-2          PRINCIPLE ANGLE
   1   1   6   7        1.99999714        0.83333236
 0.66766739E-01 -0.41536331E-01 -0.19127655E 00  0.21140933E 00 -0.18617692E 00      -52.90742493
0.21141E 00-0.18618E 00-0.52907E 02
   2   1   7   2        0.99999887        1.66666412
-0.48373938E-01 -0.50519145E 00 -0.59739470E-01 -0.40690899E-01 -0.51287448E 00      -82.67741394
-0.40691E-01-0.51287E 00-0.82677E 02
   3   2   7   8        1.99999714        3.33332920
 0.66881638E-01 -0.54338455E-01 -0.18068314E 00  0.21026170E 00 -0.17771652E 00      -55.67671204
0.21026E 00-0.17772E 00-0.55677E 02
   4   2   8   3        0.99999887        4.16666126
-0.22024989E-01 -0.30484718E 00 -0.91668997E-01  0.51966310E-02 -0.33206674E 00      -73.50030518
0.51966E-02-0.33207E 00-0.73500E 02
   5   3   8   4        0.99999887        5.83332634
 0.24433136E-01 -0.14998627E 00 -0.93925476E-01  0.65393329E-01 -0.19094646E 00      -66.44316101
0.65393E-01-0.19095E 00-0.66443E 02
   6   8   9   4        1.99999714        6.66665840
-0.35877228E-01 -0.55372238E-01 -0.98930597E-01  0.53784847E-01 -0.14503431E 00      -47.81701660
0.53785E-01-0.14503E 00-0.47817E 02
   7   4   9   5        0.99999887        8.33332348
-0.29674470E-01 -0.34691811E-01 -0.39415359E-01  0.73119700E-02 -0.71678221E-01      -46.82431030
0.73120E-02-0.71678E-01-0.46824E 02
   8   9  10   5        1.99999714        9.16665554
-0.47515869E-01 -0.10524750E-01 -0.41612029E-01  0.16516998E-01 -0.74557602E-01      -33.02040100
0.16517E-01-0.74558E-01-0.33020E 02
   9   6  11  12        4.99999428        0.83333236
 0.29022312E 00  0.23073196E-01 -0.91816902E-01  0.31873637E 00 -0.54400563E-02      -72.75335693
0.31874E 00-0.54401E-02-0.72753E 02
  10   6  12   7        3.99999523        1.66666412
 0.67365646E-01 -0.41355133E-01  0.50668716E-02  0.67601264E-01 -0.41590750E-01       87.34381104
0.67601E-01-0.41591E-01 0.87344E 02
  11  12  13   7        4.99999428        3.33332920
 0.86565971E-01  0.22644997E-01 -0.17010403E 00  0.22768593E 00 -0.11847496E 00      -50.32423401
0.22769E 00-0.11847E 00-0.50324E 02
  12   7  13   8        3.99999523        4.16666126
-0.36660194E-01 -0.91399193E-01 -0.10168362E 00  0.41272879E-01 -0.16933227E 00      -52.53625488
0.41273E-01-0.16933E 00-0.52536E 02
  13   8  13   9        3.99999523        5.83332634
-0.24860382E-01 -0.52066803E-01 -0.13011360E 00  0.92359126E-01 -0.16928631E 00      -47.98773193
0.92359E-01-0.16929E 00-0.47988E 02
  14   9  13  14        4.99999428        6.66665840
-0.10540676E 00 -0.24373055E-01 -0.15547848E 00  0.95781028E-01 -0.22556084E 00      -37.69969177
0.95781E-01-0.22556E 00-0.37700E 02
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183 111 116 117      52.99993896       8.33332348
-0.17976189E 00 -0.10180473E-01  0.48403025E-01  0.26623607E-02 -0.19260472E 00     14.86104670
0.26624E-02-0.19260E 00 0.14861E 02
184 112 111 117      51.99993896       9.16665554
-0.34027934E 00 -0.20420194E-01  0.11133671E 00  0.14517665E-01 -0.37521720E 00     17.42330933
0.14518E-01-0.37522E 00 0.17423E 02
185 114 113 118      54.99992371       0.83333236
 0.29273987E 00  0.23296356E-01  0.91800690E-01  0.32104355E 00 -0.50073266E-02     72.86985773
0.32104E 00-0.50073E-02 0.72870E 02
186 114 118 119      55.99992371       1.66666412
 0.68448067E-01 -0.41628838E-01 -0.57191849E-02  0.68744361E-01 -0.41925184E-01    -87.04010010
0.68744E-01-0.41925E-01-0.87040E 02
187 115 114 119      54.99992371       3.33332920
 0.87810516E-01  0.22883415E-01  0.17014503E 00  0.22856128E 00 -0.11786735E 00     50.40475464
0.22856E 00-0.11787E 00 0.50405E 02
188 115 119 120      55.99992371       4.16666126
-0.36286354E-01 -0.91231346E-01  0.10137463E 00  0.41272283E-01 -0.16878998E 00     52.58529663
0.41272E-01-0.16879E 00 0.52585E 02
189 115 120 121      55.99992371       5.83332634
-0.24518013E-01 -0.52001953E-01  0.13017368E 00  0.92637002E-01 -0.16915697E 00     48.01652650
0.92637E-01-0.16916E 00 0.48017E 02
190 116 115 121      54.99992371       6.66665840
-0.10538006E 00 -0.24330139E-01  0.15566444E 00  0.95997870E-01 -0.22570807E 00     37.70663452
0.95998E-01-0.22571E 00 0.37707E 02
191 116 121 122      55.99992371       8.33332348
-0.10655022E 00 -0.28234482E-01  0.65421283E-01  0.88524818E-02 -0.14363718E 00     29.55082703
0.88525E-02-0.14364E 00 0.29551E 02
192 117 116 122      54.99992371       9.16665554
-0.17625058E 00 -0.91273785E-02  0.88289261E-01  0.28873861E-01 -0.21425182E 00     23.28959656
0.28874E-01-0.21425E 00 0.23290E 02
193 119 118 123      57.99992371       0.83333236
 0.70312500E-01 -0.41079521E-01  0.19113541E 00  0.21370131E 00 -0.18446833E 00     53.12661550
0.21370E 00-0.18447E 00 0.53127E 02
194 119 123 124      58.99992371       1.66666412
-0.47615349E-01 -0.50502849E 00  0.58475137E-01 -0.40258348E-01 -0.51238543E 00     82.83502197
-0.40258E-01-0.51239E 00 0.82835E 02
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195 120 119 124      57.99992371       3.33332920
 0.87688446E-01 -0.54045677E-01  0.18099755E 00  0.21119791E 00 -0.17755514E 00      55.69512939
0.21120E 00-0.17756E 00 0.55695E 02
196 120 124 125      58.99992371       4.16666126
-0.21767795E-01 -0.30547661E 00  0.91787755E-01  0.53382516E-02 -0.33258265E 00      73.55276469
0.53383E-02-0.33258E 00 0.73553E 02
197 120 125 126      58.99992371       5.83332634
 0.24728298E-01 -0.15048748E 00  0.94171524E-01  0.65741599E-01 -0.19150072E 00      66.47087097
0.65742E-01-0.19150E 00 0.66471E 02
198 121 120 126      57.99992371       6.66665840
-0.35793304E-01 -0.55384636E-01  0.99164128E-01  0.54057777E-01 -0.14523572E 00      47.82423401
0.54058E-01-0.14524E 00 0.47824E 02
199 121 126 127      58.99992371       8.33332348
-0.29632568E-01 -0.34852028E-01  0.39621055E-01  0.74646063E-02 -0.71949184E-01      46.88763428
0.74646E-02-0.71949E-01 0.46888E 02
200 122 121 127      57.99992371       9.16665554
-0.47542572E-01 -0.10533929E-01  0.41821599E-01  0.16694184E-01 -0.74770629E-01      33.06871033
0.16694E-01-0.74771E-01 0.33069E 02
```

APPENDIX A - EXAMPLE 1, DATA AND OUTPUT

DATA

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 1
12 238 394   2   1   1   1   2     0.0          0.0
   0.00          0.0000
   0.00          0.3000
   0.00          0.5760
   0.00          1.3000
   0.00          2.5000
   0.00          4.0000
   0.00          6.0000
   0.00          8.0000
   0.00          9.5000
   0.00          10.700
   0.00          11.424
   0.00          11.700
   0.00          12.000
   1.50          0.0000
   1.50          0.5760
   1.50          1.8000
   1.50          3.2000
   1.50          4.9000
   1.50          7.1
   1.50          8.8000
   1.50          10.200
   1.50          11.424
   1.50          12.000
   3.50          0.0000
   3.50          0.3000
   3.50          0.5760
   3.50          1.3000
   3.50          2.5000
   3.50          4.0000
   3.50          6.0000
   3.50          8.0000
   3.50          9.5000
   3.50          10.700
   3.50          11.424
   3.50          11.700
   3.50          12.000
   5.50          0.0000
   5.50          0.5760
   5.50          1.8000
   5.50          3.2000
   5.50          4.9000
   5.50          7.1000
   5.50          8.8000
   5.50          10.200
   5.50          11.424
   5.50          12.000
   7.50          0.0000
   7.50          0.3000
   7.50          0.5760
   7.50          1.3000
   7.50          2.5000
   7.50          4.0000
   7.50          6.0000
   7.50          8.0000
   7.50          9.5000
   7.50          10.700
   7.50          11.424
   7.50          11.700
```

7.50	12.000
9.50	0.0000
9.50	0.5760
9.50	1.8000
9.50	3.2000
9.50	4.9000
9.50	7.1000
9.50	8.8000
9.50	10.200
9.50	11.424
9.50	12.000
10.5	2.8
10.4	3.2000
10.4	3.5000
10.4	4.2000
10.4	6.0000
10.4	7.8000
10.4	8.5000
10.4	8.8000
10.5	9.2000
10.9	2.4000
11.2	3.1000
11.05	3.3000
11.0	3.7000
11.0	4.9000
11.0	7.1000
11.0	8.3000
11.05	8.7000
11.2	8.9000
10.9	9.6000
11.5	0.0000
11.5	0.3000
11.5	0.5760
11.5	1.3000
11.5	2.0000
11.5	2.5000
11.5	3.0000
11.5	9.0000
11.5	9.5000
11.5	10.000
11.5	10.700
11.5	11.424
11.5	11.700
11.5	12.000
13.5	0.0000
13.5	0.5760
13.5	1.5000
13.5	2.4000
13.5	3.0000
13.5	9.0000
13.5	9.6
13.5	10.500
13.5	11.424
13.5	12.000
15.5	0.0000
15.5	0.3000
15.5	0.5760
15.5	1.3000
15.5	2.0000
15.5	2.7

15.5	3.0000
15.5	9.0000
15.5	9.3000
15.5	10.000
15.5	10.700
15.5	11.424
15.5	11.700
15.5	12.000
17.5	0.0000
17.5	0.5760
17.5	1.5000
17.5	2.4000
17.5	3.0000
17.5	9.0000
17.5	9.6
17.5	10.500
17.5	11.424
17.5	12.000
19.5	0.0000
19.5	0.3000
19.5	0.5760
19.5	1.3000
19.5	2.0000
19.5	2.5000
19.5	3.0000
19.5	9.0000
19.5	9.5000
19.5	10.000
19.5	10.700
19.5	11.424
19.5	11.700
19.5	12.000
20.1	2.4000
19.8	3.1000
19.95	3.3000
20.0	3.7000
20.0	4.9000
20.0	7.1000
20.0	8.3000
19.95	8.7000
19.8	8.9000
20.1	9.6000
20.5	2.8
20.6	3.2000
20.6	3.5000
20.6	4.2000
20.6	6.0000
20.6	7.8000
20.6	8.5000
20.6	8.8000
20.5	9.2000
21.5	0.0000
21.5	0.5760
21.5	1.8000
21.5	3.2000
21.5	4.9000
21.5	7.1000
21.5	8.8000
21.5	10.200
21.5	11.424

21.5	12.000
23.5	0.C000
23.5	0.3000
23.5	0.5760
23.5	1.3000
23.5	2.5C00
23.5	4.C000
23.5	6.C000
23.5	8.C000
23.5	9.5C00
23.5	10.700
23.5	11.424
23.5	11.700
23.5	12.C00
25.5	0.C000
25.5	0.5760
25.5	1.8C00
25.5	3.2C00
25.5	4.9000
25.5	7.1000
25.5	8.8C00
25.5	10.200
25.5	11.424
25.5	12.000
27.5	0.C000
27.5	0.3C00
27.5	0.5760
27.5	1.3C00
27.5	2.5000
27.5	4.C000
27.5	6.C000
27.5	8.C000
27.5	9.5000
27.5	10.700
27.5	11.424
27.5	11.700
27.5	12.C00
29.5	0.C000
29.5	0.5760
29.5	1.8000
29.5	3.2000
29.5	4.9C00
29.5	7.1000
29.5	8.8000
29.5	10.200
29.5	11.424
29.5	12.000
31.0	0.C000
31.0	0.3000
31.0	0.5760
31.0	1.3C00
31.0	2.5000
31.0	4.C000
31.0	6.C000
31.0	8.C000
31.0	9.5000
31.0	10.700
31.0	11.424
31.0	11.700
31.0	12.000

238

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125	66	77	78	1	.	.3360
126	66	78	67	1	.	.3360
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130	68	67	99	1	.	.3360
131	68	99	100	1	.	.3360
132	68	100	101	1	.	8.042
133	69	68	101	1	.	8.042
134	69	101	102	1	.	8.042
135	79	93	94	1	.	.3360
136	79	94	95	1	.	.3360
137	79	95	80	1	.	.3360
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140	71	70	81	1	.	.3360
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156	88	96	97	1	.	.3360
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163	93	92	105	1	.	.3360
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166	94	106	107	1	.	.3360
167	95	94	107	1	.	.3360
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169	97	108	109	1	.	.3360
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171	98	109	110	1	.	.3360
172	99	98	110	1	.	.3360
173	99	110	111	1	.	.3360
174	100	99	111	1	.	.3360
175	101	100	111	1	.	8.042
176	101	111	112	1	.	8.042
177	102	101	112	1	.	8.042
178	103	113	114	1	.	8.042
179	103	114	104	1	.	8.042

180	104	114	115	1	.	8.042
181	104	115	116	1	.	.3360
182	105	104	116	1	.	.3360
183	105	116	117	1	.	.3360
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186	107	106	118	1	.	.3360
187	107	118	119	1	.	.3360
188	108	120	121	1	.	.3360
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193	111	110	123	1	.	.3360
194	111	123	124	1	.	.3360
195	111	124	125	1	.	8.042
196	112	111	125	1	.	8.042
197	112	125	126	1	.	8.042
198	114	113	127	1	.	8.042
199	114	127	128	1	.	8.042
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213	123	134	135	1	.	.3360
214	124	123	135	1	.	.3360
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217	126	125	136	1	.	8.042
218	127	137	138	1	.	8.042
219	128	127	138	1	.	8.042
220	128	138	139	1	.	8.042
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233	135	134	147	1	.	.3360
234	135	147	148	1	.	.3360
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237	136	149	150	1	.	8.042
238	138	137	170	1	.	8.042
239	138	170	171	1	.	8.042

240	139	138	171	1	.	8.042
241	140	139	171	1	.	.3360
242	140	171	172	1	.	.3360
243	141	140	172	1	.	.3360
244	141	172	151	1	.	.3360
245	142	141	151	1	.	.3360
246	143	142	151	1	.	.3360
247	143	151	152	1	.	.3360
248	152	151	161	1	.	.3360
249	152	161	153	1	.	.3360
250	153	161	162	1	.	.3360
251	153	162	163	1	.	.3360
252	154	153	163	1	.	.3360
253	154	163	164	1	.	.3360
254	155	154	164	1	.	.3360
255	155	164	165	1	.	.3360
256	156	155	165	1	.	.3360
257	156	165	166	1	.	.3360
258	157	156	166	1	.	.3360
259	157	166	167	1	.	.3360
260	158	157	167	1	.	.3360
261	158	167	168	1	.	.3360
262	158	168	169	1	.	.3360
263	159	158	169	1	.	.3360
264	159	169	160	1	.	.3360
265	144	159	160	1	.	.3360
266	145	144	160	1	.	.3360
267	146	145	160	1	.	.3360
268	146	160	177	1	.	.3360
269	147	146	177	1	.	.3360
270	147	177	178	1	.	.3360
271	148	147	178	1	.	.3360
272	149	148	178	1	.	8.042
273	149	178	179	1	.	8.042
274	150	149	179	1	.	8.042
275	151	172	161	1	.	.3360
276	161	172	173	1	.	.3360
277	162	161	173	1	.	.3360
278	163	162	173	1	.	.3360
279	164	163	173	1	.	.3360
280	164	173	174	1	.	.3360
281	165	164	174	1	.	.3360
282	165	174	175	1	.	.3360
283	166	165	175	1	.	.3360
284	166	175	176	1	.	.3360
285	167	166	176	1	.	.3360
286	168	167	176	1	.	.3360
287	169	168	176	1	.	.3360
288	169	176	177	1	.	.3360
289	160	169	177	1	.	.3360
290	170	180	181	1	.	8.042
291	171	170	181	1	.	8.042
292	171	181	182	1	.	8.042
293	171	182	183	1	.	.3360
294	172	171	183	1	.	.3360
295	172	183	184	1	.	.3360
296	173	172	184	1	.	.3360
297	173	184	185	1	.	.3360
298	173	185	174	1	.	.3360
299	174	185	186	1	.	.3360

300	175	174	186	1	.	.3360
301	175	186	187	1	.	.3360
302	176	175	187	1	.	.3360
303	176	187	188	1	.	.3360
304	177	176	188	1	.	.3360
305	177	188	189	1	.	.3360
306	178	177	189	1	.	.3360
307	178	189	190	1	.	.3360
308	178	190	191	1	.	8.042
309	179	178	191	1	.	8.042
310	179	191	192	1	.	8.042
311	181	180	193	1	.	8.042
312	181	193	194	1	.	8.042
313	182	181	194	1	.	8.042
314	183	182	194	1	.	.3360
315	183	194	195	1	.	.3360
316	184	183	195	1	.	.3360
317	184	195	196	1	.	.3360
318	185	184	196	1	.	.3360
319	185	196	197	1	.	.3360
320	186	185	197	1	.	.3360
321	186	197	198	1	.	.3360
322	187	186	198	1	.	.3360
323	187	198	199	1	.	.3360
324	188	187	199	1	.	.3360
325	188	199	200	1	.	.3360
326	189	188	200	1	.	.3360
327	189	200	201	1	.	.3360
328	190	189	201	1	.	.3360
329	191	190	201	1	.	8.042
330	191	201	202	1	.	8.042
331	192	191	202	1	.	8.042
332	193	203	204	1	.	8.042
333	194	193	204	1	.	8.042
334	194	204	205	1	.	8.042
335	194	205	206	1	.	.3360
336	195	194	206	1	.	.3360
337	195	206	207	1	.	.3360
338	196	195	207	1	.	.3360
339	196	207	208	1	.	.3360
340	197	196	208	1	.	.3360
341	197	208	209	1	.	.3360
342	198	197	209	1	.	.3360
343	198	209	210	1	.	.3360
344	199	198	210	1	.	.3360
345	199	210	211	1	.	.3360
346	200	199	211	1	.	.3360
347	200	211	212	1	.	.3360
348	201	200	212	1	.	.3360
349	201	212	213	1	.	.3360
350	201	213	214	1	.	8.042
351	202	201	214	1	.	8.042
352	202	214	215	1	.	8.042
353	204	203	216	1	.	8.042
354	204	216	217	1	.	8.042
355	205	204	217	1	.	8.042
356	206	205	217	1	.	.3360
357	206	217	218	1	.	.3360
358	207	206	218	1	.	.3360
359	207	218	219	1	.	.3360

```
360 208 207 219    1         .        .3360
361 208 219 220    1         .        .3360
362 209 208 220    1         .        .3360
363 209 220 221    1         .        .3360
364 210 209 221    1         .        .3360
365 210 221 222    1         .        .3360
366 211 210 222    1         .        .3360
367 211 222 223    1         .        .3360
368 212 211 223    1         .        .3360
369 212 223 224    1         .        .3360
370 213 212 224    1         .        .3360
371 214 213 224    1         .        8.042
372 214 224 225    1         .        8.042
373 215 214 225    1         .        8.042
374 216 226 227    1         .        8.042
375 217 216 227    1         .        8.042
376 217 227 228    1         .        8.042
377 217 228 229    1         .        .3360
378 218 217 229    1         .        .3360
379 218 229 230    1         .        .3360
380 219 218 230    1         .        .3360
381 219 230 231    1         .        .3360
382 220 219 231    1         .        .3360
383 220 231 232    1         .        .3360
384 221 220 232    1         .        .3360
385 221 232 233    1         .        .3360
386 222 221 233    1         .        .3360
387 222 233 234    1         .        .3360
388 223 222 234    1         .        .3360
389 223 234 235    1         .        .3360
390 224 223 235    1         .        .3360
391 224 235 236    1         .        .3360
392 224 236 237    1         .        8.042
393 225 224 237    1         .        8.042
394 225 237 238    1         .        8.042
394
  7   1   1      0.0           0.0
232   1   1      0.0           0.0
  1  36   1  20
 15  72  21  40
 51 105  41  59
 85 154  60  78
106 172  79  98
129 207  99 119
188 241 120 139
221 289 140 160
238 310 161 179
290 346 180 199
325 382 200 219
361 394 220 238
 30000.          30000.          .3        .3        12000.
 26
  1       -.5216          0.00000
  2       -.9516          £.01210
  3       -.48150         £0.0392
  4       -0.1095         £0.0789
  5       -0.1145         £0.1174
  6       -0.0848         £0.1594
  7       0.00000         £0.1860
  8       £0.0848         £0.1594
```

9	&0.1145	&0.1174
10	&0.1095	&0.0789
11	&0.4815	&0.0392
12	&0.9516	&0.0121
13	&0.5216	0.00000
226	&1.1820	0.00000
227	&2.1557	-0.0121
228	&1.0907	-0.0392
229	&0.2482	-0.0789
230	&0.2583	-0.1174
231	&0.1920	-0.1594
232	0.00000	-0.1860
233	-0.1920	-0.1594
234	-0.2583	-0.1174
235	-0.2482	-0.0789
236	-1.0907	-0.0392
237	-2.1557	-0.0121
238	-1.1820	0.00000

OUTPUT

```
12 238 394    2    1    1    1    2        0.0                  0.0
 1             0.0                0.0
 2             0.0                0.25999995
 3             0.0                0.57599998
 4             0.0                1.29999924
 5             0.0                2.50000000
               .
               .
               .
```

X and Y coordinates for nodal points 6 through 234 have been eliminated.

```
               .
               .
               .
235          31.00000000      10.69999981
236          31.00000000      11.42359979
237          31.00000000      11.69999981
238          31.00000000      12.00000000
```

```
  1   1  14   2   1        0.0                   8.04199982
  2   2  14  15   1        0.0                   8.04199982
  3   3   2  15   1        0.0                   8.04199982
  4   4   3  15   1        0.0                   0.33599997
               .
               .
               .
```

Information for elements 5 through 391 has been eliminated.

```
               .
               .
               .
391 224 235 236   1        0.0                   0.33599997
392 224 236 237   1        0.0                   8.04199982
393 225 224 237   1        0.0                   8.04199982
394 225 237 238   1        0.0                   8.34199982
  7   1   1           0.0           0.0
232   1   1           0.0           0.0
  1  36   1  20
 15  72  21  40
 51 105  41  59
 95 154  60  78
106 172  79  98
129 207  99 119
188 241 120 139
221 299 140 160
238 310 161 179
290 346 180 199
325 382 200 219
361 394 220 238
 30000.00000000  30000.00000000  0.3000  0.3000  12000.00000000
  1 -0.52159993E 00  0.0
  2 -0.95159996E 00  0.12100000E-01
  3 -0.48149997E 00  0.39199997E-01
  4 -0.10949999E 00  0.78899980E-01
  5 -0.11449999E 00  0.11739999E 00
  6 -0.84799945E-01  0.15939999E 00
  7  0.0             0.18599999E 00
  8  0.84799945E-01  0.15939999E 00
  9  0.11449999E 00  0.11739999E 00
 10  0.10949999E 00  0.78899981E-01
 11  0.48149997E 00  0.39199997E-01
```

```
 12  0.95159996E 00  0.12100000E-01
 13  0.52159995E 00  0.0
226  0.11815992E 01  0.0
227  0.21556997E 01 -0.12100007E-01
228  0.10906992E 01 -0.39199997E-01
229  0.24820000E 00 -0.78899980E-01
230  0.25825995E 00 -0.11739999E 00
231  0.19159997E 00 -0.15939999E 00
232  0.0             -0.18599999E 00
233 -0.19159997E 00 -0.15939999E 00
234 -0.25825995E 00 -0.11739999E 00
235 -0.24820000E 00 -0.78899980E-01
236 -0.10906992E 01 -0.39199997E-01
237 -0.21556997E 01 -0.12100000E-01
238 -0.11815992E 01  0.0
RESIDUALS
-0.31E-03-0.82E-03 0.23E-03 0.11E-02-0.11E-03-0.44E-03-0.15E-04 0.0       0.57E-05 0.12E-04 0.67E-[illegible]
 0.0       -0.14E-05 0.95E-06-0.10E-04 0.20E-04-0.83E-05-0.19E-05 0.35E-04 0.17E-03 0.47E-03 [illegible]
-0.18E-03-0.52E-03 0.15E-04-0.66E-03-0.22E-03 0.75E-03-0.29E-05 0.23E-04-0.24E-04 0.22E-04 [illegible]
-0.11E-04 0.11E-04 0.29E-05 0.52E-04
-0.19E-05-0.12E-04-0.15E-04 0.50E-03 0.31E-04-0.39E-03 0.34E-03-0.71E-03-0.92E-04 0.66E-03-[illegible]
-0.19E-05-0.83E-06-0.38E-05 0.42E-04-0.86E-05 0.13E-04-0.38E-05 0.23E-04-0.29E-05 0.43E-04 [illegible]
-0.19E-05 0.26E-04 0.46E-04 0.19E-03-0.35E-03 0.19E-02 0.33E-03-0.19E-02 0.0       -0.54E-03-0.6[illegible]
-0.29E-05-0.58E-05-0.12E-04 0.12E-04
 0.11E-05 0.19E-04 0.83E-06 0.11E-04-0.18E-05 0.17E-04 0.5[illegible]E-06 0.12E-04 0.92E-04 0.45E-[illegible]
 0.61E-03-0.93E-04-0.12E-02 0.43E-03 0.26E-03 0.22E-03 0.16E-04-0.27E-05-0.14E-04 0.30E-0[illegible]
-0.12E-04 0.24E-05-0.81E-05 0.23E-05-0.23E-05-0.1[illegible]E-05 0.54E-06-0.33E-05 0.42E-04 0.86E-04-[illegible]
 0.24E-04-0.53E-03
 0.19E-03-0.94E-04-0.42E-04 0.17E-03-0.91E-05-0.13E-05 0.67E-05 0.16E-05 0.58E-05 0.60E-05 [illegible]
 0.18E-06 0.95E-06 0.56E-06 0.39E-05 0.43E-04 0.46E-04-0.35E-04-0.15E-04-0.22E-04 0.12E-04-[illegible]
-0.71E-05 0.1[illegible]E-04-0.24E-04 0.39E-05-0.34E-04 0.37E-05-0.24E-04 0.67E-05-0.54E-05 0.41E-05-[illegible]
-0.64E-05 0.13E-05
 0.36E-06-0.22E-05-0.60E-05 0.92E-05 0.35E-05 0.82E-05 0.13E-04-0.55E-05 0.68E-05-0.86E-0[illegible]
 0.38E-05-0.24E-06-0.14E-05 0.21E-05-0.47E-05-0.83E-06-0.43E-05 0.11E-05 0.29E-04 0.31E-0[illegible]
-0.31E-04 0.78E-03-0.79E-05 0.11E-04-0.15E-04-0.16E-04-0.61E-05 0.11E-04-0.30E-06-0.79E-0[illegible]
-0.23E-05-0.15E-05-0.23E-05-0.33E-05
-0.41E-05-0.11E-05-0.22E-04 0.50E-04-0.10E-04-0.76E-04 0.25E-05 0.32E-04-0.20E-04-0.51E-04-[illegible]
-0.21E-05-0.24E-05-0.50E-05 0.52E-05 0.38E-05-0.56E-05 0.4[illegible]E-05 0.44E-05-0.59E-05-0.67E-0[illegible]
-0.58E-04 0.29E-03-0.57E-05-0.31E-03-0.47E-05 0.11E-03-0.56E-04-0.14E-03 0.22E-04 0.57E-04-[illegible]
-0.19E-05 0.32E-05-0.56E-05 0.93E-05 0.38E-05-0.64E-05
 0.32E-05 0.19E-04-0.15E-04-0.31E-04-0.45E-05 0.24E-05-0.14E-04-0.51E-05 0.26E-04-0.33E-0[illegible]
 0.92E-04-0.45E-03-0.27E-04 0.69E-04-0.41E-04-0.76E-04-0.34E-05-0.27E-05 0.27E-05 0.29E-0[illegible]
 0.0       -0.59E-05-0.75E-05 0.13E-05-0.74E-05-0.51E-05-0.63E-04 0.20E-03-0.45E-05-0.22E-0[illegible]
 0.14E-04 0.14E-03 0.67E-06-0.33E-04
-0.48E-05-0.24E-05-0.42E-05 0.36E-05-0.36E-05-0.46E-05 0.24E-05 0.35E-05-0.54E-06 0.93E-0[illegible]
-0.36E-05 0.13E-04-0.57E-05-0.14E-04-0.24E-03 0.82E-03 0.30E-03-0.21E-02-0.16E-03 0.97E-0[illegible]
 0.42E-06 0.72E-06 0.24E-06-0.29E-05-0.18E-05 0.11E-05-0.12E-04-0.33E-05-0.14E-04-0.24E-0[illegible]
-0.44E-05-0.23E-05-0.42E-05-0.33E-05-0.11E-04-0.29E-05
 0.12E-06 0.3[illegible]E-05-0.53E-06-0.75E-05 0.19E-05 0.23E-05-0.66E-06-0.20E-05 0.41E-05-0.63E-0[illegible]
-0.46E-05-0.27E-05-0.33E-05-0.91E-05-0.91E-05-0.58E-05 0.19E-04 0.41E-03 0.41E-04-0.66E-0[illegible]
-0.60E-07-0.40E-05-0.27E-05-0.35E-05-0.11E-04-0.2[illegible]E-05-0.15E-04-0.12E-04-0.72E-05 0.13E-0[illegible]
 0.85E-04 0.39E-03
-0.10E-04 0.31E-03 0.35E-04-0.82E-03 0.91E-05 0.50E-03 0.60E-03-0.13E-04 0.34E-06 0.76E-0[illegible]
 0.13E-05 0.29E-05-0.70E-05-0.74E-05-0.13E-04-0.22E-04-0.40E-04 0.60E-04-0.90E-04-0.46E-0[illegible]
-0.56E-04 0.22E-02 0.23E-04 0.16E-03 0.15E-04-0.16E-03 0.39E-05-0.19E-05 0.16E-05 0.13E-0[illegible]
-0.77E-05-0.83E-06-0.22E-04-0.39E-05
-0.11E-04-0.19E-04 0.85E-04-0.13E-03-0.44E-05 0.10E-03-0.13E-03-0.71E-03 0.35E-03 0.66E-0[illegible]
 0.74E-05-0.14E-04 0.53E-05 0.47E-05 0.65E-05 0.39E-05-0.2[illegible]E-05-0.20E-05 0.33E-05 0.14E-0[illegible]
-0.40E-04 0.23E-05-0.91E-03-0.51E-03 0.71E-03-0.67E-03-0.31E-04 0.12E-02 0.18E-03 0.96E-0[illegible]
 0.57E-05 0.33E-05 0.49E-05 0.64E-05
```

0.12E-06 0.38E-05 0.51E-05 0.77E-05 0.64E-05 0.72E-05-0.23E-04 0.51E-05 0.47E-03 0.17E-03-0.36E-03-0.14E-03
0.50E-04-0.92E-04-0.15E-03 0.61E-04 0.52E-04-0.13E-04 0.83E-05 0.48E-05-0.88E-05 0.11E-04-0.43E-05-0.18E-05
0.44E-05-0.39E-05 0.10E-04-0.38E-05 0.55E-05 0.95E-06-0.80E-05 0.13E-04 0.20E-03-0.12E-03-0.44E-03 0.35E-03
0.0 -0.11E-03

NODE	X-DISPLACEMENTS	Y-DISPLACEMENTS
1	-0.40326756E-03	0.65026153E-03
2	-0.38520386E-03	0.64896327E-03
3	-0.36863307E-03	0.64788386E-03
4	-0.33722050E-03	0.64745895E-03
5	-0.28448459E-03	0.64826687E-03
6	-0.21786233E-03	0.65103080E-03
7	-0.12386634E-03	0.65734470E-03
8	-0.23352870E-04	0.66617131E-03
9	0.56843361E-04	0.67283004E-03
10	0.12417685E-03	0.67709689E-03
11	0.16480914E-03	0.67896792E-03
12	0.18405016E-03	0.68006339E-03
13	0.20500920E-03	0.68135210E-03
14	-0.38165553E-03	0.55994163E-03
15	-0.34805876E-03	0.55742310E-03
16	-0.30001113E-03	0.55415905E-03
17	-0.24396028E-03	0.55226381E-03
18	-0.17339543E-03	0.55225519E-03
19	-0.75321455E-04	0.55627804E-03
20	0.67175561E-05	0.56204596E-03
21	0.78854064E-04	0.56802970E-03
22	0.14422539E-03	0.57413778E-03
23	0.18355776E-03	0.57664397E-03
24	-0.35041641E-03	0.44472795E-03
25	-0.33400115E-03	0.44320757E-03
26	-0.31897682E-03	0.44200034E-03
27	-0.29442593E-03	0.43827784E-03
28	-0.25327737E-03	0.43336069E-03
29	-0.20071173E-03	0.42835891E-03
30	-0.12674301E-03	0.42573945E-03
31	-0.45753608E-04	0.42725983E-03
32	0.21028856E-04	0.43083006E-03
33	0.78589903E-04	0.43534930E-03
34	0.11527604E-03	0.43873582E-03
35	0.13353677E-03	0.43995632E-03
36	0.15345530E-03	0.44137053E-03
37	-0.31596934E-03	0.33975672E-03
38	-0.28820150E-03	0.33694424E-03
39	-0.25252020E-03	0.32972451E-03
40	-0.21193865E-03	0.32198615E-03
41	-0.16169123E-03	0.31403126E-03
42	-0.91169612E-04	0.30746614E-03
43	-0.29120652E-04	0.30559883E-03
44	0.29178882E-04	0.30585914E-03
45	0.84588493E-04	0.30755415E-03
46	0.12150061E-03	0.31029130E-03
47	-0.27881167E-03	0.25039166E-03
48	-0.26673893E-03	0.24861097E-03
49	-0.25568949E-03	0.24726797E-03
50	-0.23756572E-03	0.24209261E-03
51	-0.20894830E-03	0.23315613E-03
52	-0.17442556E-03	0.22265178E-03
53	-0.12695327E-03	0.20951724E-03
54	-0.72174807E-04	0.19776875E-03
55	-0.22844164E-04	0.19043115E-03

56	0.21523956E-04	0.18420967E-03
57	0.52970805E-04	0.18113888E-03
58	0.69341695E-04	0.18227301E-03
59	0.87231921E-04	0.18397474E-03
60	-0.23994155E-03	0.17809353E-03
61	-0.22135049E-03	0.17488745E-03
62	-0.19494220E-03	0.16623210E-03
63	-0.17138662E-03	0.15482366E-03
64	-0.14433610E-03	0.14153015E-03
65	-0.10166690E-03	0.11892036E-03
66	-0.64271502E-04	0.99872050E-04
67	-0.18771674E-04	0.87021588E-04
68	0.22563341E-04	0.66995955E-04
69	0.48067872E-04	0.69734000E-04
70	-0.16270096E-03	0.13173948E-03
71	-0.16097669E-03	0.13147508E-03
72	-0.15910089E-03	0.12516903E-03
73	-0.15105432E-03	0.12426029E-03
74	-0.12068381E-03	0.10606940E-03
75	-0.88296976E-04	0.79362942E-04
76	-0.75818665E-04	0.67788322E-04
77	-0.71412069E-04	0.63309824E-04
78	-0.65570217E-04	0.53234355E-04
79	-0.16107362E-03	0.12545772E-03
80	-0.14874751E-03	0.11591175E-03
81	-0.15280716E-03	0.11826599E-03
82	-0.15481592E-03	0.11783403E-03
83	-0.13801541E-03	0.10698714E-03
84	-0.98217148E-04	0.77816076E-04
85	-0.78000652E-04	0.52214251E-04
86	-0.79329402E-04	0.37849066E-04
87	-0.81548686E-04	0.25126123E-04
88	-0.62641382E-04	0.32151904E-04
89	-0.20067117E-03	0.12077233E-03
90	-0.19271916E-03	0.11896533E-03
91	-0.18542791E-03	0.11750316E-03
92	-0.17067758E-03	0.11456879E-03
93	-0.15785727E-03	0.11194059E-03
94	-0.14939833E-03	0.11034825E-03
95	-0.14163047E-03	0.10834276E-03
96	-0.86816217E-04	0.48194779E-05
97	-0.77207762E-04	0.51668894E-05
98	-0.67401605E-04	0.40161904E-05
99	-0.55813114E-04	0.70913586E-07
100	-0.48014277E-04	-0.40249098E-05
101	-0.45740846E-04	-0.20574907E-05
102	-0.43721797E-04	-0.17040776E-06
103	-0.16117540E-03	0.71974442E-04
104	-0.14835123E-03	0.68670648E-04
105	-0.13165937E-03	0.65049142E-04
106	-0.11459725E-03	0.61195390E-04
107	-0.10192001E-03	0.58352598E-04
108	-0.13468850E-03	-0.47709473E-04
109	-0.12260540E-03	-0.43867345E-04
110	-0.10793250E-03	-0.38084836E-04
111	-0.97893586E-04	-0.31691149E-04
112	-0.88811270E-04	-0.27484886E-04
113	-0.12095209E-03	0.31346659E-04
114	-0.11573694E-03	0.29466509E-04
115	-0.11094337E-03	0.27974820E-04

116	-0.10032946E-03	0.24360052E-04
117	-0.88940345E-04	0.21165833E-04
118	-0.76634809E-04	0.18045699E-04
119	-0.71150062E-04	0.16737569E-04
120	-0.17569578E-03	-0.85511187E-04
121	-0.17085274E-03	-0.83980746E-04
122	-0.16114648E-03	-0.79613921E-04
123	-0.15341441E-03	-0.74563024E-04
124	-0.14711081E-03	-0.68671550E-04
125	-0.14245471E-03	-0.66660359E-04
126	-0.13736240E-03	-0.64390464E-04
127	-0.79662390E-04	0.19992731E-05
128	-0.73858682E-04	-0.14161633E-05
129	-0.63987667E-04	-0.74029648E-05
130	-0.51489493E-04	-0.12568601E-04
131	-0.42064843E-04	-0.15472557E-04
132	-0.20853624E-03	-0.11564426E-03
133	-0.20255189E-03	-0.11268623E-03
134	-0.19746527E-03	-0.10747183E-03
135	-0.19547832E-03	-0.10095279E-03
136	-0.18882667E-03	-0.96587406E-04
137	-0.37169288E-04	-0.97172315E-05
138	-0.36854864E-04	-0.11597443E-04
139	-0.36835409E-04	-0.13230614E-04
140	-0.29394883E-04	-0.29839372E-04
141	-0.25885893E-04	-0.42534230E-04
142	-0.20762527E-04	-0.47783353E-04
143	-0.15322206E-04	-0.52544958E-04
144	-0.22874906E-03	-0.13597056E-03
145	-0.22927356E-03	-0.13327230E-03
146	-0.23108756E-03	-0.13051527E-03
147	-0.23726588E-03	-0.12415725E-03
148	-0.24361128E-03	-0.11616321E-03
149	-0.24337492E-03	-0.11421350E-03
150	-0.24307839E-03	-0.11162912E-03
151	-0.12253729E-04	-0.58152174E-04
152	-0.10819553E-04	-0.67016692E-04
153	-0.10383686E-04	-0.79281104E-04
154	-0.21068912E-04	-0.97515338E-04
155	-0.65531349E-04	-0.13525363E-03
156	-0.16028556E-03	-0.15826990E-03
157	-0.21009332E-03	-0.14545107E-03
158	-0.22455803E-03	-0.14281461E-03
159	-0.22849327E-03	-0.13935212E-03
160	-0.23601030E-03	-0.13202120E-03
161	-0.44504495E-05	-0.72656694E-04
162	-0.73065657E-05	-0.80786699E-04
163	-0.12244432E-04	-0.87401524E-04
164	-0.33529563E-04	-0.10173420E-03
165	-0.11064841E-03	-0.12877967E-03
166	-0.19091574E-03	-0.13615040E-03
167	-0.21770599E-03	-0.13446594E-03
168	-0.22623767E-03	-0.13314979E-03
169	-0.23488911E-03	-0.13301126E-03
170	0.47717840E-04	-0.17010461E-04
171	0.50202347E-04	-0.21578700E-04
172	0.26899157E-04	-0.51355615E-04
173	0.20504758E-05	-0.75360411E-04
174	-0.58164795E-04	-0.95579700E-04
175	-0.15973637E-03	-0.11261548E-03

176	-0.23010462E-03	-0.11755321E-03
177	-0.26766025E-03	-0.11514220E-03
178	-0.29228767E-03	-0.10582106E-03
179	-0.29908819E-03	-0.10126759E-03
180	0.10453019E-03	-0.17649712E-04
181	0.10234909E-03	-0.20385778E-04
182	0.10027396E-03	-0.22443404E-04
183	0.82391751E-04	-0.32268654E-04
184	0.45099529E-04	-0.46252026E-04
185	-0.11938689E-04	-0.57780213E-04
186	-0.10542486E-03	-0.68421185E-04
187	-0.20422082E-03	-0.75788004E-04
188	-0.27042534E-03	-0.77831894E-04
189	-0.31669019E-03	-0.74574345E-04
190	-0.34211110E-03	-0.69472546E-04
191	-0.34857052E-03	-0.67452260E-04
192	-0.35554240E-03	-0.64815569E-04
193	0.16400320E-03	0.10971604E-04
194	0.15174007E-03	0.61115825E-05
195	0.10438423E-03	-0.41281601E-05
196	0.41762454E-04	-0.13315134E-04
197	-0.44718763E-04	-0.20559062E-04
198	-0.16611371E-03	-0.25137168E-04
199	-0.26011909E-03	-0.24819630E-04
200	-0.33331895E-03	-0.20603344E-04
201	-0.39388239E-03	-0.13388213E-04
202	-0.41273586E-03	-0.86169512E-05
203	0.22436243E-03	0.66605076E-04
204	0.21464231E-03	0.63799875E-04
205	0.20563279E-03	0.61563536E-04
206	0.16988655E-03	0.54942284E-04
207	0.10649337E-03	0.47298876E-04
208	0.19836822E-04	0.41317398E-04
209	-0.10505770E-03	0.37767721E-04
210	-0.23448780E-03	0.40243394E-04
211	-0.33036247E-03	0.45720270E-04
212	-0.40443009E-03	0.53350785E-04
213	-0.44801855E-03	0.59983460E-04
214	-0.45921514E-03	0.62242892E-04
215	-0.47130277E-03	0.64969368E-04
216	0.28537260E-03	0.14030033E-03
217	0.26268256E-03	0.13515374E-03
218	0.18777839E-03	0.12759044E-03
219	0.95267154E-04	0.12261848E-03
220	-0.24882611E-04	0.12029224E-03
221	-0.18829678E-03	0.12299977E-03
222	-0.31593977E-03	0.12925469E-03
223	-0.41893660E-03	0.13709565E-03
224	-0.50507439E-03	0.14673077E-03
225	-0.53151790E-03	0.15187472E-03
226	0.33198530E-03	0.20332226E-03
227	0.31913980E-03	0.20050783E-03
228	0.30717347E-03	0.19815017E-03
229	0.25716703E-03	0.19626622E-03
230	0.16948188E-03	0.19550169E-03
231	0.55186538E-04	0.19664076E-03
232	-0.10692632E-03	0.20026519E-03
233	-0.27331011E-03	0.20672305E-03
234	-0.39647566E-03	0.21190367E-03
235	-0.49364590E-03	0.21613359E-03

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236 -0.54958928E-03  0.21906379E-03
237 -0.56328927E-03  0.22143417E-03
238 -0.57801581E-03  0.22424260E-03
ELEMENT NUMBER  FIRST NODE       SECOND NODE      THIRD NODE       X AND Y CO-ORDINATES OF CENTROID
  X-STRESS      Y-STRESS              XY-STRESS     STRESS-1          STRESS-2       PRINCIPLE ANGLE
  1   1  14   2       0.49999940        0.09999985
 0.43218994E 00 -0.15258789E-03 -0.18119812E-04  0.43218988E 00 -0.15252829E-03    -90.00418091
0.43219E 00-0.15253E-03-0.90004E 02
  2   2  14  15       0.99999887        0.29199964
 0.41932011E 00 -0.53710938E-02 -0.22733688E-01  0.42053354E 00 -0.65845251E-02    -86.95091248
0.42053E 00-0.65845E-02-0.86951E 02
  3   3   2  15       0.49999940        0.48399931
 0.41349316E 00  0.67148209E-02 -0.32186508E-02  0.41351855E 00  0.66894293E-02    -89.55319214
0.41352E 00 0.66894E-02-0.89553E 02
  4   4   3  15       0.49999940        0.81733161
 0.44636726E 00  0.11630440E 00 -0.20303726E 00  0.54298335E 00  0.19688308E-01    -64.55702209
0.54298E 00 0.19688E-01-0.64557E 02
  5   4  15  16       0.99999887        1.22533035
 0.36004353E 00  0.28011322E-01 -0.26467609E 00  0.50646091E 00 -0.11840606E 00    -61.05325317
0.50646E 00-0.11841E 00-0.61053E 02
  6   5   4  16       0.49999940        1.86666393
 0.34151649E 00  0.12263393E 00 -0.22173500E 00  0.47934788E 00 -0.15197456E-01    -58.13894653
0.47935E 00-0.15197E-01-0.58139E 02
  7   5  16  17       0.99999887        2.49999619
 0.26131248E 00  0.37781715E-01 -0.28000641E 00  0.45103502E 00 -0.15194082E 00    -55.88383484
0.45104E 00-0.15194E 00-0.55884E 02
  8   6   5  17       0.49999940        3.23332882
 0.22556496E 00  0.12294865E 00 -0.24536896E 00  0.42493272E 00 -0.76419115E-01    -50.90905762
0.42493E 00-0.76419E-01-0.50909E 02
  9   6  17  18       0.99999887        4.03332806
 0.15619278E 00  0.46706200E-01 -0.29206276E 00  0.39859831E 00 -0.19569933E 00    -50.31172180
0.39860E 00-0.19570E 00-0.50312E 02
 10   7   6  18       0.49999940        4.96666050
 0.78887939E-01  0.11837387E 00 -0.24896049E 00  0.34937300E 00 -0.15111119E 00    -42.73605347
0.34937E 00-0.15111E 00-0.42736E 02
 11   7  18  19       0.99999887        5.99998760
 0.72708130E-02  0.57038307E-01 -0.28967476E 00  0.32289600E 00 -0.25858688E 00    -42.54820251
0.32290E 00-0.25859E 00-0.42548E 02
 12   8   7  19       0.49999940        7.03332138
-0.10443115E 00  0.10107172E 00 -0.24429321E 00  0.26334286E 00 -0.26670229E 00    -33.59645081
0.26334E 00-0.26670E 00-0.33596E 02
 13   8  19  20       0.99999887        7.96665478
-0.15404987E 00  0.55571556E-01 -0.27561760E 00  0.24563420E 00 -0.34411252E 00    -34.59222412
0.24563E 00-0.34411E 00-0.34592E 02
 14   9   8  20       0.49999940        8.76665211
-0.23524314E 00  0.62604308E-01 -0.21984577E 00  0.17921853E 00 -0.35185730E 00    -27.94514465
0.17922E 00-0.35186E 00-0.27945E 02
 15   9  20  21       0.99999887        9.49998379
-0.26668262E 00  0.48217773E-01 -0.24402142E 00  0.18117589E 00 -0.39964074E 00    -28.56639526
0.18118E 00-0.39964E 00-0.28586E 02
 16  10   9  21       0.49999940       10.13331890
-0.34434414E 00  0.33484101E-02 -0.18498516E 00  0.83356360E-01 -0.42435205E 00    -23.39068604
0.83356E-01-0.42435E 00-0.23391E 02
 17  10  21  22       0.99999887       10.77465057
-0.35985184E 00  0.41752815E-01 -0.21168137E 00  0.13272190E 00 -0.45082092E 00    -23.25709534
0.13272E 00-0.45082E 00-0.23257E 02
 18  11  10  22       0.49999940       11.18264961
-0.42686176E 00 -0.50523996E-01 -0.16518879E 00  0.11696517E-01 -0.48908228E 00    -20.64105225
0.11697E-01-0.48908E 00-0.20641E 02
 19  12  11  22       0.49999940       11.51598263
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-0.41322327E 00 -0.48802495E-02 -0.20751953E-02 -0.48696995E-02 -0.41323376E 00      -0.29130292
-0.48697E-02-0.41323E 00-0.29130E 00
 20  12  22  23       0.99999887      11.70798397
-0.41802406E 00  0.51422119E-02 -0.18374443E-01  0.59384704E-02 -0.41882032E 00      -2.48154631
0.59385E-02-0.41882E 00-0.24815E 01
 21  13  12  23       0.49999940      11.89998531
-0.42904377E 00  0.16403198E-03  0.69618225E-03  0.16510487E-03 -0.42904484E 00       0.08830470
0.16510E-03-0.42904E 00 0.88305E-01
 22  14  24  25       2.83332920       0.09999985
 0.46480560E 00 -0.12588501E-01 -0.34671783E-01  0.46731055E 00 -0.15093446E-01     -85.87390137
0.46731E 00-0.15093E-01-0.85874E 02
 23  15  14  25       2.16666412       0.29199964
 0.45383072E 00  0.49638748E-02  0.73986053E-02  0.45395255E 00  0.48420429E-02      89.06242371
0.45395E 00 0.48420E-02 0.89062E 02
 24  15  25  26       2.83332920       0.48399931
 0.43611050E 00 -0.36621094E-03 -0.39304733E-01  0.43962157E 00 -0.38772821E-02     -84.90142822
0.43962E 00-0.38773E-02-0.84901E 02
 25  15  26  27       2.83332920       0.81733197
 0.42851925E 00 -0.25680542E-01 -0.28561497E 00  0.56631690E 00 -0.16347820E 00     -64.24925232
0.56632E 00-0.16348E 00-0.64249E 02
 26  16  15  27       2.16666412       1.22533035
 0.38921738E 00  0.36761284E-01 -0.23223495E 00  0.50451869E 00 -0.78540027E-01     -63.60087585
0.50452E 00-0.78540E-01-0.63601E 02
 27  16  27  28       2.83332920       1.86666393
 0.33415031E 00 -0.22683144E-01 -0.29609203E 00  0.50142556E 00 -0.18995839E 00     -60.54034424
0.50143E 00-0.18996E 00-0.60540E 02
 28  17  16  28       2.16666412       2.49999619
 0.29499149E 00  0.47883987E-01 -0.23867130E 00  0.44019318E 00 -0.97317696E-01     -58.68896484
0.44019E 00-0.97318E-01-0.58689E 02
 29  17  28  29       2.83332920       3.23332882
 0.22108936E 00 -0.23708344E-01 -0.30549812E 00  0.42779613E 00 -0.23041511E 00     -55.92091370
0.42780E 00-0.23042E 00-0.55921E 02
 30  18  17  29       2.16666412       4.03332806
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0.35662E 00-0.14167E 00-0.51734E 02
 31  18  29  30       2.83332920       4.96666050
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0.34000E 00-0.27892E 00-0.49881E 02
 32  19  18  30       2.16666412       5.99998760
-0.21222115E-01  0.48490107E-01 -0.23621559E 00  0.25240737E 00 -0.22513938E 00     -40.80596924
0.25241E 00-0.22514E 00-0.40806E 02
 33  19  30  31       2.83332920       7.03332138
-0.10584450E 00 -0.89464188E-02 -0.29227543E 00  0.23886824E 00 -0.35365915E 00     -40.29692078
0.23887E 00-0.35366E 00-0.40297E 02
 34  20  19  31       2.16666412       7.96665478
-0.19498515E 00  0.43292344E-01 -0.21333504E 00  0.16850144E 00 -0.32019418E 00     -30.41145325
0.16850E 00-0.32019E 00-0.30411E 02
 35  20  31  32       2.83332920       8.76665211
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0.16152E 00-0.42066E 00-0.32320E 02
 36  21  20  32       2.16666412       9.49998379
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0.11443E 00-0.39749E 00-0.23459E 02
 37  21  32  33       2.83332920      10.13331890
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0.11642E 00-0.47462E 00-0.25829E 02
 38  22  21  33       2.16666412      10.77465057
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A STUDY OF THE PLANE STRESS OR STRAIN FINITE ELEMENT ANALYSIS FOR SOLUTION OF STRESS DISTRIBUTION IN PLANE ELASTIC CONTINUA

by

THOMAS C. HELBING

B.S., Kansas State University, 1965

AN ABSTRACT OF A MASTER'S REPORT

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The "finite element method" for solution of stress distribution in a plane elastic continuum is studied in this report. This numerical method of stress analysis can be used for obtaining a solution to problems, which heretofore relied upon approximate calculations of doubtful validity. The finite element analysis, when coupled with a high-speed computer, can provide quick solutions that converge to "exact method" answers.

O. C. Zienkiewicz and Y. K. Cheung[1] have presented the theory behind the finite element method and a computer program which applies the plane stress or strain finite element analysis to a plane elastic continua. The theory of the finite element method and the computer program are included in this report.

A plane elastic continua is divided into a finite number of nodal points which are interconnected to form triangular elements. Force-displacement relationships are determined for these triangular elements. "Displacement method" equations[2] in matrix notation are formed with the displacements of the nodal points as unknowns. Inversion of the force-displacement matrix and multiplication by the force matrix leads to a solution for the unknown displacements. These displacements are used to calculate the stresses at the centroids of the triangular elements which are then converted to principal stresses and their angles of deviation from the original X-Y coordinate system.

The finite element method computer program taken from reference 1 is written in FORTRAN IV language and is intended for use on an IBM 360 series computer. Detailed flow charts of the main program and its subroutines are included in the report, along with a listing of the operational program and an explanation of the data preparation for the program.

The accuracy of the stress solutions obtained using the finite element method program is dependent upon the fineness of the triangular grid. An infinite number of combinations of loading and support conditions can be approximated using this method.

Two example problems are included in this report. One example shows the solution of a simple problem based on a well-known "classical" method compared to the solution using the computer program. The other example shows the solution of a complex problem, namely, the calculation of the stress distribution around a rectangular hole in the web of a wide-flange beam.