AN ABSTRACT OF THE THESIS OF

Virgilio Asuncion Fernandez for the degree of Doctor of Philosophy

in Forest Products presented on December 13, 1977

Title: MODEL AND PROCEDURE FOR DETERMINATION OF STRENGTH AND STIFFNESS OF WOOD STUDS

Abstract approved: Redacted for privacy

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Elasticity properties of wood studs are essential inputs for the structural analysis of wood-stud wall systems.

A theoretical procedure was developed to determine the probability distributions for the deflection-load relations of stud samples. The procedure is based on the finite element analysis and a Monte-Carlo type simulation and accounts for the nonlinearity and local material variability caused by stud defects. The procedure was verified experimentally; the results displayed a good agreement between the theoretical and experimental values. A parameter study showed that the deflection-load curves were greatly affected by the local elasticity and strength of clear wood, grain angle, and knots.

A listing of the computer program prepared is included. The program allows various options as to the types and geometry of stud defects.

Model and Procedure for Determination of Strength and Stiffness of Wood Studs

by

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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

June 1978

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ACKNOWLEDGMENTS

I wish to express my sincere thanks to Dr. Anton Polensek of the Forest Products Department for his advice and assistance in this study. I also thank Prof. George H. Atherton of the Forest Products Department, Dr. Harold Laursen of the Civil Engineering Department, and Dr. Kenneth Rowe of the Statistics Department for their helpful suggestions; Ken Bastendorff of the Forest Research Laboratory for his assistance in the collection of specimens and in the setting-up of the testing equipment; and my wife, Elvira, for typing the rough draft of the thesis.

I am grateful to the Oregon State University Forest Research Laboratory for financial support for this study.

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MODEL AND PROCEDURE FOR DETERMINATION OF STRENGTH AND STIFFNESS OF WOOD STUDS

I. INTRODUCTION

The present design method for wood-stud walls considers each stud as an independent beam-column carrying its own proportionate share of the load. This procedure neglects factors such as the non-linear nature and variability of stud stiffness, composite effect of covering materials and load sharing between studs of various strengths and stiffnesses, which combine to result in general over-design in currently-built walls. This method is uneconomical and puts wood in a poor competitive position with other construction materials. Research at the Forest Research Laboratory, Oregon State University, has resulted in a rational design procedure, based on an accurate theoretical analysis (37) and computer simulation method (38), that accounts for these factors. To use the rational procedure, however, properties and probability distribution of studs must be available. Currently, such information can only be obtained by in-grade testing of studs, which is an expensive and time-consuming method. There is, therefore, a need to develop an alternative non-destructive procedure to evaluate stud properties.

1.1. Present Design Procedure

The allowable stress, F_b, for a grade and species of studs is based on the ultimate bending strength or the modulus of rupture (MOR). First the MOR value is selected at the five-percent exclusion value on the cumulative probability distribution of the MOR for the small-size clear wood bending specimens from the species considered (3, 25). The selected value is then adjusted for the grade according to the effects of seasoning, strength-reducing defects, general adjustment factor and depth. The resulting value is the F_b for studs of grade and species considered.

The design modulus of elasticity (MOE) is based on the average MOE of species, which was determined from bending tests of small clear specimens (3, 25). The average MOE is then adjusted for the grade according to defects and effects of seasoning.

1.2. Previous Works and Present Outlook

The shortcomings of the present design method for wood-stud walls are due to its failure to account for the load sharing between studs, composite action of covering materials, and the nonlinear behavior of studs.

1.2.1. Load Sharing

Past studies have demonstrated that the present design method is too conservative. Johnson (28) and Snodgrass (50), investigated Construction and Standard grades of Douglas-fir 2- by 4-inch dimension lumber. They independently concluded that the average bending and compression stresses for pieces in groups of three were consistently higher than the stresses of pieces taken singly at one, five and ten percent exclusion limits. This conclusion is recognized by the National Forest Products Association (34) which now allows higher unit stresses for repetitive-member uses where load sharing is known to exist.

1.2.2. Composite Action

Composite action between the wall covering and studs increases the strength and stiffness of walls. Polensek and Atherton (40) reported that the experimental walls with Utility grade studs deflected 30% to 60% more if the gypsum boards wall covering was removed. However, the connection between the coverings and the studs is not infinitely stiff. Slip between the studs and wall coverings must be considered. Studies conducted by Amana and Booth (1, 2) show that deflection of a composite I-beam is directly related to the amount of slip between the flanges and the web.

1.2.3. Nonlinear Behavior of Studs

Some studs especially those of low strength and stiffness respond nonlinearly to an increasing load. Nonlinear response of studs is the main subject of this investigation.

The complete deflection-load curve of studs is obtained by plotting on the X-Y recorder the deflection and load of a beam continuously loaded to destruction.

Many studs display linear behavior during the early stages of a test. A typical deflection-load curve of such a stud is shown in Figure 1.1. The curve is linear up to the proportional limit (PL) after which it becomes non-linear. The slope at a certain point or section of the curve is directly related to the MOE at that particular point or section. The MOE at a discrete point, such as B in Figure 1.1, is usually defined by the tangent on the deflection-load curve at B, beam cross-section and the conditions of loading. The resulting MOE is called tangent MOE. The MOE for a section such as AB in Figure 1.1 often is related to the secant connecting A and B. The resulting MOE is called secant MOE. The highest point of the curve gives the maximum load which defines the stress at the point of rupture, i.e., the MOR. An approximate procedure to numerically define an experimental deflection-load curve consists of subdividing the curve into

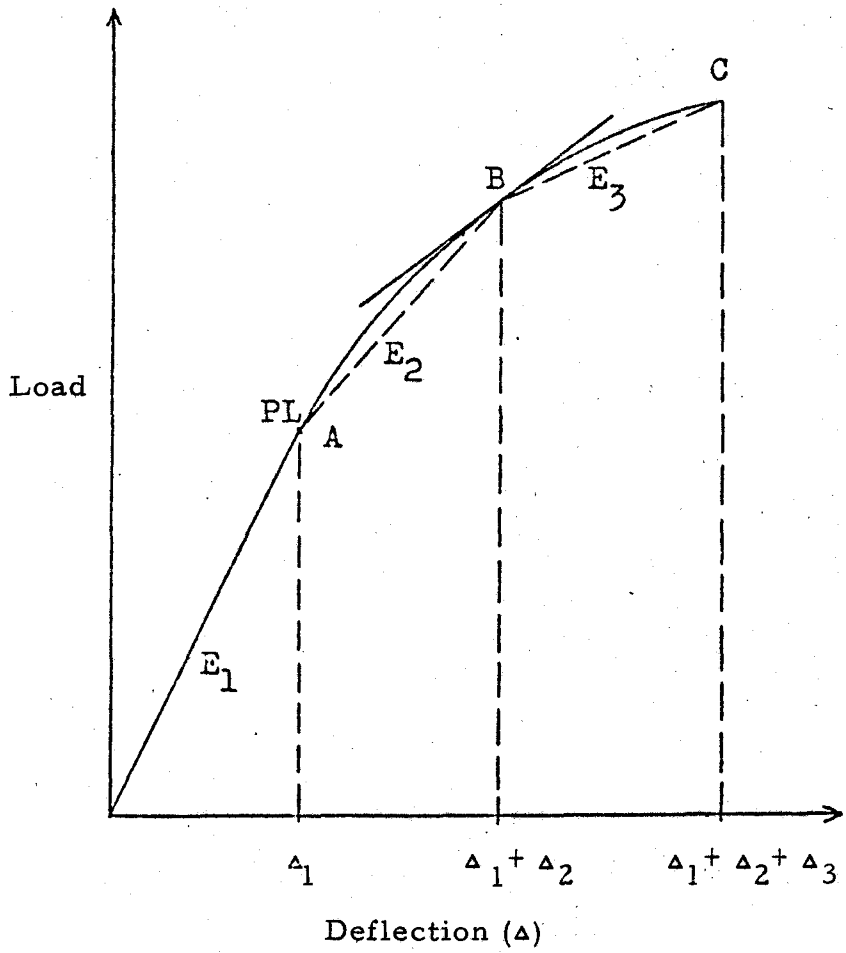

Figure 1.1. Typical deflection-load curve of lumber.

sections defined in terms of the secant MOE, such as E_2 and the associated deflection Δ_2. The whole curve may be defined by pairs of E_i's and Δ_i's (i=1, 2, 3) with surprisingly high accuracy (37).

Young's modulus (E_1), i.e., the MOE value below the PL (36, 51) can be obtained experimentally without causing damage to the lumber. However, to obtain MOR the lumber has to be broken. In the past, experimental-statistical studies were conducted to express MOR in terms of E_1 (14, 29, 46). Both moduli were obtained experimentally and regression equations were developed. The correlation coefficients for these equations varied widely. Johnson (29), in his study on Douglas-fir Select Structural, Construction, and Utility grades, obtained a correlation of 0.87. Schroeder and Atherton (46) found a correlation of 0.68 for Utility grade redwood studs. Polensek and Atherton (40) obtained correlations of 0.74 and 0.71 for Utility grade Engelmann spruce and Douglas-fir studs, respectively. Fernandez (14) investigated Douglas-fir studs of Stud grade for which a correlation of 0.66 was obtained. The results of these studies indicate that E_1 does not accurately predict the MOR. Even with E_1 and MOR known the total deflection-load curve is not defined. Either the deflection at the MOR or the nonlinear part of the curve is necessary to estimate the deflection-load curve.

The deflection-load curve can be more precisely defined in terms of the PL and MOR. Recent studies (14, 46) have shown that the stress at proportional limit (SPL) is a better predictor of MOR, as indicated by a correlation of 0.90. However, the SPL can only be determined by loading the lumber beyond the PL, which probably causes some damage to the wood fibers. Ther currently is no satisfactorily accurate procedure for obtaining MOR without damaging the lumber.

1.2.4. Finite Element Method

With the advent of high-speed computers, the finite element method (8, 11, 62) was developed. The finite element method has been described as a physical idealization of a material continuum into an assemblage of a finite number of elements which interconnect at certain points called nodal points. A piece of lumber can be represented as an assembly of a discrete number of elements. Next, a stiffness matrix and force vector are generated for each element. The element stiffness matrix and force vector represent the element elastic properties, and loads, respectively. The element matrices and force vectors are combined into an overall stiffness matrix and force vector, respectively, representing the continuum. The element stresses and nodal deflection are obtained by operating on the overall matrices and vectors, using mathematical operations, derived from equilibrium and compatibility conditions. Finite element idealization permits accounting for changes in elastic properties within the piece and nonelastic changes at loads above the PL.

As an alternative to actual testing, a finite element model can be developed for the stud. The nonlinear behavior may be included in the model. Imposing test loads on this model and analyzing it should result in a complete deflection-load trace. Then studs representing a certain grade and species can be simulated and analyzed by the finite element method. Such a simulation requires the establishment of a mathematical-logical model of a system and the experimental manipulation of it on a digital computer (41). A simulator is an artificial laboratory or testing machine. Once a system is modeled and programmed, experiments can be performed using the model.

The finite element method has been used successfully in the analyses of wood-joist floors (39), wood-stud walls (37), plates and shells (17, 20, 33, 57), and compression tests on nonlinear materials (18). Its application to deflection-load curves of lumber is expected to yield accurate results.

1.3. Future Outlook

Analysis procedures for improved design of wood-stud walls are available. To apply these procedures, accurate information on the elasticity properties of wall components such as studs is necessary. Better methods of analysis (37, 38) and improved information on the properties of wall components should result in less conservative designs of wood-stud walls than those produced by the present method.

Wood-stud walls can be made more economical by using lumber of lower grades like Utility grade, by reducing the stud cross-section, and by increasing the stud spacings. Cross-sections such as 1- by 6-inch may allow more insulation. The conventional 16-inch stud spacing in walls could be increased. The Uniform Building Code (26) presently allows 24 in. stud spacing for single-story dwellings and top stories of multi-story dwellings. The above improvements may be extended to other constructions if an improved design method demonstrates that the safety of the structure is not jeopardized.

The development of the finite element method that would simulate stud testings could lead to a new method of determining allowable design properties for studs of any grade and species. Stud probability distribution of a certain grade can be simulated from probability distributions for clear MOE and for grade defects which are already available to most wood species and grades.

1.4. Justification and Objectives

The development of an improved design method for wood-stud walls requires an accurate information on the properties of studs, the principal structural component of the wall. Traditionally, such an information has been obtained only by testing, which is expensive and time-consuming. An efficient and more economical alternative calls for developing a theoretical procedure to determine the strength and stiffness of studs. Once the theoretical model and computer program are developed and verified, studs of the commonly-used grades and species can be simulated, modeled, and then theoretically tested to determine the probability distributions for their strengths and stiffnesses. Such a procedure should make not only wall design more economical, but also could be applied to other lumber such as floor joists and components for roof trusses. The development of such a procedure is the main objective of this investigation. The specific objectives are:

1. To develop a theoretical procedure and computer program for determination of elasticity properties of studs.
2. To verify the method and computer program by physical testing.
3. To develop a simulation procedure for generation of probability distribution of elasticity properties for studs.
4. To investigate how the parameters such as grain and ring angles, MOE and MOR for clear wood, nodulus of rigidity and Poisson's ratio affect the stud stiffness and strength.

II. METHOD OF ANALYSIS

The finite element method was used to evaluate the strength and stiffness of the studs. The method is ideal for systems with complex boundary conditions and material properties.

The specific task was the development of a model and method that would simulate a stud testing procedure according to Standard D 198 (3) of the American Society for Testing and Materials (ASTM). The ASTM test requires the symmetrical loading of the stud at points one-third of the span (Figure 3.2). The load is increased continuously until the stud fails. A deflection-load curve, such as that of Figure 1.1, is obtained by plotting the load against the midspan deflection.

The chosen stud model will simulate the ASTM test. The load Q, will be increased by small increments until the stud fails. The stresses and deflections at certain points in the stud will be calculated after each increment. A computer program will be prepared for this model and test procedure.

2.1. Finite Element Method

The finite element method represents a study by an assembly of small stud sections, that is, subdivisions called finite elements. These elements are connected at joints which are called nodes or nodal points. The chosen displacement functions will secure the compatibility of deflections along the boundary lines of adjacent elements. Loads simulating the test conditions are applied at the nodal points at 1/3 and 2/3 of the span. The final solution yields the displacements at the nodes including the node at L/2. The applied forces and nodal displacements are related by the overall stud stiffness matrix which is defined by the local elasticity properties and internal material geometry of the stud. The overall stiffness matrix is formed by combining the individual stiffness matrices of all the elements of the stud. The overall stiffness matrix accounts for the boundary conditions, that is, for zero displacements at point A and the vertical displacements at point B (Figure 3.2).

The nodal displacements may be obtained by (8, 11, 62)

$$\{D\} = [K]^{-1}\{Q\} \tag{2.1}$$

where

$\{D\}$ = nodal displacement vector

$[K]$ = stud stiffness matrix

$\{Q\}$ = defined external loads acting on stud

The element stresses and strains are determined by (8, 11, 62)

$$\{\varepsilon_e\} = \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = [A]\{d\} \tag{2.2}$$

and

$$\{\sigma_e\} = \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = [S]\,[A]\,\{d\} = [B]\,\{d\} \tag{2.3}$$

where

$\{\varepsilon_e\}$ - element strain vector

[A] - element strain displacement matrix

$\varepsilon_x, \varepsilon_y$ - normal strains

γ_{xy} - shear strain

{d} - element nodal displacement vector

x, y - local coordinates denoting the direction of strains and stresses

σ_e - element stress vector

σ_x, σ_y - normal stresses

τ_{xy} - shear stress

[B] - element stress displacement matrix and

[S] - stress strain matrix

The element strain vector (ε_e) represents the displacements in the element. It is a function of the element geometry, displacement functions and nodal deflections.

The element stress vector (σ_e) represents the stresses acting within the element. It is a function of the element elastic properties and geometry, displacement functions, and nodal deflections. For chosen displacement functions, the stresses are constant throughout the element. The stress at the node can be obtained by taking the average of the stresses of the elements surrounding the node.

2.2. Assumptions

The finite element method is based on general assumptions such as:

1. Structural compatibility exists along the total boundary among the adjacent elements. A proper selection of displacement functions usually prevents the violation of this assumption. When the stud starts to develop cracks, the assumption is violated, but the finite element model may still represent the actual conditions on the stud.
2. Stresses exist only in two perpendicular directions, that is, the problem is reduced to a plane stress problem. This assumption may not be entirely true because of Poisson's effects in the direction of thickness. However, the stresses because of Poisson's effects are small compared to those of the other two directions.
3. The material properties are constant in the direction of the element thickness. Therefore, there is no change of stresses within the thickness. Some violation of this assumption is expected because of the material variability of wood properties in the thickness direction.

The specific assumptions pertaining to the stud analysis are:

1. The elasticity and strength properties, and the grain and ring angles are constant within the element. Some violation of this

assumption is expected because of local variations in material properties. The errors due to this violation may be reduced by a very fine finite element mesh.

2. Knots have no resistance to tension, and have the same elastic and strength properties as the tangential direction of the wood in compression. No information is available on the strength and elastic properties of knots. A casual observation of knots suggests that the knot may resist some small tension forces.
3. The elasticity properties of the elements are linear within one load increment. This assumption is true before the PL is reached. After the PL, some violation occurs, but it may be minimized by choosing small load increments.
4. When the stress in the element reaches failure stresses, the whole element is considered broken. This assumption is violated if only a part of the element fails and the adjacent parts keep on resisting forces. The errors due to this assumption may be reduced by refining the mesh.

2.3. The Finite Elements and their Stiffness Matrices

Two types of plane stress elements were used to model the stud. One type was a rectangular element and the other type was a triangular element.

2.3.1. Rectangular Elements

The main element is Cook's modified assumed stress hybrid rectangular element (9). This element has been used successfully by White (58) in his study on the analysis of end fixity in stud wall panels. Under pure bending, this element yields exact displacements and exact stresses. Stresses within the element are given by an assumed field which satisfies the differential equations of equilibrium. Figure 2.1 shows the element with its local coordinate system and differential element. The nodal points i, j, k and l are oriented counter-clockwise. The size and location of the element are defined in terms of the global Cartesian coordinates x and y. The components of the nodal displacements are u and v.

The element stiffness matrix is defined by (9)

$$[K_e] = [T]^T [H]^{-1} [T] \tag{2.4}$$

The size of $[T]$ is five by eight, and its 24 nonzero elements are obtained from (10):

$$\left.\begin{aligned} T_{1,2g-1} &= T_{5,2g} = (y_h - y_f)/2 \\ T_{5,2g-1} &= T_{3,2g} = (x_f - x_h)/2 \\ T_{2,2g-1} &= [y_h(y_h + y_g) - y_f(y_f + y_g)]/6 \\ T_{4,2g} &= [x_f(x_f + x_g) - x_n(x_n + x_g)]/6 \end{aligned}\right\} \tag{2.5}$$

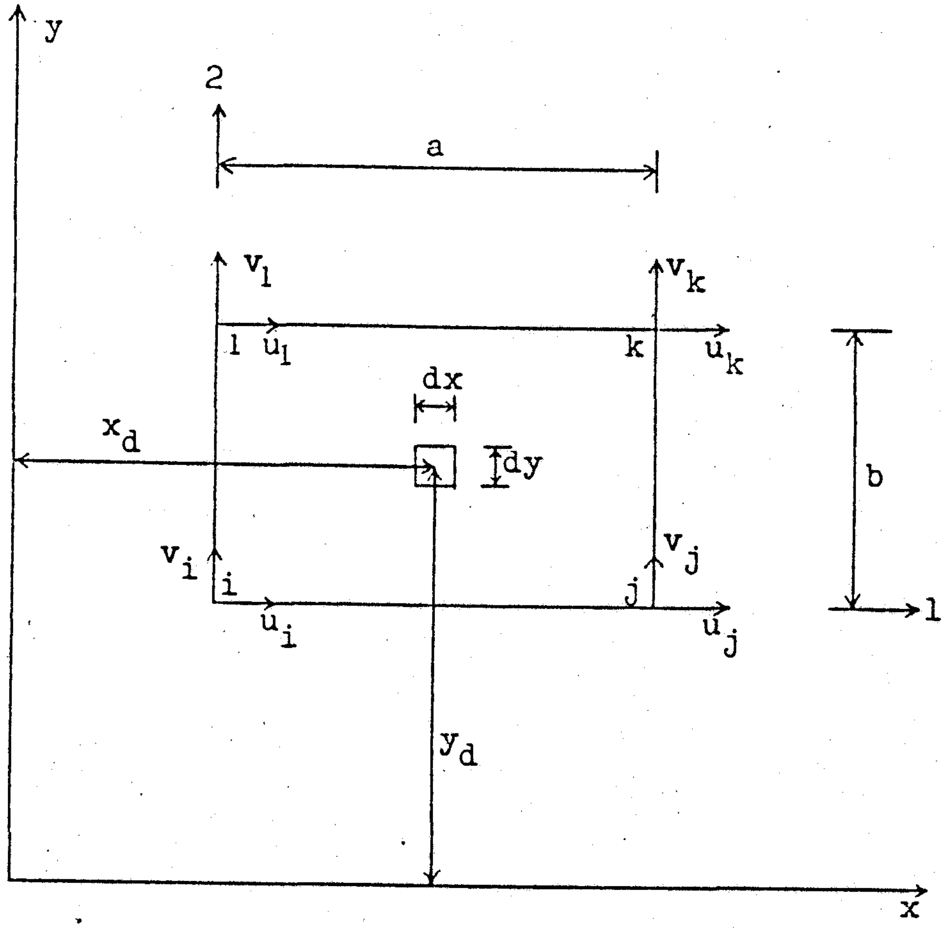

Figure 2.1. Rectangular plane stress element.

in which g = 1, 2, 3, 4 and f, g, h are cyclically permuted from one to four with f = g-1, and h = g+1. For example, $T_{11} = (y_2 - y_4)/2$, $T_{12} = 0$, $T_{13} = (y_3 - y_1)/2$. The subscripts 1, 2, 3 and 4 correspond to the nodes i, j, k and l, respectively. Using equation (2.5), the non-zero elements of matrix [T], expressed in terms of the nodal coordinates, are (58):

$$T_{11} = T_{52} = -T_{15} = -T_{56} = (y_j - y_l)/2 \quad (2.6)$$

$$T_{13} = T_{54} = -T_{17} = -T_{58} = (y_k - y_i)/2 \quad (2.7)$$

$$T_{34} = T_{53} = -T_{38} = -T_{57} = (x_i - x_k)/2 \quad (2.8)$$

$$T_{36} = T_{55} = -T_{32} = -T_{51} = (x_j - x_l)/2 \quad (2.9)$$

$$T_{21} = [y_j(y_j + y_i) - y_l(y_l + y_i)]/6 \quad (2.10)$$

$$T_{23} = [y_k(y_k + y_j) - y_i(y_i + y_j)]/6 \quad (2.11)$$

$$T_{25} = [y_l(y_l + y_k) - y_j(y_j + y_k)]/6 \quad (2.12)$$

$$T_{27} = [y_i(y_i + y_l) - y_l(y_l + y_k)]/6 \quad (2.13)$$

$$T_{42} = [x_l(x_l + x_i) - x_j(x_j + x_i)]/6 \quad (2.14)$$

$$T_{44} = [x_i(x_i + x_j) - x_k(x_k + x_j)]/6 \quad (2.15)$$

$$T_{46} = [x_j(x_j + x_k) - x_l(x_l + x_k)]/6 \quad (2.16)$$

and

$$T_{48} = [x_k(x_k + x_l) - x_i(x_i + x_l)]/6 \quad (2.17)$$

The five by five matrix [H] of equation (2.4) equals (9)

$$[H] = \iint \frac{1}{t} [P]^T [C] [P] \, dxdy \quad (2.18)$$

in which integration is performed over the entire element area. The symbols in equation (2.18) are defined as follows (9):

t = element thickness

$$[P] = \begin{bmatrix} 1 & y_d & 0 & 0 & 0 \\ 0 & 0 & 1 & x_d & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2.19)$$

and

$$[C] = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{xy}}{E_x} & 0 \\ \frac{-\nu_{yx}}{E_y} & \frac{1}{E_y} & 0 \\ 0 & 0 & \frac{1}{G_{xy}} \end{bmatrix} \qquad (2.20)$$

where

E_x, E_y - modulus of elasticity in direction indicated by subscript

ν_{xy}, ν_{yx} - Poisson's ratio, i. e., the ratio of the strain in the direction of the second subscript to the strain in the direction of the first subscript with the stress applied in the direction of the first subscript.

G_{xy} - shear modulus in the x-y plane.

Equations (2. 4) through (2. 19) are valid for any quadrilateral element. White (58) first modified [H] for rectangles and then inverted it to obtain matrix [F] which was valid only for rectangles. Further simplification was made by applying

$$E_x \nu_{yx} = E_y \nu_{xy} \qquad (2.21)$$

The non-zero elements of matrix [F] are (58)

$$F_{11} = \frac{4E_x^2 E_y - 3E_x(E_y \nu_{xy})^2}{[E_x E_y - (E_y \nu_{xy})^2]abt} \tag{2.22}$$

$$F_{21} = F_{12} \quad \frac{-6E_x}{ab^2 t} \tag{2.23}$$

$$F_{22} = \frac{12E_x}{ab^3 t} \tag{2.24}$$

$$F_{31} = F_{13} \quad \frac{E_x E_y (E_x \nu_{yx})}{[E_x E_y - (E_y \nu_{xy})^2]abt} \tag{2.25}$$

$$F_{33} = \frac{4E_x E_y^2 - 3E_y(E_y \nu_{xy})^2}{[E_x E_y - (E_y \nu_{xy})^2]abt} \tag{2.26}$$

$$F_{34} = F_{43} \quad \frac{-6E_y}{a^2 bt} \tag{2.27}$$

$$F_{44} = \frac{12E_y}{a^3 bt} \tag{2.28}$$

and

$$F_{55} = \frac{G_{xy}}{abt} \tag{2.29}$$

The stresses of the differential element are calculated by equation (2.3) with

$$[B] = \frac{1}{t}[P][F][T] \tag{2.30}$$

The stress variation within the element in one direction is linear with respect to the perpendicular direction.

2.3.2. Triangular Elements

The triangular element was used for locations on the stud where the rectangular element could not easily be applied such as around knots and transition locations between two different sizes of elements. The displacements within the triangular elements are linear and have a polynomial form. It is expressed in terms of generalized coordinates and hence referred to as generalized coordinate displacement model. The element, shown in Figure 2.2, has its nodal points, i, j, and k oriented counterclockwise. The displacement functions of this element are linear and equal to (11, 62)

$$\left.\begin{aligned} u &= \alpha_1 + \alpha_2 X + \alpha_3 Y \\ v &= \alpha_4 + \alpha_5 X + \alpha_6 Y \end{aligned}\right\} \tag{2.31}$$

where

u, v - displacements in the x and y directions, respectively, of a certain point within the element

$\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6$ - generalized coordinates

x, y - Cartesian coordinates of certain points within the element.

The triangular element stiffness matrix is defined by

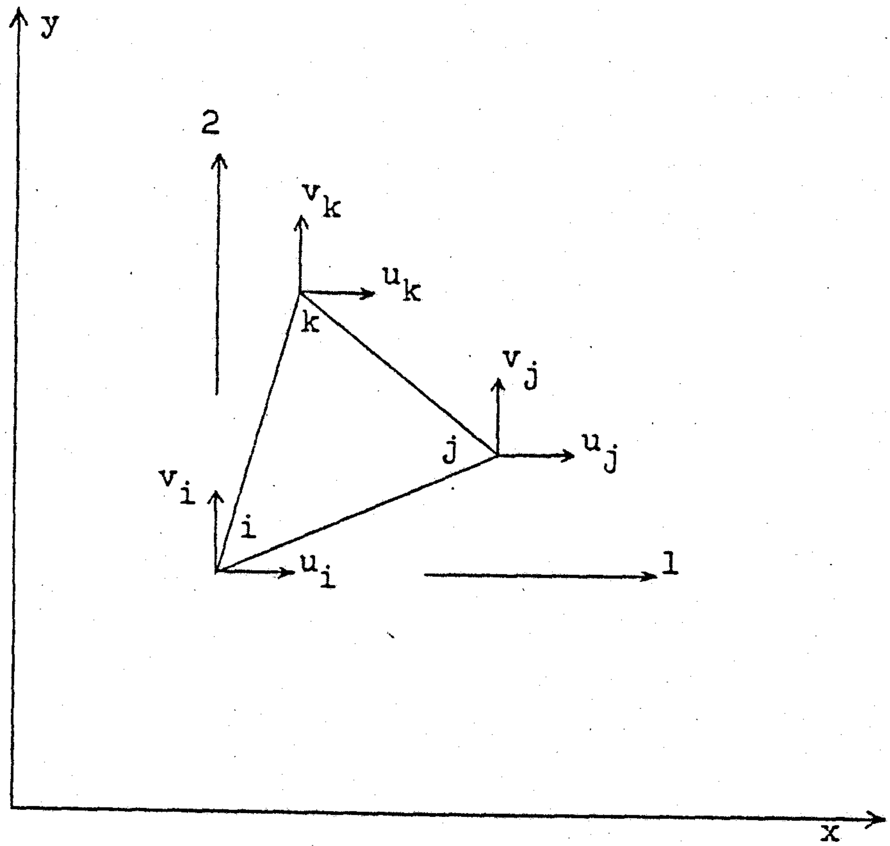

Figure 2. 2. Triangular plane stress element.

$$[K_e] = \int_A [A]^T [S][A]\ tdA \tag{2.32}$$

where

A - area of triangle

[A], [S] - defined in equation (2.3)

The strain-displacement matrix, defined in terms of the nodal coordinates x and y, equals (62)

$$[A] = \frac{1}{2A} \begin{bmatrix} -y_{kj} & 0 & y_{ki} & 0 & -y_{ji} & 0 \\ 0 & x_{kj} & 0 & -x_{ki} & 0 & x_{ji} \\ x_{kj} & -y_{kj} & -x_{ki} & y_{ki} & x_{ji} & -y_{ji} \end{bmatrix} \tag{2.33}$$

where

$$y_{ij} = y_i - y_j \tag{2.34}$$

$$x_{ij} = x_i - x_j \tag{2.35}$$

The stress-strain matrix is (11, 62)

$$[S] = \frac{1}{(1-\nu_{xy}\nu_{yx})} \begin{bmatrix} E_x & E_y\nu_{xy} & 0 \\ E_x\nu_{yz} & E_y & 0 \\ 0 & 0 & (1-\nu_{xy}\nu_{yx})G_{xy} \end{bmatrix} \tag{2.36}$$

The area of the triangular element is given by

$$A = (x_{ji}y_{ki} - x_{ki}y_{ji})/2 \tag{2.37}$$

Because of the linear displacement functions the stresses are constant throughout the element.

2.4. Elasticity Parameters

The parameters used to define the stud elasticity are:

1. Three moduli of elasticity denoted by E_L, E_T and E_R. The subscripts L, T and R denote the longitudinal, tangential and radial directions in the wood, respectively.
2. Three moduli of rigidity denoted by G_{LT}, G_{LR} and G_{TR}. The subscripts LT, LR and TR are the three planes of elastic symmetry. For example, G_{LT} is the modulus of rigidity based on the shear strain in the LT (longitudinal-tangential) plane and shear stresses in the LR (longitudinal-radial) and TR (tangential-radial) planes.
3. Six Poisson's ratios denoted by ν_{LR}, ν_{RL}, ν_{LT}, ν_{TL}, ν_{RT} and ν_{TR}. The first symbol of the subscript refers to the direction of applied stress and the second symbol refers to the direction of lateral deformation.

The E_L for each of the studs may be obtained experimentally by tension and compression tests of small, clear specimens according to ASTM Standard D 143-52 (3). The approximate values for Poisson's ratios are available in the Wood Handbook (54). Estimates of the remaining moduli may be calculated from the Wood Handbook regression relations (54) as follows

$$E_T = 0.050\ E_L \tag{2.38}$$

$$E_R = 0.068\ E_L \tag{2.39}$$

$$G_{LT} = 0.078\ E_L \tag{2.40}$$

$$G_{LR} = 0.064\ E_L \tag{2.41}$$

$$G_{TR} = 0.007\ E_L \tag{2.42}$$

The Wood Handbook elasticity values and equations were determined from test results accumulated over the years (54). They have their own inherent variability and are affected by specific gravity, moisture content, temperature, and strain rate (4, 6, 30, 31, 32, 35, 48, 49, 52, 54, 61).

Elasticity values are also available from other sources such as the studies conducted by Hearmon (21), and Bodig and Goodman (4).

The finite element model uses the elastic properties in the direction of the geometric stud axes x, y, and z as shown in Figure 2.3. If the axis of elastic symmetry does not coincide with the geometric axis, the affected property should be modified.

2.4.1. Modification of Elastic Properties by Axial Transformation

Wood is often quoted as a typical example of an orthotropically elastic material (12, 21, 22, 27, 42, 44, 45, 55), i.e., it is elastically symmetric about three mutually perpendicular planes. It has nine independent compliance parameters expressed by the

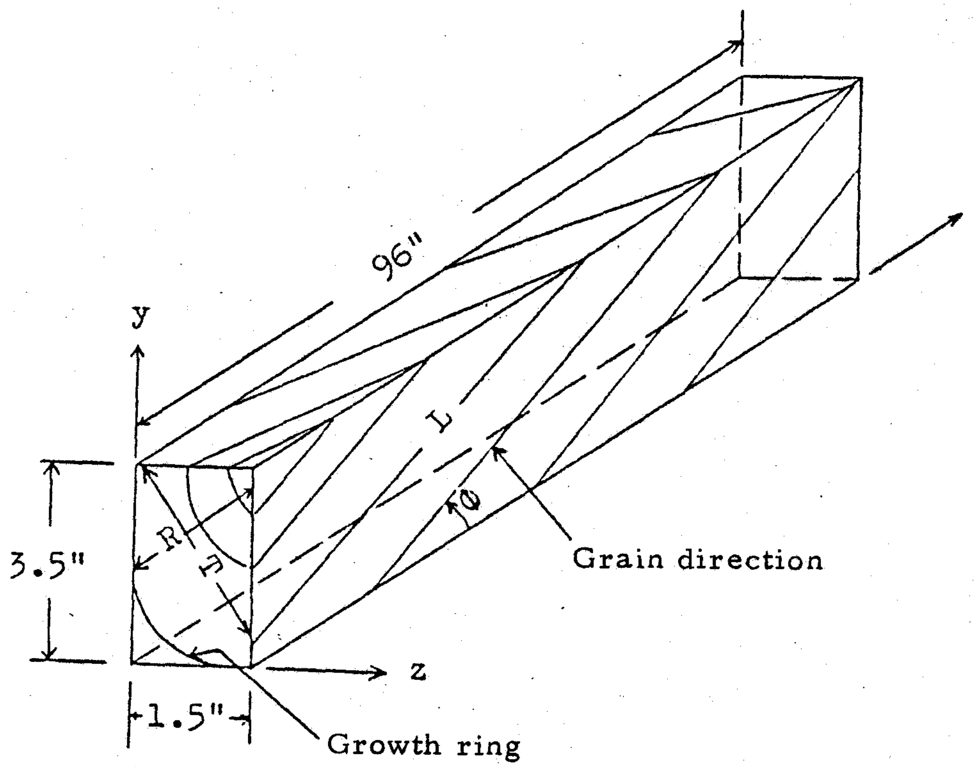

Figure 2.3. Geometry and elasticity of studs: the geometric axes x, y and z, and the elastic axes L, T and R do not coincide. ϕ is the grain angle.

corresponding elastic parameters: E_L, E_R, E_T, G_{LR}, G_{LT}, G_{TR}, ν_{RL}, ν_{LT} and ν_{TR}. Its strain-stress relationship can be expressed in matrix form as (19, 23)

$$\{\varepsilon\} = [s]\ \{\sigma\} \tag{2.43}$$

or

$$\begin{Bmatrix} \varepsilon_L \\ \varepsilon_T \\ \varepsilon_R \\ 2\,\varepsilon_{TR} \\ 2\,\varepsilon_{LR} \\ 2\,\varepsilon_{LT} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_L} & -\frac{\nu_{LT}}{E_L} & -\frac{\nu_{LR}}{E_L} & 0 & 0 & 0 \\ -\frac{\nu_{TL}}{E_T} & \frac{1}{E_T} & -\frac{\nu_{TR}}{E_T} & 0 & 0 & 0 \\ -\frac{\nu_{RL}}{E_R} & -\frac{\nu_{RT}}{E_R} & \frac{1}{E_R} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{TR}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{LR}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{LT}} \end{bmatrix} \begin{Bmatrix} \sigma_L \\ \sigma_T \\ \sigma_R \\ \sigma_{TR} \\ \sigma_{LR} \\ \sigma_{LT} \end{Bmatrix} \tag{2.44}$$

in which $\{\varepsilon\}$ = strain vector

$[s]$ = flexibility matrix

$\{\sigma\}$ = stress vector

and other symbols have been defined earlier in the text.

The strain-stress relation in wood can also be expressed in tensor form as (19, 23)

$$\varepsilon_{ij} = s_{ijkl} T_{kl} \tag{2.45}$$

in which

ε_{ij} = strain tensor

s_{ijkl} = elastic compliance tensor and

T_{kl} = stress tensor

Axial transformation of the elasticity parameters was accomplished by the tensor transformation law (19):

$$s'_{ijkl} = a_{im} a_{jn} a_{ko} a_{lp} s_{mnop} \tag{2.46}$$

in which s'_{ijkl} = transformed s_{ijkl}; a_{im}, a_{jn}, a_{ko}, and a_{lp} are the direction cosines of the angles of rotation of the x-, y- and z-system to L-, T- and R-system. The subscripts i, j, k, l, m, n, o, and p are equal to 1, 2, or 3. Figure 2.4 defines the rotation of the coordinate axes and Table 2.1 identifies the direction cosines.

Table 2.1. Direction cosines of the angles of rotation.

	x(L)	z(T)	y(R)
x'	$a_{11}=\cos\phi$	$a_{12}=0$	$a_{13}=\sin\phi$
z'	$a_{21}=\sin\phi\sin\theta$	$a_{22}=\cos\theta$	$a_{23}=-\cos\phi\sin\theta$
y'	$a_{31}=-\sin\phi\cos\theta$	$a_{32}=\sin\theta$	$a_{33}=\cos\theta\cos\phi$

Equation 2.46 was used to obtain the effective values of the

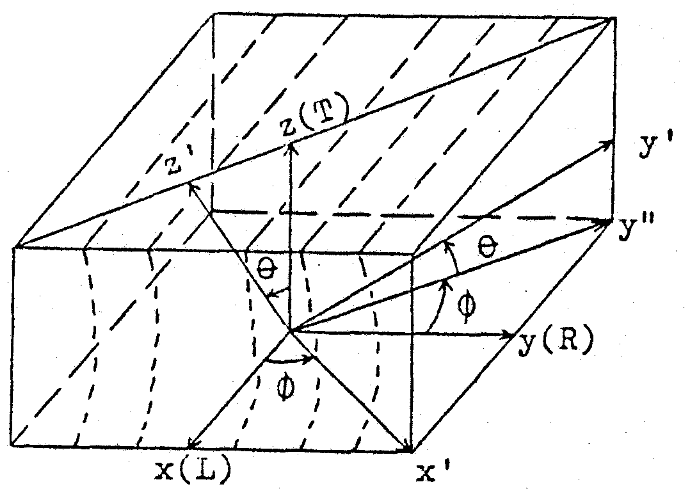

Figure 2.4. Rotation of axes. The rotation was first done along axis z at a grain angle ϕ to positions x' and y''. The second rotation was along x' axis at a ring angle θ to positions z' and y'.

elasticity parameters for various grain angles, ϕ. The following transformation equations were obtained:

$$s'_{11} = \frac{\cos^4\phi}{E_L} + \frac{\sin^4\phi}{E_R} + \cos^2\phi\sin^2\phi\left[\frac{1}{G_{RL}} - \frac{2\nu_{LR}}{E_L}\right] \tag{2.47}$$

$$s'_{13} = \sin^2\phi\cos^2\theta\left[\frac{\cos^2\phi}{E_L} - \frac{\nu_{RL}\sin^2\phi - \cos^2\phi}{E_R} - \frac{\cos^2\phi}{G_{RL}}\right]$$

$$- \frac{\cos^2\phi}{E_L}\left[\nu_{LT}\sin^2\theta + \nu_{LR}\cos^2\phi\cos^2\theta\right]$$

$$- \frac{\nu_{RT}\sin^2\phi\sin^2\theta}{E_R} \tag{2.48}$$

$$s'_{33} = \frac{\sin^4\phi\cos^4\theta}{E_L} + \frac{\sin^4\theta}{E_T} + \sin^2\theta\sin^2\phi\cos^2\theta$$

$$\left[\frac{1}{G_{LT}} - \frac{2\nu_{LT}}{E_L}\right] + \cos^2\theta\cos^2\phi\left[\frac{\cos^2\theta\cos^2\phi}{E_R}\right.$$

$$- \frac{2\nu_{LR}\cos^2\theta\sin^2\phi}{E_L} - \frac{2\nu_{TR}\sin^2\theta}{E_T} + \frac{\sin^2\theta}{G_{TR}}$$

$$\left. + \frac{\sin^2\phi}{G_{RL}}\right] \tag{2.49}$$

$$s'_{55} = 4\cos^2\phi\cos^2\theta\sin^2\phi\left[\frac{1 + 2\nu_{LR}}{E_L} + \frac{1}{E_R}\right]$$

$$+ \sin^2\theta\left[\frac{\sin^2\phi}{G_{TR}} + \frac{\cos^2\phi}{G_{LT}}\right] + \frac{\cos^2\theta}{G_{RL}}$$

$$\left[\cos^2\phi - \sin^2\phi\right]^2 \tag{2.50}$$

in which ϕ and θ are defined in Figure 2.3 and the other symbols have been defined earlier in the text. The transformed strain-stress relation can now be written as

$$\{\varepsilon'\} = [s'] \{\sigma'\} \tag{2.51}$$

in which $\{\varepsilon'\}$ and $\{\sigma'\}$ are the strains and stresses, respectively, along the stud geometric axes; and $[s']$ is defined earlier in the text.

2.5. Nonlinear Analysis

Three main techniques are available for the solution of nonlinear problems by the finite element method (11): incremental or stepwise procedure (linear step-by-step analysis), iterative or Newton method, and step-iterative or mixed procedure.

The incremental procedure was used in this study because of the following reasons:

a. it is relatively simple and applicable to nearly all types of nonlinear behavior,

b. it provides a relatively completely description of the deformation-load behavior, and

c. it provides the results at intermediate stages of the analysis.

It consumes, however, more computer time than the iterative technique.

The iterative method is faster and easier to use than the incremental method. It is useful in the case in which the materials have different elastic properties in tension and compression (59). Its principal disadvantage is that there is no assurance that it will converge to the exact solution (13). Furthermore, the displacements, stresses, and strains are determined for only the total load; hence, no information concerning the behavior at intermediate loads is obtained.

The mixed method combines the incremental and iterative procedures. It was not used in this study because there is no assurance that it will converge to the exact solution.

2.5.1. Linear Step-by-step Analysis

As previously mentioned, the theoretical model and procedure simulate the ASTM (3) flexure test depicted in Figure 3.2. The stud was modeled by rectangular and triangular elements described in Sections 2.3.1 and 2.3.2. The flow diagram in Figure 2.5 shows the most important steps in the linear step-by-step analysis. The corresponding computer program is listed in Appendix A.

Load Q was applied gradually at increments of ΔQ and represented by $\{\Delta Q\}$. The incremental displacements and stresses were calculated by

$$\{\Delta D\} = [K_i]^{-1} \{\Delta Q\} \tag{2.52}$$

$$\{\Delta\sigma_e\} = [B] \{\Delta d\} \tag{2.53}$$

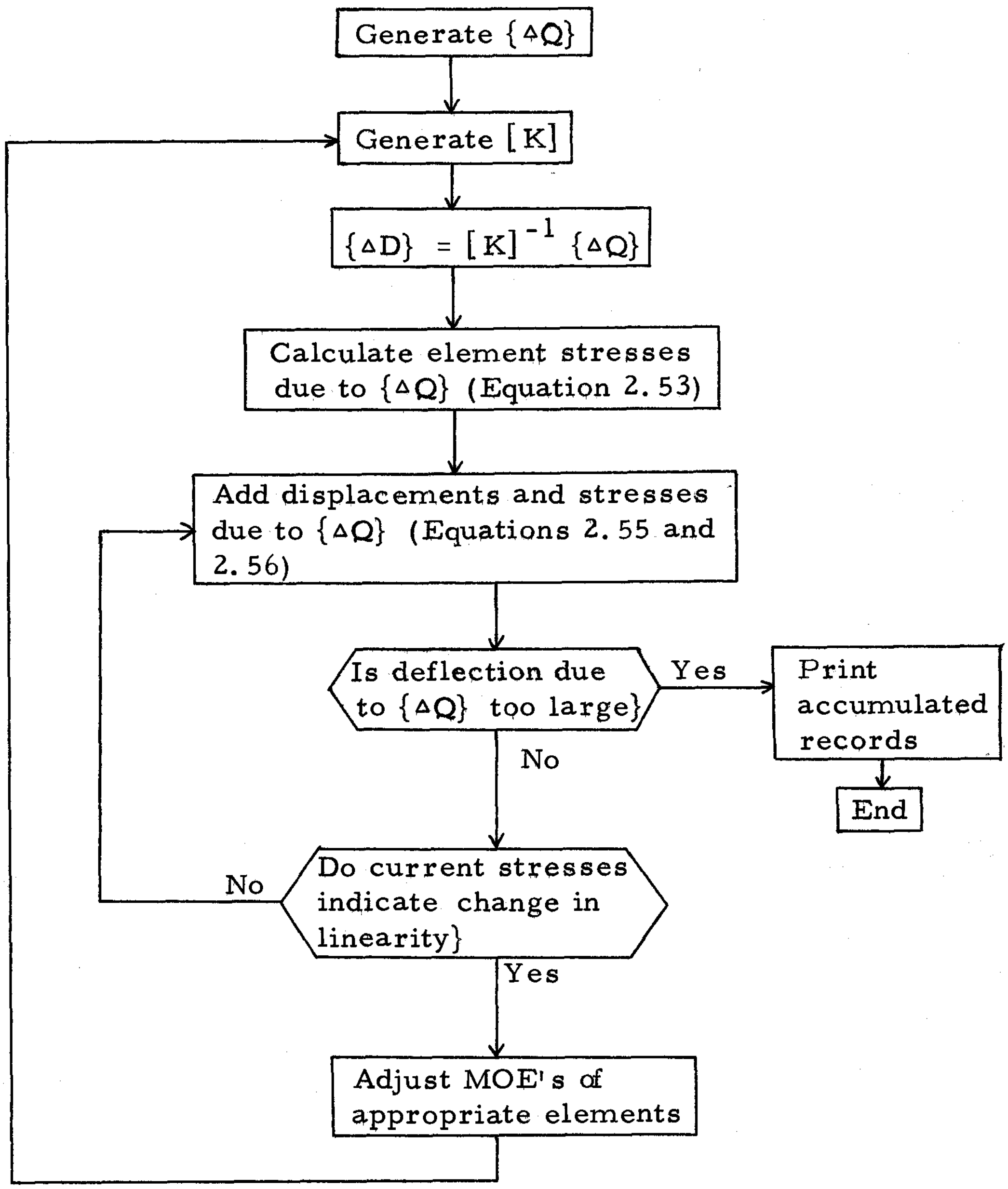

Figure 2.5. Flow diagram for linear step-by-step analysis.

in which

$\{\Delta D\}$ = displacements due to $\{\Delta Q\}$

$[K_i]$ = stud stiffness matrix. The subscript i is associated with changes in linearity at any point in the stud.

$\{\Delta\sigma_e\}$ = element stresses due to $\{\Delta Q\}$

$\{\Delta d\}$ = element nodal displacements due to $\{\Delta Q\}$

$\{\Delta Q\}$ and $[B]$ are defined earlier in the text. After the nth increment, the accumulated loads, displacements, and stresses are the sum of the corresponding incremental values:

$$\{Q_n\} = \sum_{j=1}^{n} \{\Delta Q_j\} \tag{2.54}$$

$$\{D_n\} = \sum_{j=1}^{n} \{\Delta D_j\} \tag{2.55}$$

$$\{\sigma_{e(n)}\} = \sum_{j=1}^{n} \{\Delta \sigma_{e(j)}\} \tag{2.56}$$

in which $\{Q_n\}$, $\{D_n\}$ and $\{\sigma_{e(n)}\}$ are the accumulated load, displacement, and stress vector, respectively, and j is a dummy index of summation.

The accumulated stresses along the grain, $\bar{\sigma}_L$, were compared with clear wood stresses σ_L, associated with the actual elasticity properties of each finite element. A typical example of the σ_L to ε_L diagram is shown in Figure 2.6. For example, the MOE of an element changes from E_1 to E_2 after the element stress σ_L reaches its actual PL-value. When σ_L reaches the clear-wood failure stress,

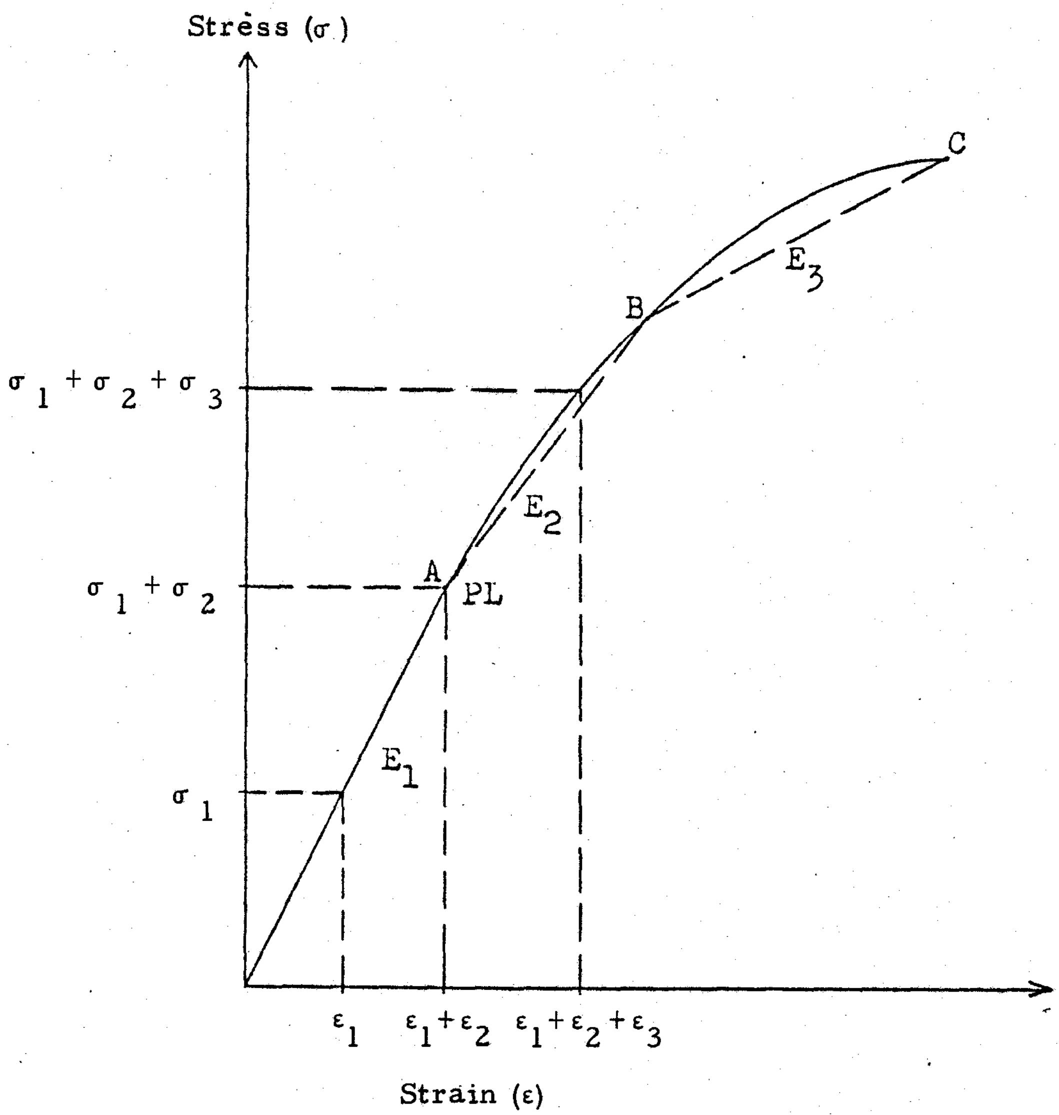

Figure 2.6. A strain-stress curve of an element. Such relations should be obtained experimentally for each representative location of the stud.

the element is considered broken and its elastic properties were reduced close to zero.

When the MOE of one or more of the elements changed, a new stud stiffness matrix is generated to account for such changes. The analysis procedure continues as shown in the flow diagram in Figure 2.5.

The analysis is terminated when the change in midspan deflection due to ΔQ is greater than four times the corresponding deflection during the initial load increment. This criterion was selected after comparing the deflection-load curves of the experimental beams with their corresponding theoretical solutions.

In cases where the geometric longitudinal axis of the stud does not coincide with the grain direction, σ_L was evaluated by the Mohr's circle (7, 43, 47, 53) according to

$$\sigma_\phi = \frac{\sigma_x - \sigma_y}{2} \cos 2\phi - \tau_{xy} \sin 2\phi + \frac{\sigma_x + \sigma_y}{2} \qquad (2.57)$$

in which the subscripts x, y and ϕ are defined in Figure 2.3 and τ_{xy} is the shear stress in the x-y plane.

The midspan deflection, y_n was obtained after each increment from the accumulated vertical displacement of an element node at midspan (equation 2.55). The corresponding load equals to $Q_n = n\Delta Q_j$. The relation of y_n to Q_n is the desired deflection-load curve of the stud.

III. VERIFICATION

The verification of the procedure and computer program was accomplished by comparing the experimental results with the corresponding theoretical results.

The experimental results were obtained by testing in flexure five 96 inches long Douglas-fir studs of nominal size 2- by 4-inches in accordance with the ASTM Standard D198 (3). The studs were then theoretically analyzed by the developed finite element procedure using the experimentally obtained elasticity properties for the representative locations on each stud.

3.1. Selection, Preparation and Characterization of Specimens

Douglas-fir studs were chosen regardless of grade with the prime consideration that they can be easily characterized. Studs with clustered knots, warps and splits were avoided. Those with smaller grain angles were preferred.

The specimens were obtained from the sawmill unseasoned. They were dried and equalized to about 8% moisture content in the dry kiln of the Forest Research Laboratory, Oregon State University. Five specimens, three of which were clear of knots, were chosen out of about 150 studs selected at the mill.

Each of the five chosen specimens was carefully inspected and mapped for strength-reducing characteristics. The diameter and location of knots were recorded. The grain angles were measured every 12 inches or less depending on whether there were local grain disturbances between the 12-inch intervals. The ring angles were measured, after the test, every 18 inches. Figure 3.1 shows the characteristics of specimen number 5. The moisture content and specific gravity were also determined and are shown in Appendix I.

3.2. Flexure Test

The specimens were tested in flexure to failure in accordance with ASTM Standard D198 (3) on a Tinius Olsen testing machine with a maximum load capacity of 60,000 pounds. The undamaged parts of broken studs were saved for elasticity evaluation. The beam span was 90 inches. Strains were measured by Linear Variable Differential Transformers (LVDT) at the tension and compression sides of the specimen as shown in Figure 3.2. Figure 3.3 shows a direct-current LVDT used in this study.

Generally the LVDTs measured elongations or contractions at certain spans. They produce electrical outputs proportional to the displacements of a separate movable core (24). In this investigation the electrical signals were sent to a data acquisition system where they were converted into linear displacements in inches and plotted by an X-Y recorder.

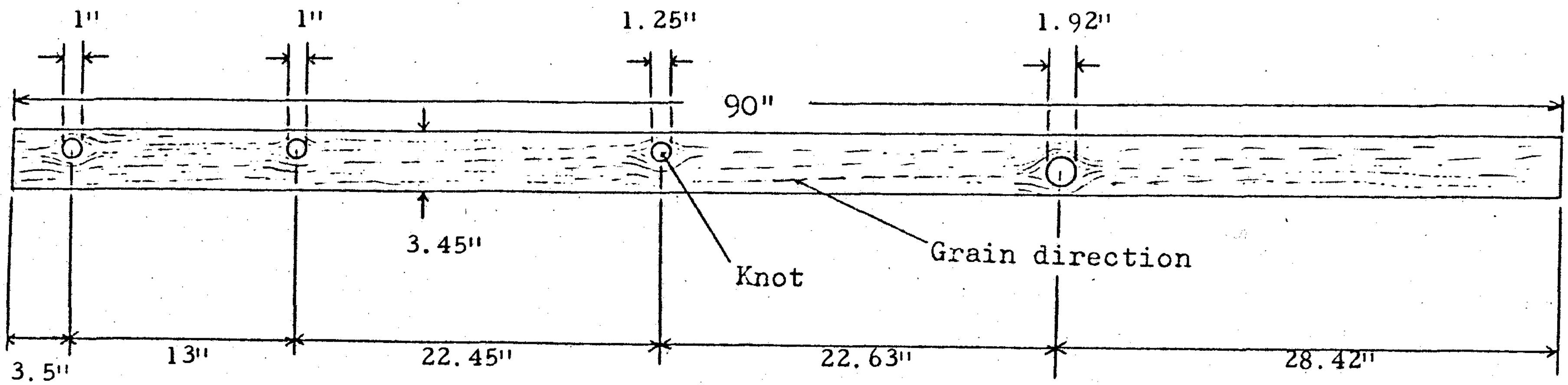

Figure 3.1. Characteristics of stud No. 5.

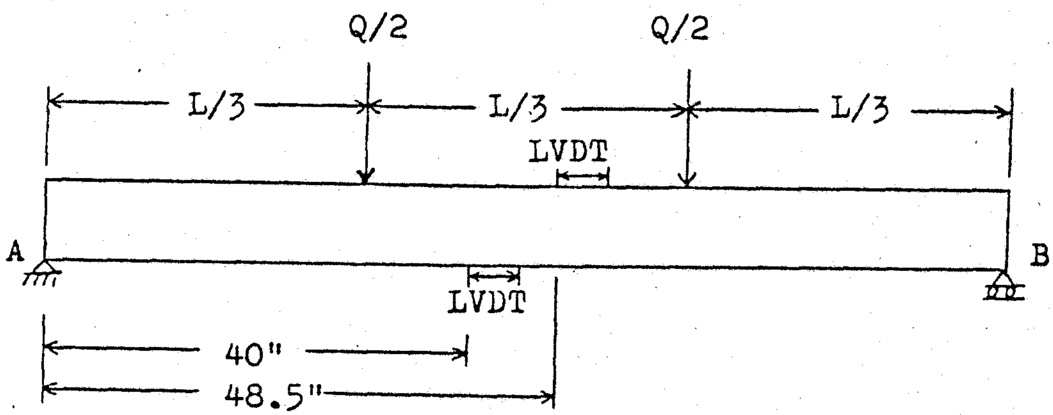

Figure 3.2. Stud loading condition and location of LVDT's. Q is the load and L is the beam span. The LVDT span was about four inches.

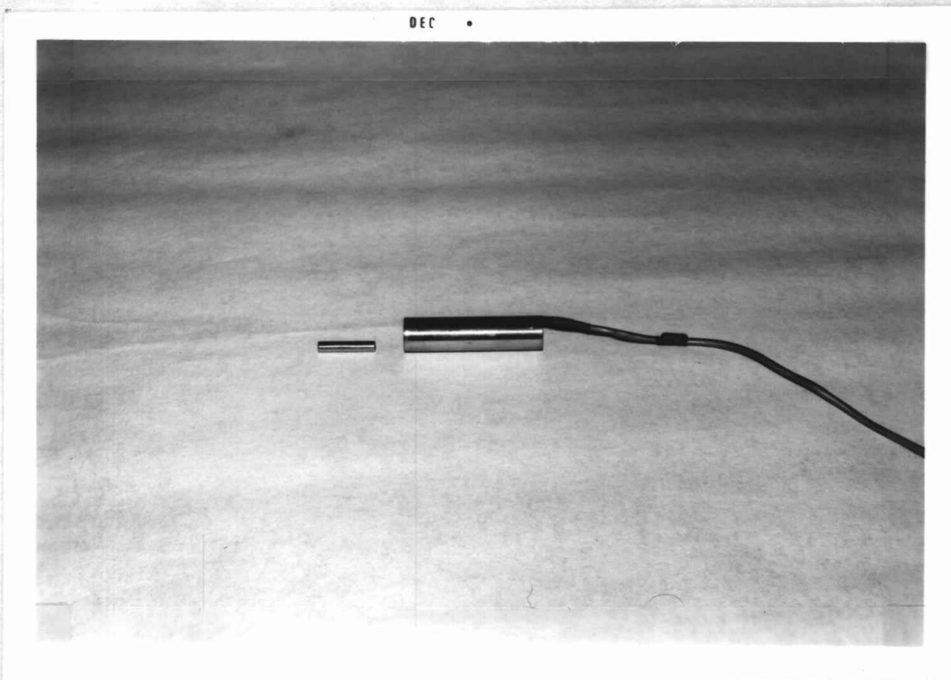

Figure 3.3. A photograph of an LVDT with the movable core at left. The LVDT is about 3.25 inches long and the core is about 1.31 inches long. The resolution of the LVDT was 0.0001 inch.

Continuous graphs of the load to the midspan deflection, also recorded for the specimens, are shown in Figures 3.11 and 3.12. From these deflection-load graphs, subdivided in three linear sections, the secant moduli of elasticity were calculated by:

$$E_1 = \frac{23\,Q_1 L^3}{1296\, y_1 I} \tag{3.1}$$

$$E_2 = \frac{23(Q_2 - Q_1) L^3}{1296\,(y_2 - y_1) I} \tag{3.2}$$

$$E_3 = \frac{23(Q_3 - Q_2) L^3}{1296\,(y_3 - y_2) I} \tag{3.3}$$

in which

E_1, E_2, E_3 = moduli of elasticity at the three sections of the deflection-load curve (psi)

Q_1, Q_2, Q_3 = total stud loads at points A, B, and C, respectively, in Figures 3.11 and 3.12 (pounds)

L = beam span (inches)

y_1, y_2, y_3 = midspan deflections (inches) due to loads Q_1, Q_2, and Q_3, respectively,

and

I = moment of inertia of the beam (inches^4)

The stresses associated with loads Q_1, Q_2 and Q_3 were calculated from

$$S_1 = \frac{Q_1 L}{bh^2} \tag{3.4}$$

$$S_2 = \frac{Q_2 L}{bh^2} \tag{3.5}$$

$$S_3 = \frac{Q_3 L}{bh^2} \tag{3.6}$$

in which

b = breadth of beam and

h = depth of beam

The calculated experimental moduli of elasticity and stresses in bending for the experimental studs are shown in column three of Table 3.1. The load at PL (Q_1) was obtained by determining where the deflection-load curve starts to deviate from a straight line. Q_3 is the load at the maximum point of the curve. Q_2 is the load at a point about midway between Q_1 and Q_3. The three section moduli (E_1, E_2 and E_3) were calculated considering the points where Q_1, Q_2 and Q_3 were located.

3.3. Compression and Tension Tests of Small, Clear Specimens

The elasticity properties of the representative locations for each of the five experimental studs were obtained by testing small, clear specimens cut from the undamaged parts of each of the broken studs. The specimens obtained from the lower half of the beam depth were tested in tension and those from the upper half were tested in compression.

The dimensions of the tension and compression specimens are shown in Figure 3.4.

The tension specimens were tested by the Instrom testing machine (Figure 3.5). The compression specimens were tested on the Tinius Olsen testing machine (Figure 3.6) which has much higher load capacity than that of the Instron. The test speed was chosen to correspond to the stud-beam test; strain rate of 0.001 in./in. min. corresponded to the ASTM Standard D198 (3) and was the same for both kinds of test. LVDT's were used to measure deformations. Specimens were tested to failure. Continuous curves were recorded for each point monitored. Elongation-load curves were determined for tension specimens and shrinkage-load curves for compression specimens.

The experimental deflection-load curves were subdivided into three sections as shown in Figure 1.1. The moduli of elasticity and the corresponding stresses were calculated for each specimen by:

$$E_1 = \frac{Q_1 L}{y_1 A} \tag{3.7}$$

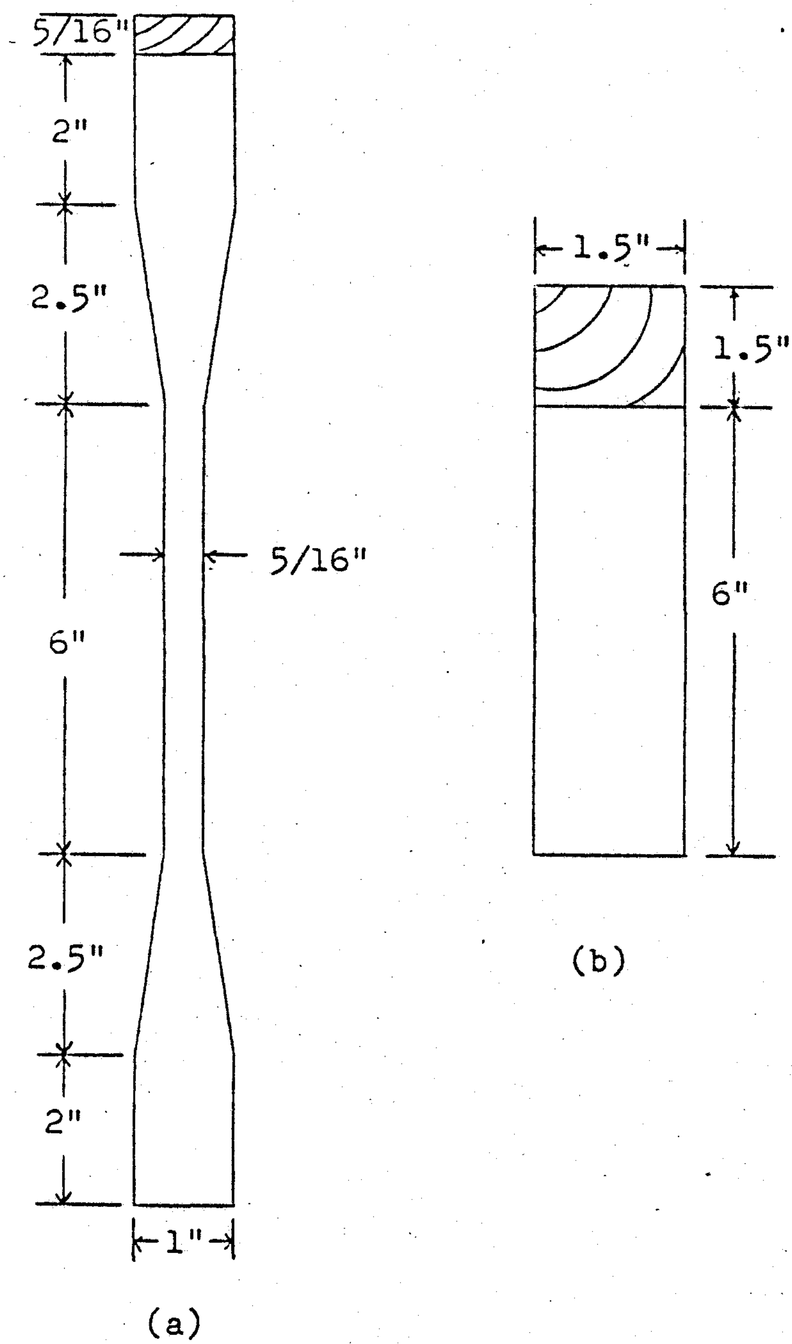

Figure 3.4. Dimensions of the tension (a) and compression (b) specimens.

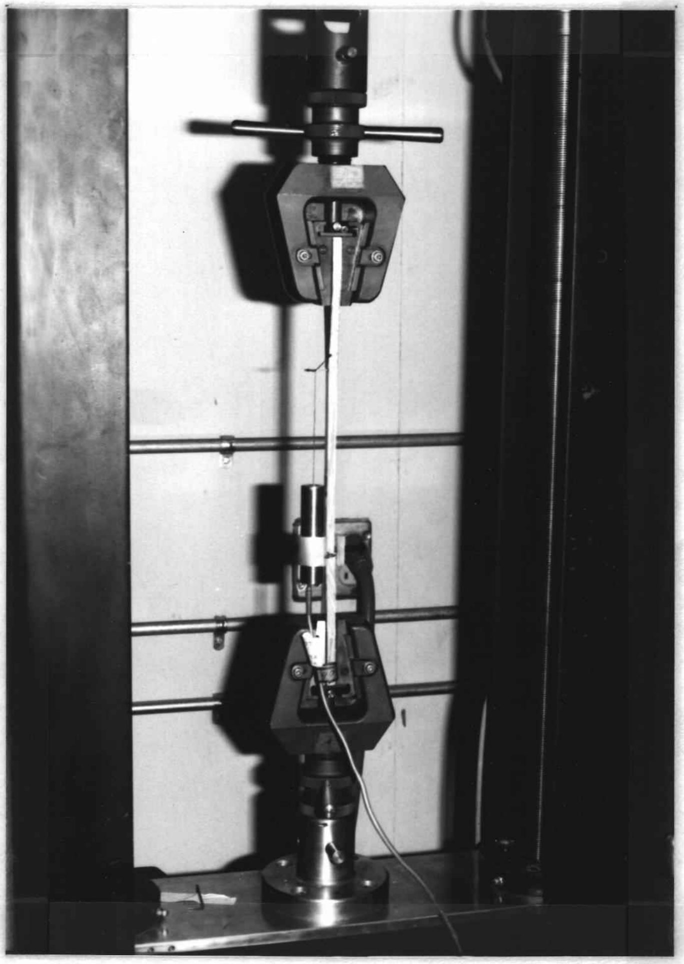

Figure 3.5. The arrangement for tension tests in the Instron testing machine. The LVDT was adjusted to a span of about six inches.

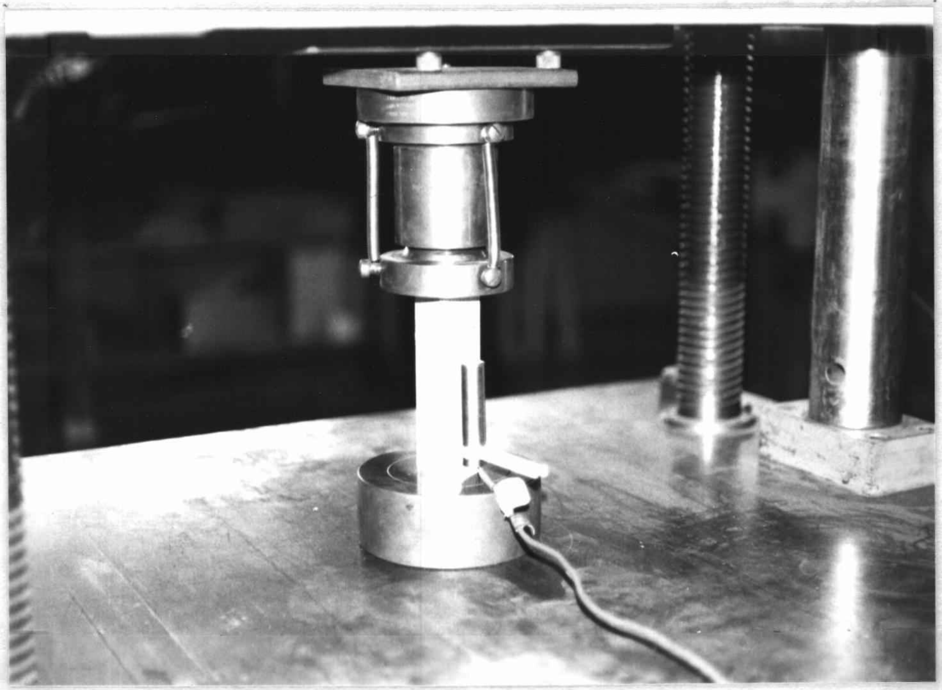

Figure 3.6. The arrangement for compression tests in the Tinius Olsen testing machine. The LVDT span was about four inches.

$$E_2 = \frac{(Q_2 - Q_1)L}{(y_2 - y_1)A} \tag{3.8}$$

$$E_3 = \frac{(Q_3 - Q_2)L}{(y_3 - y_2)A} \tag{3.9}$$

$$S_1 = \frac{Q_1}{A} \tag{3.10}$$

$$S_2 = \frac{Q_2}{A} \tag{3.11}$$

$$S_3 = \frac{Q_3}{A} \tag{3.12}$$

in which:

A = cross sectional area of specimen (inches^2)

L = span length within which deflections were measured (inches) and

y_1, y_2, y_3 = deflections within span L due to loads Q_1, Q_2 and Q_3, respectively.

All other symbols have been defined earlier in the text. The results, listed in Appendix J, were used to represent the elasticity and strength properties of the locations on the stud from which the corresponding specimens were cut.

The properties of the broken sections of the studs are the most important elements in the analysis. However, no clear specimens can be obtained from these sections. Therefore, the average elasticity and strength values of the undamaged sections were used to approximate the properties of the broken sections of the stud.

3.4. Finite Element Mesh

The mesh refinement for the experimental studs was limited by the capacity of the computer system used. For the Cyber 73, the computer system of the Oregon State University, the limit was the mesh with 170 elements and 190 nodes. The mesh refinement is important because the finer the mesh the closer the results to the true solution (8, 11).

The three experimental studs of clear wood are denoted as stud No. 1, 2 and 3. These studs had no other defects except for the grain orientation. The final finite element mesh for these studs was chosen after analyzing stud No. 2 with two kinds of mesh and examining the results. The first mesh had 156 elements and 135 nodes (Figure 3.7a). The second mesh, with 200 elements and 157 nodes (Figure 3.7b), had finer elements than the first mesh in the middle third of the stud. The results shown in Figure 3.8 indicate that the deflection-load curve obtained by using the finer mesh (Figure 3.7b) is not very different from that obtained using the coarser mesh (Figure 3.7a). Since it is less expensive to analyze the mesh with fewer elements, the mesh in Figure 3.7a was adopted to analyze studs Nos. 1, 2 and 3.

The mesh for the two studs containing knots, stud No. 4 with

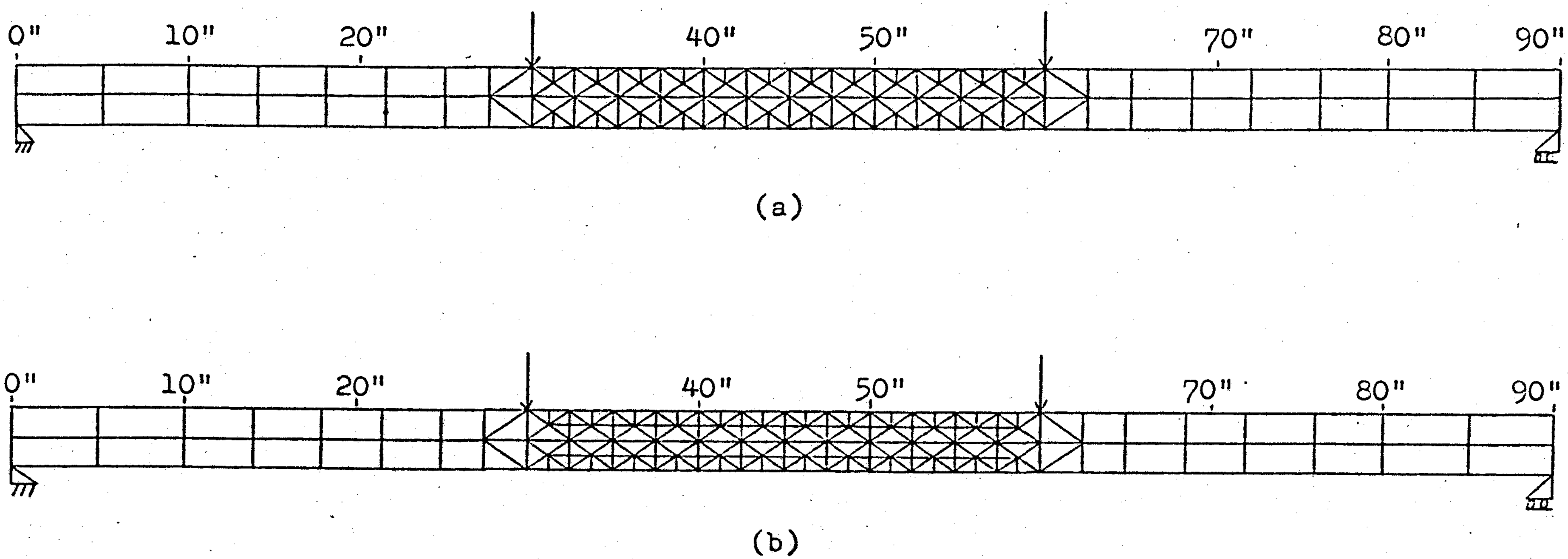

Figure 3.7. The two mesh refinements studied to determine the sizes and number of elements used in the analyses of the three clear wood studs.

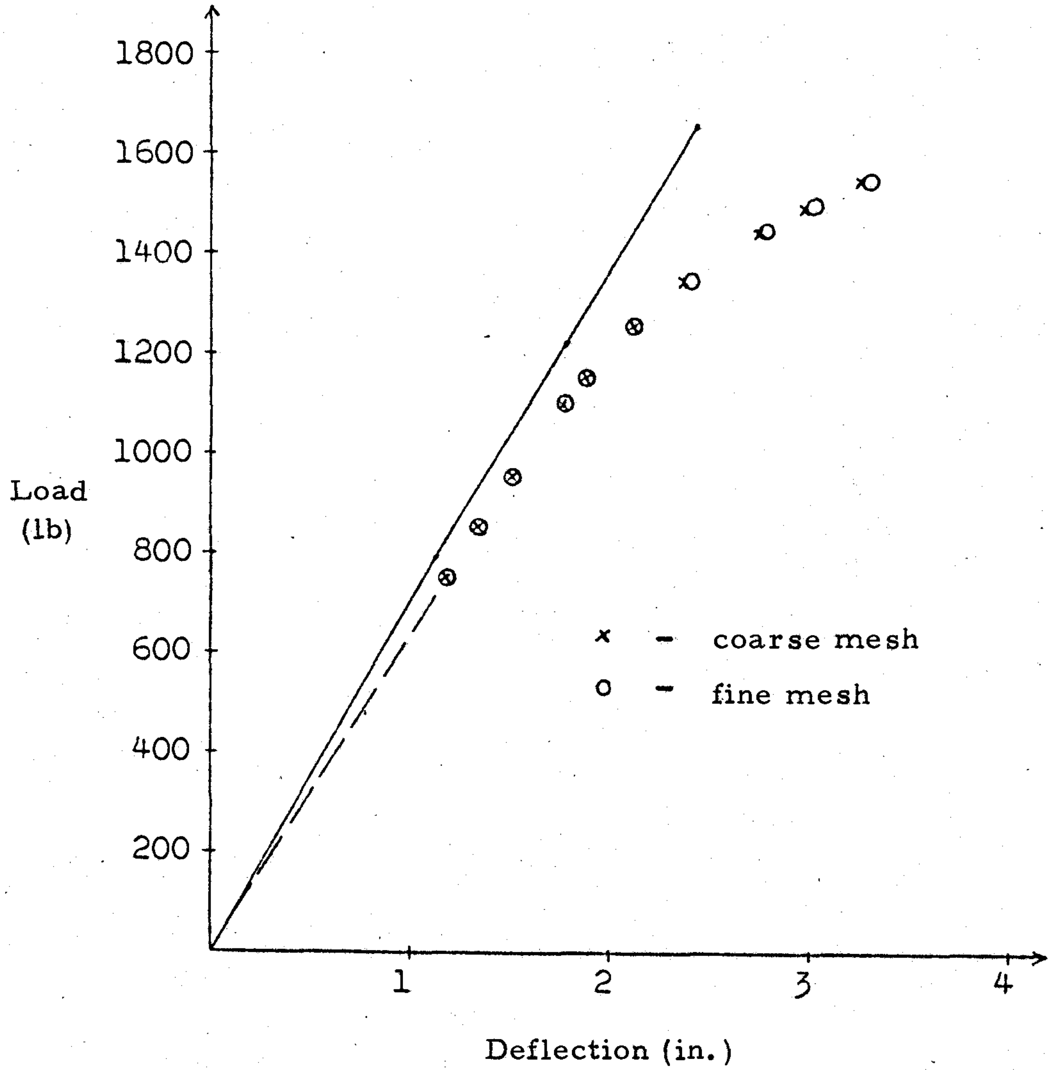

Figure 3.8. Deflection-load curves of stud No. 2 obtained experimentally (solid line), and theoretically using two finite element models. The coarse mesh contains 156 elements while the fine mesh has 200 elements.

189 elements and 199 nodes and stud No. 5 with 173 elements with 184 nodes are shown in Figures 3.9a and 3.9b, respectively. The material properties of stud Nos. 1, 2, 3, 4, and 5 are listed under the input data in Appendices B, C, D, E, and F, respectively. The data may be identified from the commentaries of the computer program (Appendix A).

Figures 3.7 and 3.9 also depict the boundary and loading conditions. The left bottom corner of the stud is fixed against horizontal translation and the right bottom corner is free. Two equal loads are applied at a distance of 30 and 60 inches from the supports.

In the analysis the load is continuously being increased by small increments. The smaller the increment the closer the approximation to the solution. Therefore, stud No. 2 was analyzed three times using the increments of total load, ΔQ, of 30, 50 and 200 pounds. Figure 3.10 shows the results. The deflection-load curves for ΔQ equalling 30 pounds and 50 pounds are almost identical. The curve with ΔQ equalling 200 pounds is somewhat stiffer than the first two.

Small load increments require more loading cycles which requires more computer time. Large load increments require less computer time, but the analysis is less sensitive to changes in load and deflection. To optimize between computer time needed and the analysis sensitivity, ΔQ was selected as 50 pounds.

Knots are assumed to have negligible resistance to tensile

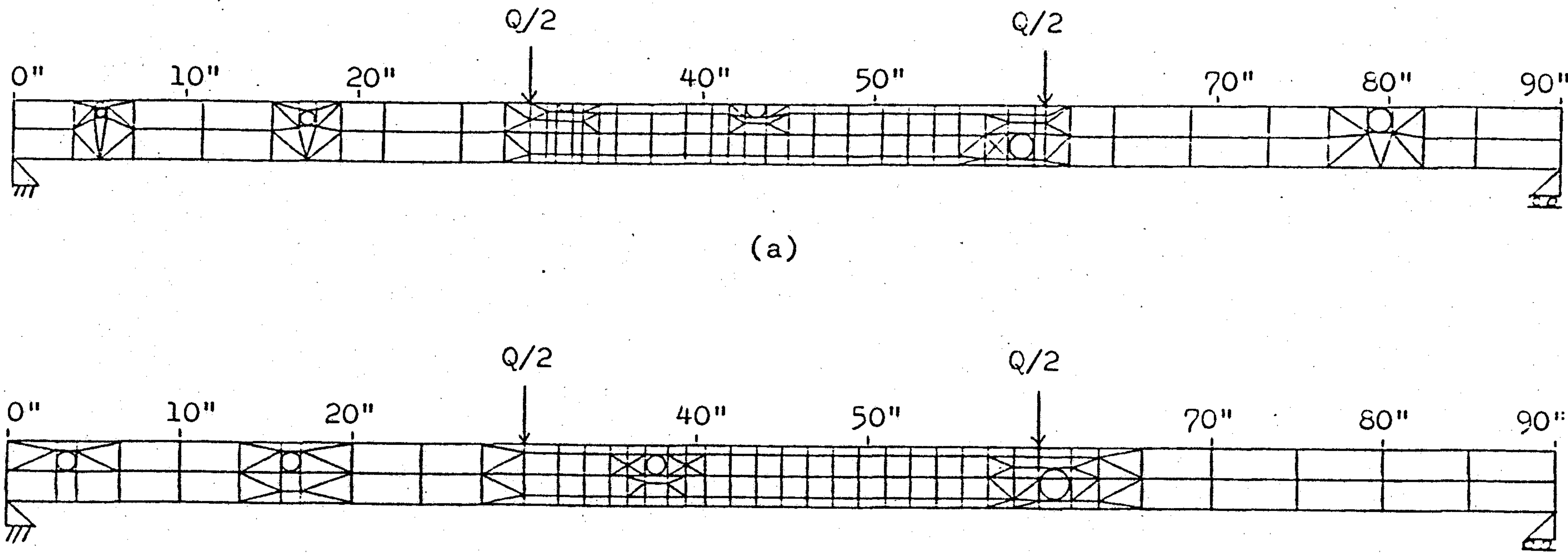

Figure 3.9. Finite element models used to analyze stud numbers four (a) and five (b). The circles enclosed by squares are the areas occupied by knots.

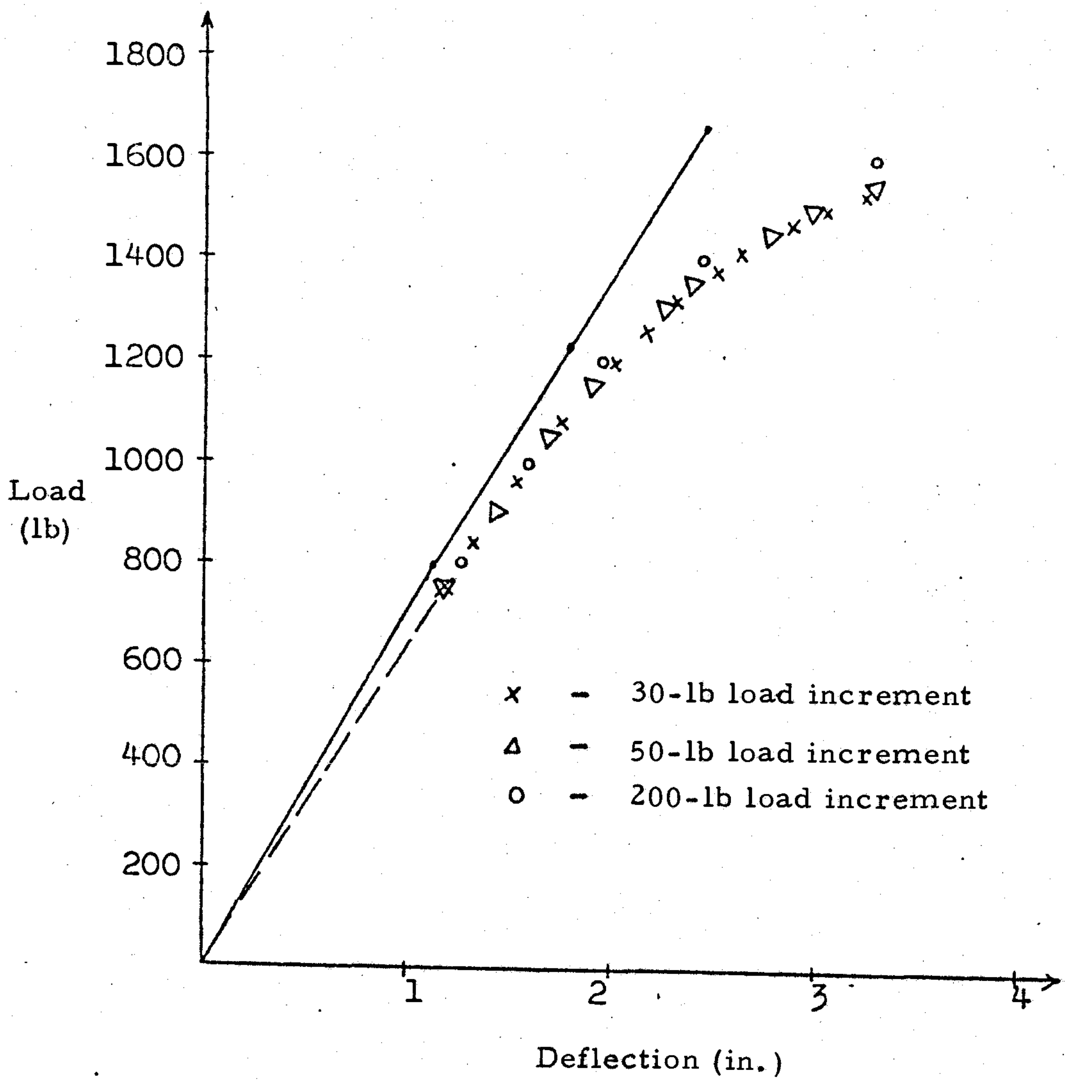

Figure 3.10. Deflection-load curves of stud No. 2 showing the experimental solution (solid line) and three theoretical solutions using three different load increments (30-, 50-, and 200 lb).

stresses. In compression, they are assumed to resist higher loads than normal clear wood. The elastic properties of elements containing knots on the tension half of the specimen were assigned values close to zero. Elements containing knots in the compression side were assigned values equal to those of the normal clear wood in tangential direction, that is, the weakest orthotropic direction in wood.

3.5. Comparison of Experimental and Theoretical Results

The deflection-load curves obtained theoretically and experimentally for the experimental studs are shown in Figures 3.11 and 3.12. The moduli of Elasticity E_1, E_2 and E_3 and the maximum stress (S_3) were calculated using equations 3.1, 3.2, 3.3, and 3.6, respectively. The deflections y_1 and y_2 were the same as those of the experimental curves. The percentage difference between the theoretical and experimental values were calculated by:

$$\% \text{ difference} = \frac{\text{Experimental} - \text{Theoretical}}{\text{Experimental}} \times 100\% \qquad (3.13)$$

The results are shown in Table 3.1.

The differences between the experimental and theoretical results for the MOR range from 10.1% to 25.3%.

This can be considered as a significant improvement over the current method for allowable stresses, that develops the allowable stress from the values for the clear wood MOR, which is reduced for

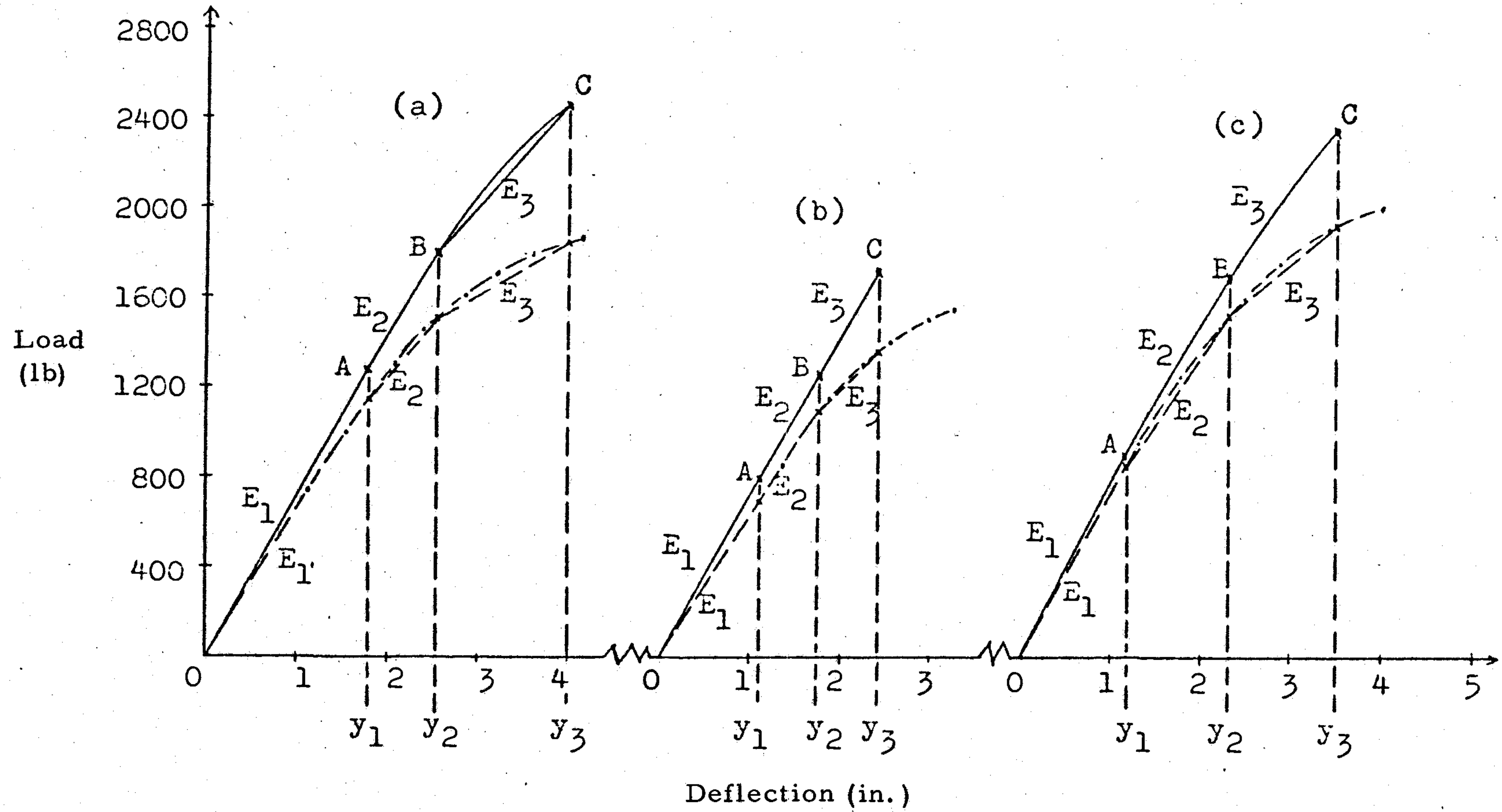

Figure 3.11. Deflection-load curves obtained experimentally (solid lines) and theoretically (broken lines) for stud numbers 1 (a), 2 (b), and 3 (c).

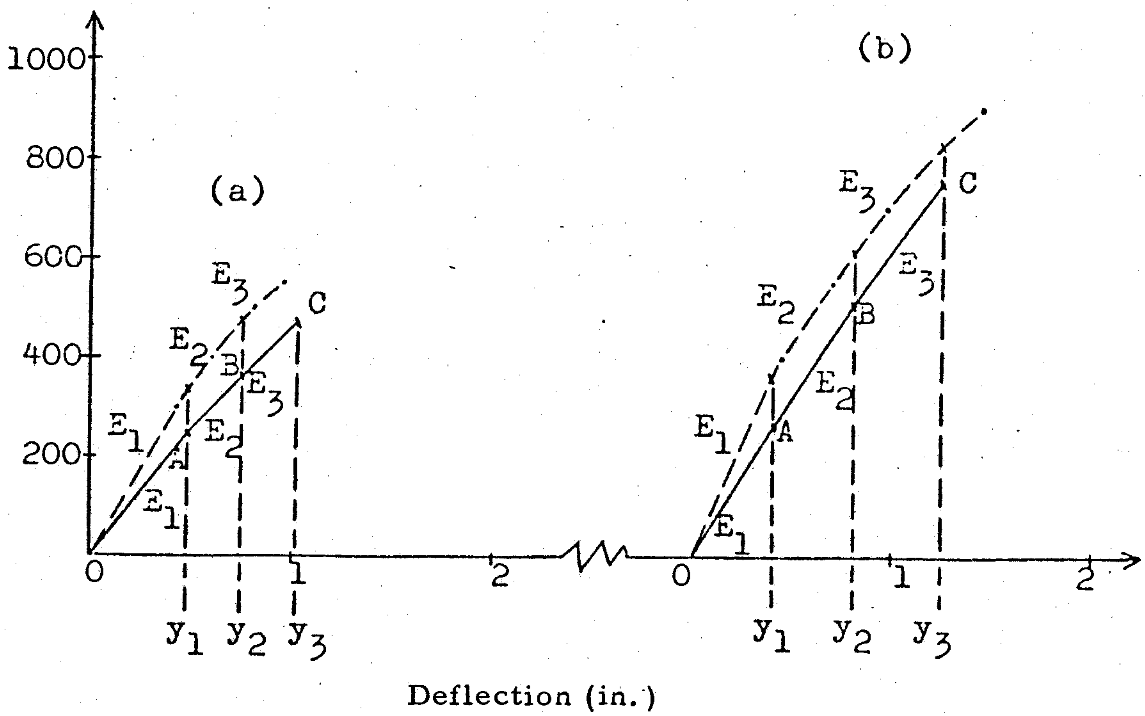

Figure 3.12. Deflection-load curves obtained experimentally (solid lines) and theoretically (broken lines) for stud numbers four (a) and five (b).

Table 3. 1. Experimental and theoretical values of load, MOE and MOR. The percentage difference between the experimental and theoretical values of MOE and MOR are given.

Stud No. 1	Property 2	Experimental value 3	Theoretical value 4	Percentage difference 5
1	Q_1 (lb)	1, 284	1, 140	
	Q_2 (lb)	1, 800	1, 500	
	Q_3 (lb)	2, 465	1, 840	
	E_1 (psi)	1, 856, 000	1, 647, 800	11. 2
	E_2 (psi)	1, 733, 900	1, 209, 700	30. 2
	E_3 (psi)	1, 203, 200	615, 200	48. 8
	MOR (psi)	12, 640	9, 440	25. 3
2	Q_1	797	700	
	Q_2	1, 231	1, 090	
	Q_3	1, 661	1, 350	
	E_1	1, 801, 700	1, 582, 500	12. 2
	E_2	1, 732, 300	1, 556, 700	10. 1
	E_3	1, 689, 900	1, 021, 800	39. 5
	MOR	8, 490	6, 900	18. 7
3	Q_1	888	850	
	Q_2	1, 690	1, 520	
	Q_3	2, 352	1, 920	
	E_1	1, 953, 700	1, 870, 100	4. 3
	E_2	1, 890, 600	1, 579, 400	16. 5
	E_3	1, 481, 200	895, 000	39. 5
	MOR	12, 310	10, 050	18. 3
4	Q_1	247	330	
	Q_2	360	470	
	Q_3	472	550	
	E_1	1, 336, 300	1, 785, 400	-33. 6
	E_2	1, 152, 200	1, 427, 500	-23. 9
	E_3	1, 060, 400	1, 009, 900	4. 8
	MOR	2, 470	2, 870	-16. 2
5	Q_1	264	360	
	Q_2	511	610	
	Q_3	748	825	
	E_1	1, 612, 200	2, 198, 400	-36. 4
	E_2	1, 508, 400	1, 526, 700	-1. 2
	E_3	1, 412, 900	1, 281, 700	9. 3
	MOR	3, 750	4, 130	-10. 1

defects and safety. The current method was reported to produce a working stress which is 400% lower than the actual stress (38).

The difference range for E_1 is 4.3% to 36.4%, for E_2, 1.2% to 30.2%, and for E_3, 4.8% to 48.8%.

The effects of the stud properties used in the analysis on the accuracy of the theoretical deflection-load curves are discussed in section VI.

IV. PARAMETER STUDY

A parameter study was conducted to determine the effect of six parameters on the deflection-load curves. The parameters are: moduli of elasticity E_L, E_R and E_T, clear-wood stresses S_1, S_2 and S_3, moduli of rigidity G_{LT}, G_{LR} and G_{TR}, Poisson's ratios ν_{LT}, ν_{TL}, ν_{LR}, ν_{RL}, ν_{TR}, ν_{RT}, grain angle, and ring angle.

4.1. Procedure

Experimental stud No. 2 was selected for the parameter study. Only one parameter was increased at a time leaving the others unchanged. Table 4.1 depicts the parameter changes. The magnitude of the parameter change was determined on the basis of the author's opinion as to a possible margin of error in experimentally determined parameter values. For each parameter change, the stud was analyzed by the procedure developed to obtain the deflection-load curve. The curves were divided into same three sections as the curves for control model with no parameter change (Figures 4.1 and 4.2). The moduli of elasticity E_1, E_2, E_3, and modulus of rupture S_3 were calculated by equations 3.1, 3.2, 3.3 and 3.6, respectively, and compared to the corresponding values computed for the control model. The percentage differences between the results for the actual and changed properties were calculated by equation 3.13.

Table 4.1. Magnitude of parameter increases used in parameter study.

Parameter	Magnitude of Increase
Moduli of elasticity	25%
Moduli of rigidity	25%
Poisson's ratios	100%
Clear wood stresses	50%
Grain angle	5°
Ring angle	20°

4.2. Results

Figures 4.1 and 4.2 show the results of the parameter study. Table 4.2 gives for each parameter change the stud moduli and the percentage differences between the results from the control and changed values.

The E_1 of the stud increased by 20% when the MOE used for the elements was increased by 25%. E_3 increased by 13%. E_2 and MOR did not change much.

If the grain angle of the stud is increased by 5°, the E_1 decreased by 12.9%, E_2 decreased by 5.7%, whereas E_3 and MOR did not change much.

When the clear wood stresses used for the elements were increased by 50%, the stud MOR increased by 48.4%. However,

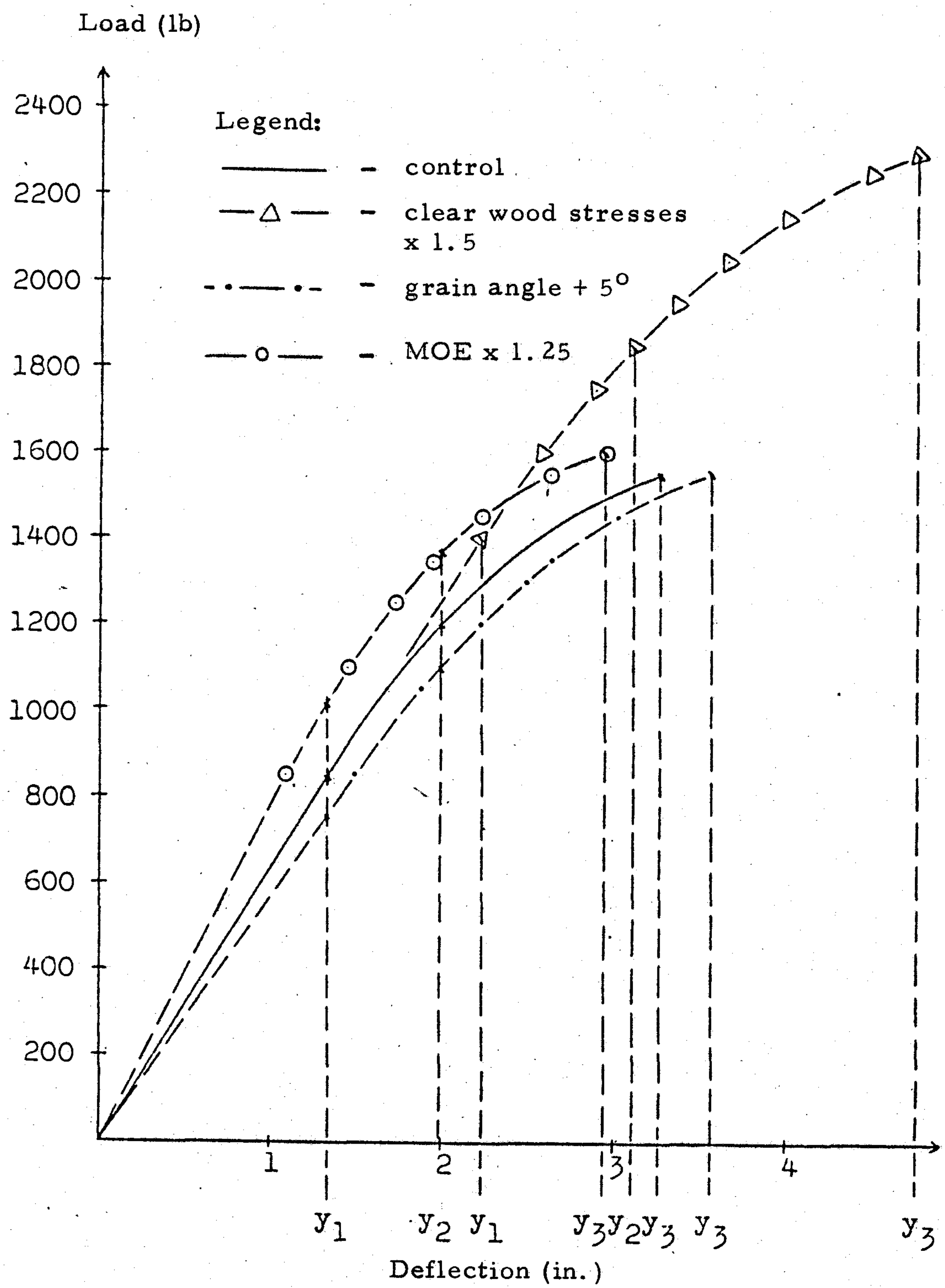

Figure 4.1. Deflection-load curves for the control model, and for the model with increased MOE's, grain angle and clear wood stresses.

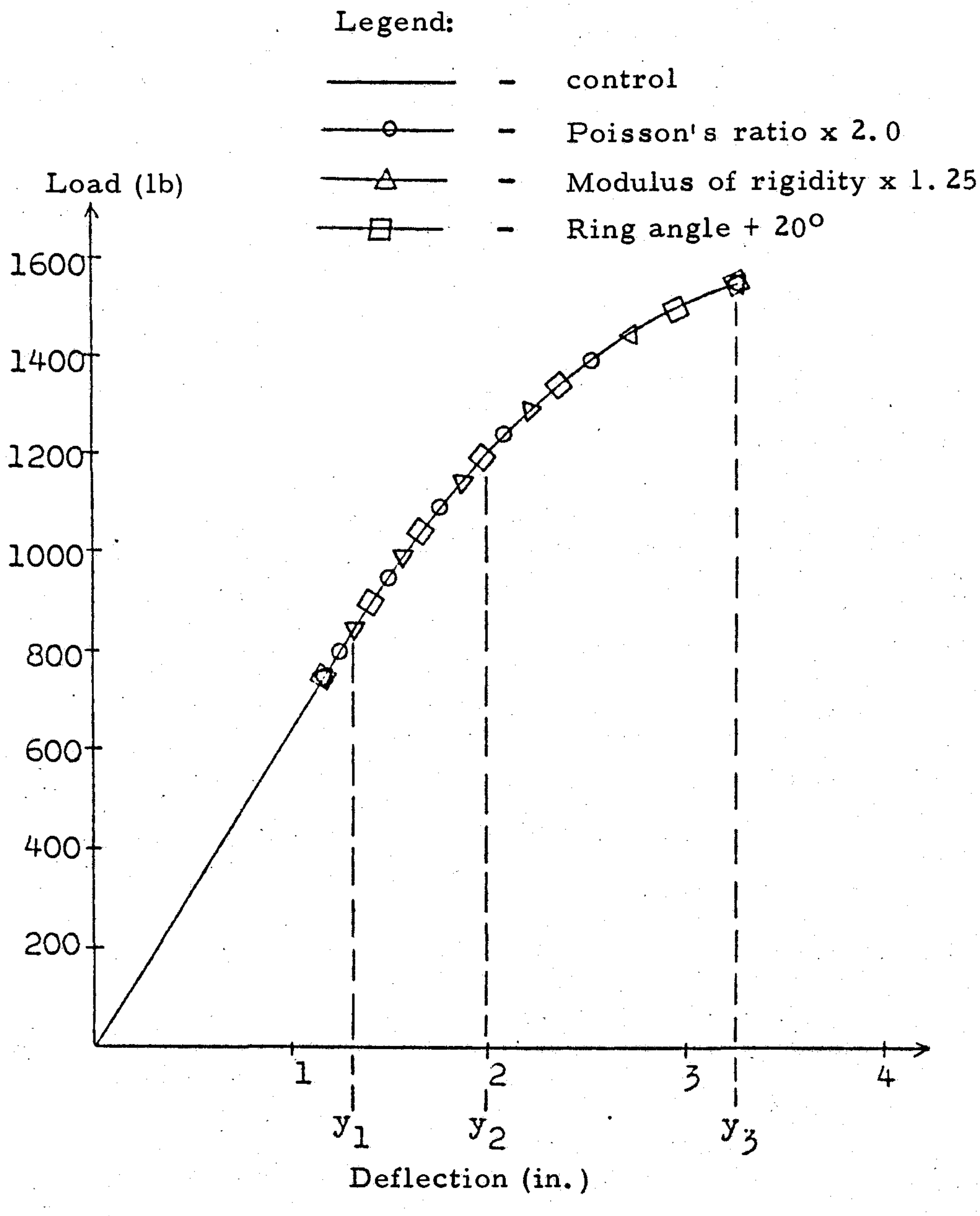

Figure 4.2. Deflection-load curves for the control model, and for the model with increased Poisson's ratio, modulus of rigidity, and ring angle.

Table 4.2. Moduli of elasticity and rigidity for deflection-load traces of control model and models with changed elasticity property.

Parameter value changed	E_1 (psi)	E_2 (psi)	E_3 (psi)	MOR (psi)
Control	1, 620, 400	1, 354, 700	704, 000	7, 920
MOE x 1. 25	1, 944, 500	1, 316, 000	795, 700	8, 170
% difference	-20. 0	2. 9	-13. 0	-3. 2
Grain angle + 5°	1, 410, 700	1, 432, 100	725, 200	7, 920
% difference	12. 9	5. 7	-3. 0	0. 0
Clear wood srresses x 1. 5	1, 611, 000	1, 291, 600	692, 500	11, 750
% difference	0. 6	4. 7	1. 6	-48. 4
Poisson's ratio x 2. 0	1, 620, 400	1, 354, 700	726, 900	7, 920
% difference	0. 0	0. 0	-3. 3	0. 0
Modulus of rigidity x 1. 25	1, 632, 600	1, 334, 500	682, 500	7, 920
% difference	-0. 8	1. 5	3. 1	0. 0
Ring angle + 20°	1, 620, 400	1, 334, 500	715, 300	7, 920
% difference	0. 0	1. 5	-1. 6	0. 0

E_1, E_2 and E_3 did not change much.

Changes in Poisson's ratio, shear modulus and ring angle values had a negligible effect on E_1, E_2, E_3 and MOR.

V. SIMULATION PROCEDURE

The finite element method for wood stud analysis may be applied to model study populations. Studs may have any of the commonly found wood defects such as ring angles, grain angles and knots. Figure 5.1 depicts a flow diagram of the procedure. The most important steps are the generation of stud properties, formulation of a finite element model, axial transformation of elasticity properties, and application of the linear step-by-step analysis. These steps were individually discussed earlier in the text.

A computer program prepared for the simultaion procedure is explained and listed in Appendix A.

5.1. Generation of Material Properties

The procedure generates a stud model with diameter and location of knots, grain and ring angles, and elastic and strength properties from their corresponding probability distribution.

5.1.1. Diameter and Location of Knots

The knot diameter, determined by assuming that its probability distribution is uniform (60), was obtained from:

$$DIAM = 10\,[RANF(A)] - 2.5\,X \tag{5.1}$$

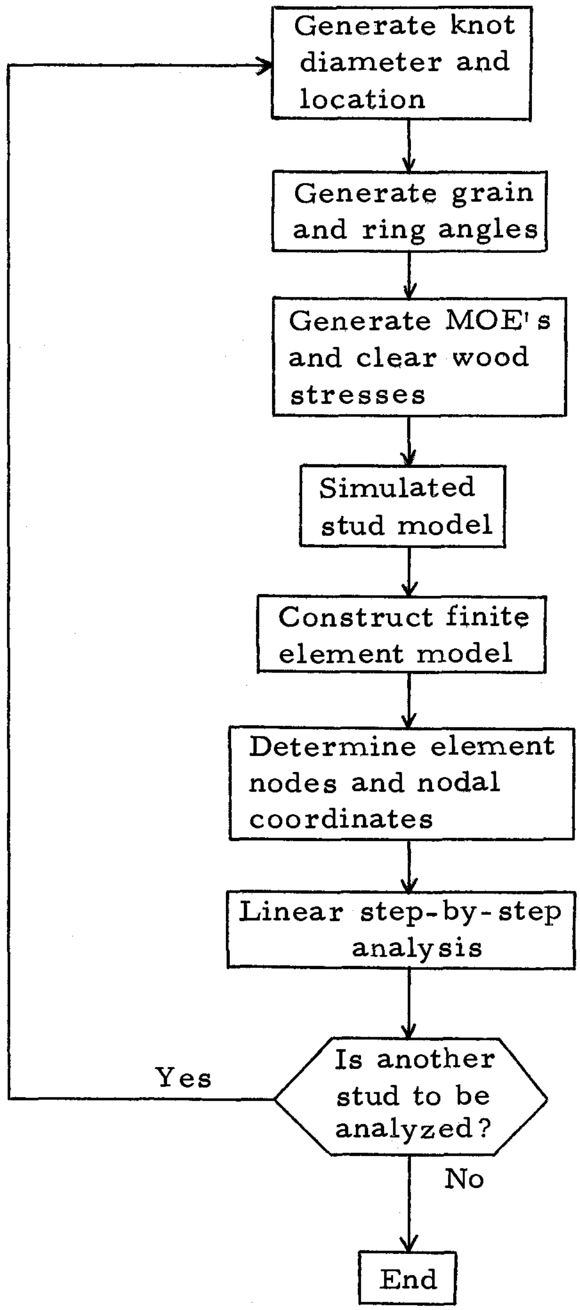

Figure 5.1. Flow diagram for simulation procedure.

where

RANF(A) = random number generator on OSU Cyber 73. It generates numbers from a uniform distribution with a range from 0 to 1.

DIAM = knot diameter with a range from 0 to 2.5 inches.

X = multiple of 2.5 which would reduce the knot diameter within the desired range.

The knots were assumed to be solid and formed continuous parts of the stud. However, they have material properties different from those of clear wood. The area they occupy are, therefore, designated by separate elements. Because knot diameters follow a continuous distribution, it would be impossible to develop a finite element mesh that could account for knot sizes with very small size increments. Therefore, for convenience in modeling knots, an increment of 0.5 in. in the range from 0.0 to 2.5 in. was chosen to classify knot diameters. Table 5.1 gives the knot diameter corresponding to the generated diameter values. Two and one-half inches is the maximum diameter allowed under the Stud grade (56). The computer program allows to reduce the range of knot diameters, if desired. Table 5.2 gives the range of knot diameters chosen in examples of this study. Some of the knot diameter ranges were chosen to account for the requirements of Stud, Construction, Standard and Utility grades (56). The Stud grade was used in this study. The other diameter ranges were included for an eventual future use.

Table 5.1. Generated value and the corresponding knot diameter used in simulating the stud model.

Generated value	Knot diameter (in.)
0.00 to 0.25	0.0
0.26 to 0.75	0.5
0.76 to 1.25	1.0
1.26 to 1.75	1.5
1.76 to 2.25	2.0
2.26 to 2.75	2.5

Table 5.2. Values of variable IP and the corresponding knot diameter ranges considered by the model.

IP*	Knot diameter range (in.)
1	1.0-2.5
2	1.5-2.5
3	2.0-2.5
4	0.0-2.5
5	0.0-1.5
6	0.0-1.0
7	1.0-2.0
8	0.0-2.0

*IP is the variable in the computer program which controls the range of knot diameters.

The knot location was assigned by dividing the stud into 1260 sections of size 0.5- by 0.5-inch. One section, designated as the center of the knot, was picked at random by the equation

$$LOC = 10,000\ [RANF(A)] - 1,260\ X \tag{5.2}$$

where

LOC = number of part where the center of the knot is located

X = multiple of 1,260 which would reduce the location number within the desired range

RANF(A) = defined earlier in the text.

5.1.2. Grain and Ring Angles

The grain and ring angles were obtained in the same manner as that of the knot diameter and location. The range of the ring angles is from 0° to 90^{9}, and that of the grain angles is from 0° to 14°. Fourteen degrees is the maximum grain angle allowed under the Stud grade (56).

The generated values for grain angles were used for elements not disturbed by knots. For elements around knots, the grain angles are distorted and are, therefore, increased according to their location around the knot as shown in Figure 5.2. If the diameter of the knot is larger, the area of the affected elements is increased proportionately.

5.1.3. Elastic and Strength Properties

The MOE's and stresses of clear wood were based on the assumption that their frequency distributions are normal (60). The following equation (15) was used:

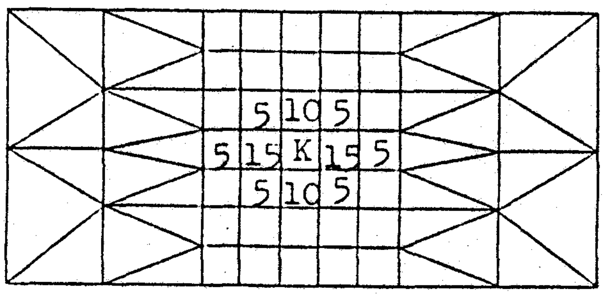

Figure 5.2. Elements disturbed by knots. The square containing letter K is the area occupied by the knot. A knot can be located in any of the square elements. The numbers in elements around the knot are the magnitude in which the grain angles are increased over the actual local orientation in these elements. The magnitude of the grain angle increment around knots was determined by inspecting the grain angle distortions around knots in lumber.

$$X = \mu + (-2\sigma^2 \ln U_1)^{\frac{1}{2}} \cos 2\pi U_2 \qquad (5.3)$$

in which

X = generated value of the property

μ = average value of the property

σ^2 = variance of the property, and

U_1, U_2 = random numbers ranging from 0.0 to 1.0 generated from a uniform distribution.

The frequency distributions of MOE's and stresses of clear wood were obtained from the results (unpublished) of a recent bending test of small, clear Douglas-fir specimens conducted at the Forest Research Laboratory, Oregon State University.

5.2. Finite Element Mesh

Figure 5.3 shows the stud model. It could be applied to studs generated in the simulation procedure. This model was chosen because of its efficiency in modeling knots. The stud was divided into 36 sections along its length with each section 2.5 inches long. Each section was designated by letters A through F. For clear wood stud, the mesh in Figure 5.3a is used. Knots may be modeled by substituting sections of the clear-wood mesh with the appropriate mesh defined in Figure 5.3b through 5.3g. Any one of Figures 5.3b through 5.3g may be substituted with a section of a stud in Figure 5.3a depending

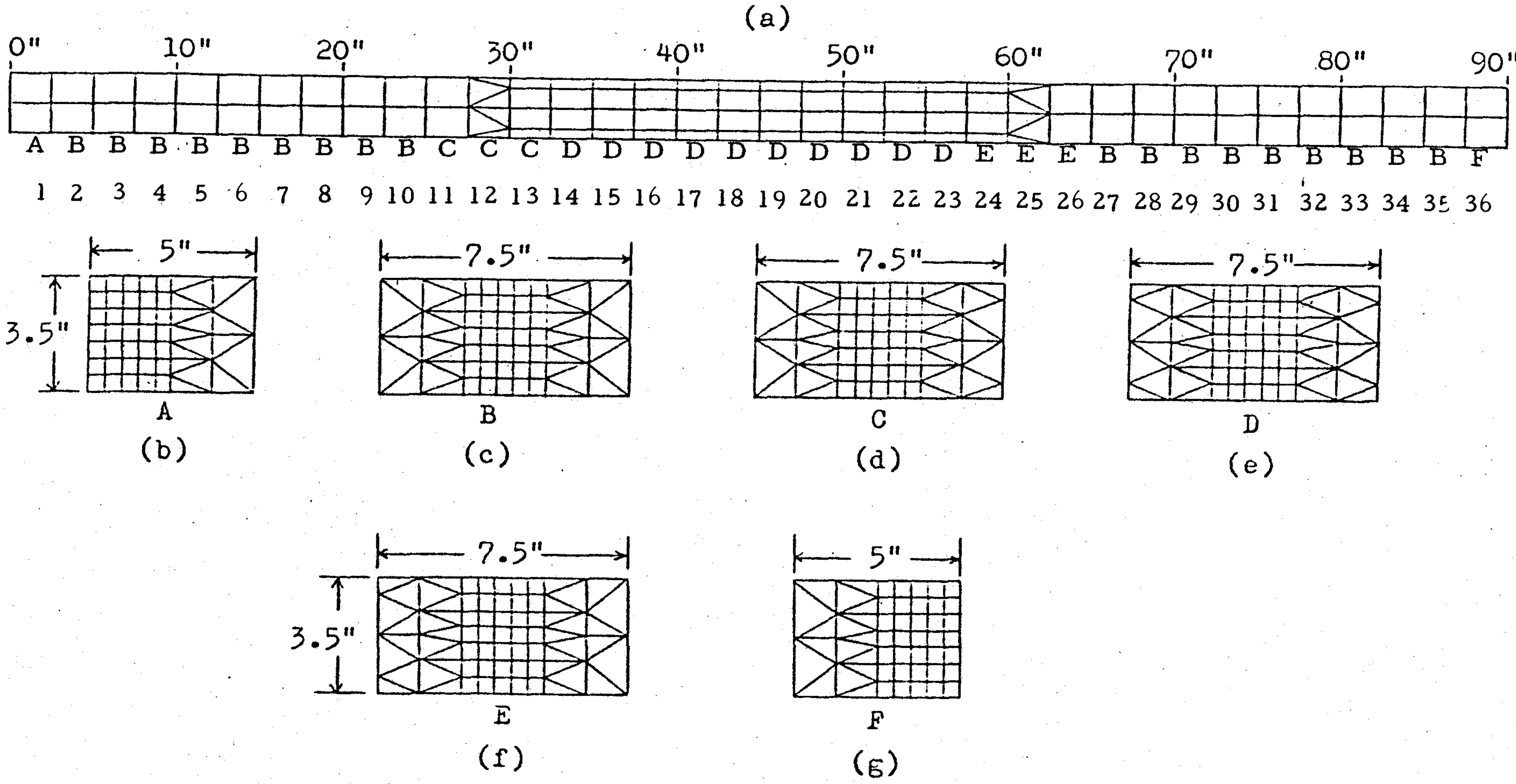

Figure 5. 3. Finite element mesh used in the analyses of wood studs. Figure 5. 3a is the unmodified mesh associated with clear wood. Figures 5. 3b through 5. 3g are the replacements for sections affected by knots. The letters A through F in Figure 5. 3a designate the position of the mesh defined in Figures 2. 7b through 2. 7g.

on the location of the knot. The letter designating a section in Figure 5.3a corresponds to the letter in one of Figures 5.3b through 5.3g to be substituted where the critical knot is located in the stud. The knot is located in one of the square elements in Figures 5.3b through 5.3g. For example, if the knot is located in section 15 of Figure 5.3a, sections 14, 15 and 16 are replaced by Figure 5.3e. The elements and nodes are re-numbered and nodal coordinates determined.

One limitation of the method is that edge knots can not be modeled. However, this could easily be added to the procedure by assigning a certain area in the wide face of the stud to a knot with the same strength-reducing effect as that of the edge knot.

VI. DISCUSSION

This chapter deals with the finite element model and simulation procedure, accuracy of stud properties for verification and its effect on the theoretical results, and with the applications of the finite element model and simulation procedure.

6.1. Finite Element Model and Simulation Procedure

The finite element method used in this study is able to predict the deflection-load curves of studs with sufficient accuracy. However, the method has some limitations. The material properties are assumed to be constant within the element, which usually is not true in case of wood. The number of elements, which has an effect on the accuracy of the results, is limited by the memory capacity of the computer being used. Finally, the actual three-dimensional stud is described by a two-dimensional finite element model.

The simulation procedure has also its limitation. The material properties of studs follow certain probability distributions which can not be exactly defined. These distributions are approximated by known probability distributions.

6.2. Accuracy of Stud Properties for Verification and Effect on the Theoretical Results

The stud properties for the analysis are obtained by testing, from previous studies, and methodical mapping and inspection of stud defects.

6.2.1. Moduli of Elasticity

The E_L's used in the verification of the finite element method were obtained from tension and compression tests of the undamaged parts of the stud after testing. The broken parts, the most important sections of the studs used for the verification, were only approximated by the average E_L's of the undamaged parts. Considering the high variability of wood even in the same piece of lumber, the average E_L's of the undamaged sections could be different from those of the broken parts. The E_T and E_R values were determined by using regression relations developed in previous studies. The regression relations were based on a specific sample of small clear specimens. Therefore, it is highly possible the properties of studs used for verification deviated from the actual values. Such deviations or errors in the determination of the true MOE's of the stud could significantly alter the computed deflection-load curve of the stud. Because, as shown in the parameter study, an increase of the MOE values used in the analysis by 25% caused an increase in the stud E_1 value by 20%.

6.2.2. Shear Moduli and Poisson's Ratio

The shear moduli were determined using regression relations from previous studies, and Poisson's ratio values were taken from previous research. These values and relations could be different from those of the stud. However, this is not very important because, as shown in the parameter study, these factors did not affect the deflection-load curve of the stud. The results of the parameter study on Poisson's ratio agrees with the works of Brodeau (5), Fung (16) and Walker (55) who concluded that accurate determination of Poisson's ratio does not seem very critical in solving plane stress problems.

6.2.3. Grain and Ring Angles

The grain and ring angles were obtained by measurement. They were measured at a certain interval along the stud length. Due to the natural variability in the grain and ring directions, it is virtually impossible to obtain the exact angles for the elements. Only the grain angles at the stud surface can be measured. It can not be ascertained if the grains are twisted or changed directions inside the wood. The grain angles of elements around knots are also difficult to obtain because they are not constant. Errors in the angle determination should lead to errors in the theoretical deflection-load curve of the stud. From the parameter study discussed in an earlier section of the text, the ring angle was not a significant factor in the analysis. However, an increase in the grain angle by 5° caused a decrease in the E_1 value of the stud by 12.9%, or about 2.6% change in E_1 per degree error in grain angle.

6.2.4. Clear Wood Stresses

The clear wood stresses (S_1, S_2, S_3) associated with the MOE's (E_1, E_2, E_3) like the E_L's were obtained from tests of small clear specimens. They are, therefore, subject to the same type of error as those of the E_L's. The clear wood stresses of the broken sections of the stud were approximated by the average stresses obtained from the undamaged parts. From the parameter study earlier in the text, the clear wood stresses are critical in the determination of MOR. An increase in clear wood stresses by 50% caused an increase in MOR of the stud by 48.4%.

6.2.5. Knots

The elastic properties used for the knots could also have affected the theoretical deflection-load curve of the stud. The negligible value assigned to the elasticity properties of knots in the tension side of the stud could have decreased the MOE of the stud. The elasticity properties assigned to knots in the compression side, i.e., properties of clear wood in the tangential direction, could be too low thus decreasing the MOE of the stud. These suggest that studies on the properties of knots are necessary.

6.3. Applications of the Finite Element Model and Simulation Procedure

The finite element model and simulation procedure developed in this study could be used to determine the stiffness and strength of studs used in walls. This will make it possible to obtain a more precise information on the behavior of walls under certain loading conditions.

The theoretical method could also be used as a substitute for an actual bending test. The allowable design stresses and MOE of different lumber grades and species could be determined theoretically. This is possible for wood species in which clear wood values are available. This procedure is less expensive than the current method of actual tests.

VII. CONCLUSIONS AND RECOMMENDATIONS

The most important conclusions of this study are:

1. The finite element method is an excellent procedure to employ in the analysis of wood studs.
2. The finite element model and simulation procedure developed in this study can be used to approximate the deflection-load curves of studs.
3. An increase in the accuracy of stud properties will increase the precision of the computed deflection-load curves.
4. An increase in the MOE values alone by 25% increased the stud E_1 value by 20%; an increase in grain angles alone by 5° decreased the stud E_1 value by 12.9%; and an increase in clear wood stresses alone by 50% increased the stud MOR value by 48.4%.
5. Poisson's ratio, shear modulus and ring angle, taken singly, are not important properties affecting the accuracy of the deflection-load curve of the stud.

The recommendations of the study are:

1. Studies on the elasticity properties of knots should be done.
2. The probability distributions of wood properties should be defined.
3. Further studies should be conducted on the application of the

developed model and procedure on the determination of allowable design properties of different lumber grades and species.

4. A study should be conducted to determine the effects of combinations involving any of MOE, MOR, grain and ring angles, Poisson's ratio and shear modulus on the theoretical deflection-load curve.

BIBLIOGRAPHY

1. Amana, E. J. and L. G. Booth. Theoretical and experimental studies on nailed and glued plywood stress-skin components: Part I. Theoretical study. London. Journal of the Institute of Wood Science 4(1):43-69. 1967.

2. ______________________. Theoretical and experimental studies on nailed and glued plywood stress-skin components: Part II. London. Journal of the Institute of Wood Science 4(20): 19. 1968.

3. American Society for Testing and Materials. Annual book of ASTM standards, part 22. Philadelphia, Pa. 1975.

4. Bodig, J. and J. R. Goodman. Prediction of elastic parameters for wood. Wood Science, Vol. 5, No. 4. April, 1973.

5. Brodeau, A. Theoretical study of the flexure of prismatic wooden beams when the wood fiber is not parallel to the beam axis. Centre Technique du Bois, Paris. 1966.

6. Brown, H. P., Panshin, A. J., and C. C. Forsaith. Textbook of wood technology, Vol. II. The physical, mechanical and chemical properties of the commercial woods of the United States. McGraw-Hill, New York. 783 p. 1952.

7. Byars, E. E. and R. D. Snyder. Engineering mechanics of deformable bodies. Third Edition. Intext Educational Publishers, New York. 1975.

8. Cook, R. D. Concepts and applications of finite element analysis. John Wiley and Sons, Inc. New York. 1974.

9. __________. Improved two-dimensional finite element. Journal of the Structural Division, American Society of Civil Engineers. September, 1974.

10. Cook, R. D. and J. K. Al-Abdulla. Some plane quadrilateral 'hybrid' finite elements. American Institute of Aeronautics Journal, Vol. 7, no. 11, Nov., 1969, pp. 2184-2185.

11. Desai, C. S. and J. F. Abel. Introduction to the finite element method. Van Nostrand Reinhold Co., New York. 1972.

12. Ethington, R. L. and H. C. Hilbrand. Anisotropy in wood. American Society for Testing and Materials, Spec. Publ. No. 405, p. 21-38. 1965.

13. Felippa, C. A. Refined finite element analysis of linear and nonlinear two-dimensional structures. Ph. D. Dissertation, Department of Civil Engineering, University of California, Berkeley, 1966.

14. Fernandez, V. A. A method for approximating distributions of mechanical properties for structural lumber. M. S. thesis. Dept. of Forest Products, Oregon State University, Corvallis, June, 1975.

15. Fishman, G. S. Concepts and methods in discrete event digital simulation. John Wiley and Sons. New York. 1973.

16. Fung, Y. C. Foundations of solid mechanics. Prentice Hall, Engelwood Cliffs, N. J. 1965.

17. Gallagher, R. H. Analysis of plate and shell structures. Proceedings of the symposium on application of finite element methods in Civil Engineering. School of Engineering, Vanderbilt University, ASCE, 1969.

18. Girijavallabhan, C. V. and K. C. Mehta. Stress-strain relationship from compression tests on nonlinear materials. Proceedings of the symposium on application of finite element methods in Civil Engineering. School of Engineering, Vanderbilt University, ASCE, 1969.

19. Goodman, J. R. and J. Bodig. Orthotropic elastic properties of wood. Proceedings of National Structural Engineering Meeting, ASCE, Portland, Oregon. Journal of the Structural Division, Nov., 1970.

20. Harris, H. G. and A. B. Pifko. Elastic-plastic buckling of stiffened rectangular plates. Proceedings of the symposium on application of finite element methods in Civil Engineering. School of Engineering, Vanderbilt University, ASCE, 1969.

21. Hearmon, R. F. S. The elasticity of wood and plywood. Forest Products Research, Department of Scientific and Industrial Research, London. Special Report No. 7, 1948.

22. Hearmon, R. F. S. The theory of elasticity of orthotropic materials. Proceedings of the Conference on the Mechanical Behavior of Wood. University Extension, University of California, pp. 84-95, 1962.

23. ____________________. An introduction to applied anisotropic elasticity. Oxford University Press. 1961.

24. Herceg, E. E. Handbook of measurement and control. Schaevitz Engineering, Pennsauken, N.J. 1972.

25. Hyle, R. J., Jr. Wood technology in the design of structures. Mountain Press Publishing Company. Missoula, Montana. Oct., 1973.

26. International Conference of Building Officials. Uniform building code. Whittier, California. 1973.

27. Jayne, B. A. and S. K. Suddarth. Mechanics of fibrous orthotropic materials. Paper presented at the Fifth Pacific Area National Meeting of the American Society for Testing and Materials, Seattle, Wash., 1965.

28. Johnson, J. W. Random products method to set stresses for lumber. Report No. T-20. Oregon Forest Research Center. Feb., 1961.

29. _______________. Relationships among moduli of elasticity and rupture: seasoned and unseasoned coast-type Douglas-fir and seasoned western hemlock. Proceedings of the second symposium on Nondestructive Testing of Wood. Spokane, Wash., April, 1965.

30. Kollmann, F. The influence of temperature on some mechanical properties of wood. C.S.I.R.O., Transl. No. 2017, Melbourne, Australia. 1953.

31. Kollman, F. and W. A. Cote, Jr. Principles of wood science and technology. Vol. I. Solid wood. Springer-Verlag, New York. 592 p. 1968.

32. Liska, J. A. Research progress on the relationships between density and strength. Proc. Symp. Density, U.S. Forest Prod. Lab., Madison, Wis., p. 89-97. 1965.

33. McNeice, G. M. An elastic-plastic finite element analysis for plates with edge beams. Proceedings of the symposium on application of finite element methods in Civil Engineering. School of Engineering, Vanderbilt University, ASCE, 1969.

34. National Forest Products Association. National design specification for stressed-graded lumber and its fastenings. Washington, D.C., 1973.

35. Palka, L. C. Predicting the effect of specific gravity, moisture content, temperature and strain rate on the elastic properties of softwoods. Wood Science and Technology, Vol. 7, p. 127-141. 1973.

36. Pearson, C. E. Theoretical elasticity. Harvard University Press. Cambridge, Massachusetts. 1959.

37. Polensek, A. Finite element analysis of wood-stud walls. J. of the Structural Division (American Society of Civil Engineers) 102 (ST 7):1317-1335. 1976.

38. ____________. Rational design procedure for wood-stud walls under bending and compression loads. Wood Science 9(1):8-20. 1976.

39. ____________. Static and dynamic analysis of wood-joist floors by the finite element method. Ph.D. thesis. Dept. of Civil Engineering, Oregon State University, Corvallis. June, 1972.

40. Polensek, A. and G. H. Atherton. Compression-bending strength and stiffness of walls with Utility grade studs. Forest Products Journal, Vol. 26, No. 11, November, 1976.

41. Pritsker, A. A. B. The GASP IV simulation language. Wiley-Interscience, New York. 1974.

42. Radcliffe, B. M. A theoretical evaluation of Hankinson's formula for modulus of elasticity of wood at an angle to the grain. Quart. Bull. Mich. Agr. Exp. Sta. 48(2):286-295. 1965.

43. Rogers, G. L. Mechanics of solids. J. Wiley and Sons, Inc. New York. 1964.

44. Schniewind, A. P. Transverse anisotropy of wood. Forest Products Journal, Vol. 9, No. 10, 1959.

45. ________________. The mechanical behavior of wood. Proceedings of a conference held at the University of California, Berkeley, Aug. 27-Sept. 1, University Extension, University of California, 1962.

46. Schroeder, G. A. and G. H. Atherton. Mechanical properties of utility grade redwood two-by-four studs. Dept. of Forest Products, Oregon State University, Corvallis, May, 1973.

47. Seely, F. B. and J. O. Smith. Advanced mechanics of materials. Second Edition. J. Wiley and Sons, Inc., New York. 1952.

48. Siimes, F. E. Effect of specific gravity, moisture content, temperature and heating time on the tension and compression strength and elasticity properties perpendicular to the grain of Finnish pine, spruce and birch wood and the significance of these factors on the checking of timber at kiln drying. Finnish State Inst. Tech. Res., Publ. No. 84, Helsinki. 86 p. 1967.

49. Sliker, A. Young's modulus parallel to the grain in wood as a function of strain rate, stress level and mode of loading. Wood and Fiber, Vol. 4, no. 4, 1973.

50. Snodgrass, J. D. Statistical approach to working stresses for lumber. Journal of the Structural Division. Proceedings of the American Society of Civil Engineers. Feb, 1959.

51. Sokolnikoff, I. S. Mathematical theory of elasticity. Second Edition. McGraw-Hill Book Company, Inc., New York. 1956.

52. Sulzberger, P. H. The effect of temperature on the strength of wood, plywood and glued joints. Aeron. Res. Cons. Comm., Australia, Rep. ACA-46. 44 p. 1953.

53. Timoshenko, S. and J. M. Lessells. Applied elasticity. First Edition. Westinghouse Technical Night School Press, East Pittsburgh, Pa., 1925.

54. U.S. Forest Products Laboratory. Wood handbook: wood as an engineering material. Washington, D.C., U.S. Department of Agriculture. 1974.

55. Walker, J. Interpretation and measurement of strains in wood. Ph. D. thesis, Purdue Univ., Lafayette, Ind., 150 p. 1961.

56. West Coast Lumber Inspection Bureau. Standard grading rules for west coast lumber. 1975.

57. Whang, B. Elasto-plastic orthotropic plates and shells. Proceedings of the symposium on application of finite element methods in Civil Engineering. School of Engineering. Vanderbilt University, ASCE. 1969.

58. White, R. H. Finite element analysis of end fixity in stud wall panels. M. S. thesis, Oregon State University. 1975.

59. Wilson, E. L. Finite element analysis of two-dimensional structures. Ph. D. Dissertation, University of California, Berkeley, 1963.

60. Wood, L. W. The factor of safety in design of timber structures. Proceedings of the American Society of Civil Engineers, Paper No. 1838. Journal of the Structural Division, Vol. 84, No. ST7. Nov., 1958.

61. Ylinen, A. Comparative investigation on the influence of loading and deformation rate on the ultimate strength of wood. U. S. Forest Prod. Lab., Transl. FPL-562, Madison, Wis., 11 p. 1962.

62. Zienkiewicz, O. C. The finite element method in engineering science. London, McGraw-Hill, 1971.

APPENDICES

APPENDIX A: COMPUTER PROGRAM

A computer program written in Fortran IV language was prepared for the model and procedure described in Sections II and V. It is based on the programs reported by Zienkiewicz (62) and White (58). The program is listed at the end of this appendix. Subroutines were added to

1. Check element stresses and change, if necessary, elasticity properties of the elements,
2. Generate material properties of a hypothetical stud, and
3. Determine the finite element mesh used in the analysis.

One subroutine was modified to account for changes in elasticity properties due to grain and ring angles.

The computer program was adapted for the Oregon State University Control Data Corporation Cyber 73 computer system which has enough storage for 170 elements, 190 nodes, 10 nodal boundary conditions and 170 different materials. The maximum half-band width of the stiffness matrix is 20. It takes about 85 seconds of computer time to analyze the problem given in Appendix C and 280 seconds for the problem in Appendix G.

The program consists of the main program and 11 subroutines. More information about the program and

PLEASE NOTE:

Computer print-out on pages 89-142 is small and indistinct. Best available copy. Filmed as received.

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subroutines is shown in the numerous commentaries of the program. The program is listed as follows:

```
      PROGRAM FERN(INPUT=/80,OUTPUT,TAPE5=INPUT
     2,TAPE15,TAPE21=OUTPUT)
C
C          PLANE STRESS FINITE ELEMENT PROGRAM
C  PART OF THE PROGRAM WAS TAKEN FROM THE FINITE ELEMENT
C  METHOD IN ENGINEERING SCIENCE(1971) BY ZIENKIEWICZ, AND
C  R. WHITE'S M.S. THESIS. IT WAS MODIFIED AND EXPANDED
C  TO HANDLE STUD TESTS
C
      COMMON/DATA/TITLE(8),NP,NE,NB,NDF,NMAT,NSZF,NLD,IP
     1,CD,PINC,NMP,DMAX,NLNP,IV,I6,JSIM,NSIM
     2,ISTD,IENDD,JSTS,JENDS,EAV,ESD,AMOR,SDMOR
     3,AST2,ASPL,E12,E13,RING,ADEF,ISEED
      COMMON CORD(190,2),NOP(170,4),IMAT(170),ORT(171,7)
     1,NBC(10),NFIX(10),R1(380),SK(380,20),NODES(170)
     2,KP(170),LD(170),IK(170),EST(170,36),BDATA(170,24)
     3,R(3),ESTIFM(12,12),A(8,6),B(3,8),RS(8),SMAX(170)
     4,NQ(10),LB(170),RR(10,2),SMIN(170),ANG(170)
     5,ERAT(12,2),SPL(12),STR2(12),XMOR(12),NI(170)
     6,ST(170),IX(170),ORTHO(12,14),GR(170),STGRN(170)
     7,FORC(170,3),DISP(2,190),RAND(5),COORD(190,2)
     8,NOPP(170,4),ASMAX(170)
C
C  READ INPUT GEOMETRY AND PROP.
C
      READ(5,*)NSIM,JSIM,IP,ISEED
      DO 300 JN=1,NSIM
      CALL GDATA(JN)
      NSZF=NP*NDF
C
C  NSIM=NO. OF SPECIMENS TO BE THEORETICALLY TESTED
C  JSIM=1 IF SPECS. ARE TO BE THEORETICALLY OBTAINED
C  IP=4 IF RANGE OF KNOT DIA. (RKD)=0. TO 2.5 IN.
C    =1 IF RKD = 1.0 TO 2.5 IN.
C    =2 IF RKD= 1.5 TO 2.5 IN.
C    =3 IF RKD= 2.0 TO 2.5 IN.
C    =5 IF RKD= 0. TO 1.5 IN.
C    =6 IF RKD= 0. TO 1.0 IN.
C    =7 IF RKD= 1.0 TO 2.0 IN.
C    =8 IF RKD= 0. TO 2.0 IN.
C  IF ISEED=1,THE STARTING SEED IN RANDOM NO.
C           GENERATION IS THE SAME.
C  NSZF=NUMBER OF EQUATIONS IN THE SYSTEM
C  NLD=NUMBER OF LOAD CASES
C
      DO 200 LI=1,NLD
C
C  READ LOAD
C
      CALL LOAD(LI)
C
C  FORM,THEN SOLVE SIMULTANEOUS EQUATIONS
C
      CALL FORMK(LI)
      CALL SOLVE
C
C  CALCULATE FORCES AND STRESSES
C
      CALL STRESS(LI,JN)
      IF(ADEF.GT.CD)GO TO 300
      CALL CHECK(LI)
  200 CONTINUE
  300 CONTINUE
```

```
      STOP
      END
C
      SUBROUTINE GDATA(JN)
      COMMON/DATA/TITLE(8),NP,NE,NB,NDF,NMAT,NSZF,NLO,IP
     1,CD,PINC,NMP,DMAX,NLNP,IV,I6,JSIM,NSIM
     2,ISTO,IENOD,JSTS,JENDS,EAV,ESD,AMOR,SDMOR
     3,AST2,ASPL,E12,E13,RING,ADEF,ISEED
      COMMON CORD(190,2),NOP(170,4),IMAT(170),ORT(171,7)
     1,NBC(10),NFIX(10),RI(380),SK(380,20),NODES(170)
     2,KP(170),LD(170),IK(170),EST(170,36),BDATA(170,24)
     3,R(3),ESTIFM(12,12),A(6,6),B(3,8),RS(8),SMAX(170)
     4,NQ(10),LB(170),RR(10,2),SMIN(170),ANG(170)
     5,ERAT(12,2),SPL(12),STR2(12),XMOR(12),NI(170)
     6,ST(170),IX(170),ORTHO(12,14),GR(170),STGRN(170)
     7,FORC(170,3),DISP(2,190),RAND(5),COORD(190,2)
     8,NOPP(170,4),ASMAX(170)
      REWIND 15
C
C   READ TITLE AND CONTROL
C
      IF(JN.GT.1)GO TO 221
      READ(5,7)TITLE
    7 FORMAT(8A6)
      IF(JSIM.NE.1)GO TO 504
      READ(5,*)EAV,ESD,AMOR,SDMOR,AST2,ASPL,E12,E13
  504 READ(5,*)NP,NE,NB,NDF,NMAT,II,NMP,DMAX
     2,PINC,NLNP,NLO,ISTO,IENDO,JSTS,JENDS
      NPP=NP
      NEE=NE
      IF(JSIM.NE.1)GO TO 280
  221 CALL SIM1
  280 DO 200 I=1,NE
      LB(I)=LD(I)=IK(I)=IX(I)=0
      SMAX(I)=SMIN(I)=STGRN(I)=ST(I)=0.
      DO 200 J=1,3
      FORC(I,J)=0.
  200 CONTINUE
      DO 201 I=1,NP
      DO 201 J=1,NDF
      DISP(J,I)=0.
  201 CONTINUE
C
C   NP=NUMBER OF NODAL POINTS
C   NE=NO. OF ELEMENTS
C   NB=NUMBER OF RESTRAINED BOUNDARY NODES
C   NDF=NO. OF DEGREES OF FREEDOM PER NODE
C   NMAT=NUMBER OF ELEMENT MATERIAL TYPES
C   II= 0 IF INPUT DATA ARE TO BE PRINTED
C   PINC=LOAD INCREMENT (NEGATIVE DOWNWARD)
C   DMAX=DEFLECTION AFTER THE FIRST LOAD BEYOND WHICH
C         PROGRAM STOPS (NEGATIVE DOWNWARD).
C   NMP=NODE AT POINT WHERE DMAX IS DETERMINED
C   NLNP=NO. OF LOADED NODAL POINTS
C   ISTD=NODE NO. IN WHICH PRINTING OF DISPLACEMENTS STARTS
C   IENDO=NODE NO. IN WHICH PRINTING OF DISPLACEMENTS ENDS
C   JSTS=ELEMENT NO. IN WHICH PRINTING OF STRESSES STARTS
C   JENDS=ELEMENT NO. IN WHICH PRINTING OF STRESSES ENDS
C   EAV=AVE. CLEAR WOOD MOE OF SPECIES
C   ESD=STANDARD DEVIATION(SD) OF MOE
C   AMOR=AVE. MODULUS OF RUPTURE(MOR)
C   SDMOR=SD OF MOR
C   ASPL=AVE. STRESS AT PROPORTIONAL LIMIT
C   AST2=AVE. STRESS AT POINTS BET. MOR AND SPL(DEPENDS -
C        ON WHERE SECANT E CHANGES)
C   E12=RATIO OF AVE. E2 TO EAV
C   E13=RATIO OF AVE. E3 TO EAV
C
C        READ MATERIAL PROPERTIES
C
      IF(JSIM.NE.1)GO TO 808
      IENDO=NP
      JENDS=NE
      WRITE(21,807)JN
  807 FORMAT(//1X,"SIMULATION SPECIMEN NO.",I4)
  808 IF(II.NE.0)GO TO 28
      WRITE(21,100)TITLE
  100 FORMAT(//1X,8A6//)
      IF(JSIM.EQ.1)GO TO 150
   28 DO 30 J=1,NMAT
   30 READ(5,*)N,(ORTHO(N,I),I=1,14)
      GO TO 153
C
C   GENERATE MATERIAL PROPERTIES
C
  150 IF(ISEED.NE.1)GO TO 902
      DO 152 I=1,2
  152 RAND(I)=RANF(A)
      GO TO 904
  902 XT=RANSET(TIME(A))
      RAND(1)=RANF(B)
      XT1=RANGET(XT)
      RAND(2)=RANF(C)
  904 ORTHO(1,1)=EAV+SQRT(-2.*ESD**2*ALOG(RAND(1)))*
     2COS(2.*3.1416*RAND(2))
      N2=NE+1
      ORTHO(1,2)=ORTHO(1,1)*0.068
```

```
      ORTHO(1,3)=ORTHO(2,3)=ORT(N2,3)=0.292
      ORTHO(1,4)=ORTHO(2,4)=ORT(N2,4)=0.020
      ORTHO(1,5)=ORTHO(1,1)*0.064
      ORTHO(1,6)=ORTHO(1,1)*0.050
      ORTHO(1,7)=ORTHO(1,1)*0.078
      ORTHO(1,8)=ORTHO(1,1)*0.007
      ORTHO(1,9)=ORTHO(2,9)=0.449
      ORTHO(1,10)=ORTHO(2,10)=0.022
      ORTHO(1,11)=ORTHO(2,11)=0.390
      ORTHO(1,12)=ORTHO(2,12)=0.287
      ORTHO(1,13)=ORTHO(1,1)*E12
      ORTHO(1,14)=ORTHO(1,1)*E13
      ORT(N2,1)=ORTHO(2,1)=1000.
      ORT(N2,2)=ORTHO(2,2)=68.
      ORT(N2,5)=ORTHO(2,5)=64.
      ORTHO(2,6)=50.
      ORTHO(2,7)=78.
      ORTHO(2,8)=7.
      ORTHO(2,13)=700.
      ORTHO(2,14)=500.
      GO TO 222
C
C       N2=NE+1
C
  153 READ(5,*)N2,(ORT(N2,I),I=1,5)
  222 DO 61 J=1,NMAT
      ERAT(J,1)=ORTHO(J,13)/ORTHO(J,1)
   61 ERAT(J,2)=ORTHO(J,14)/ORTHO(J,1)
      IF(JSIM.EQ.1)GO TO 223
C
C  READ STRESSES
C
      DO 31 I=1,NMAT
   31 READ(5,*)N,SPL(I),STR2(I),XMOR(I)
      GO TO 260
  223 IF(ISEED.NE.1)GO TO 906
      DO 224 J=1,2
  224 RAND(J)=RANF(A)
      GO TO 908
  906 XT=RANSET(TIME(A))
      RAND(1)=RANF(B)
      XT1=RANGET(XT)
      RAND(2)=RANF(C)
  908 XMOR(1)=AMOR+SQRT(-2.*SDMOR**2*ALOG(RAND(1)))*
     2COS(2.*3.1416*RAND(2))
      STR2(1)=XMOR(1)*AST2/AMOR
      SPL(1)=XMOR(1)*ASPL/AMOR
      XMOR(2)=3000.
      STR2(2)=2000.
      SPL(2)=1000.
C
C  N=MATERIAL NUMBER
C  ORTHO(N,1)=MODULUS OF ELASTICITY (MOE) IN L-DIRECTION
C  ORTHO(N,2)=MOE IN R-DIRECTION
C  ORTHO(N,3)=POISSON RATIO (LR)
C  ORTHO(N,4)=POISSON RATIO (RL)
C  ORTHO(N,5)=MODULUS OF RIGIDITY (RL)
C  ORTHO(N,6)=MOE IN T-DIRECTION
C  ORTHO(N,7)=MODULUS OF RIGIDITY (LT)
C  ORTHO(N,8)=MODULUS OF RIGIDITY (TR)
C  ORTHO(N,9)=POISSON RATIO (LT)
C  ORTHO(N,10)=POISSON RATIO (TL)
C  ORTHO(N,11)=POISSON RATIO (RT)
C  ORTHO(N,12)=POISSON RATIO (TR)
C  ORTHO(N,13)=E2
C  ORTHO(N,14)=E3
C
C  READ NODAL POINT DATA
C  N=NODAL POINT(NO)
C  COORD(N,1)=NO X-COORDINATE
C  COORD(N,2)=NO Y-COORDINATE
C
      IF(JN.GT.1)GO TO 225
  260 DO 40 J=1,NPP
   40 READ(5,*)N,(COORD(N,M),M=1,2)
C
C  READ ELEMENT DATA
C  N=ELEMENT NO.
C  NOPP(N,1)=NUMBER OF THE ELEMENT NODE I
C  NOPP(N,2)=NUMBER OF THE ELEMENT NODE J
C  NOPP(N,3)=NUMBER OF THE ELEMENT NODE K
C  NOPP(N,4)=NUMBER OF THE ELEMENT NODE L
C  IMAT(N)=ELEMENT MATERIAL TYPE. (EQUAL TO ELEMENT NO.)
C  NODES(N)=NUMBER OF NODES IN ELEMENT N
C  NI(N)=NUMBER OF LOCAL MATERIAL PROPERTY OF ELEMENT
C
      IF(JSIM.EQ.1)GO TO 52
      DO 50 J=1,NEE
   50 READ(5,*)N,(NOPP(N,M),M=1,4),NODES(N),IMAT(N),NI(N)
      GO TO 51
   52 DO 53 J=1,NEE
   53 READ(5,*)N,(NOPP(N,M),M=1,4)
   51 IF(JSIM.EQ.1)GO TO 225
      DO 227 K=1,NP
      DO 227 L=1,2
  227 CORD(K,L)=COORD(K,L)
      DO 270 N=1,NE
      DO 270 M=1,4
```

```
 270  NOP(N,M)=NOPP(N,M)
      GO TO 251
 225  DO 824 I=1,NE
      NI(I)=1
 824  IMAT(I)=I
      CALL SIM2
      CALL SIM4
 251  DO 252 J=1,NE
      NF=NI(J)
      ORT(J,6)=ORTHO(NF,13)
      ORT(J,7)=ORTHO(NF,14)
 252  CONTINUE
      IF(I1.NE.0)GO TO 41
      WRITE(21,311)
 311  FORMAT(//1X,"ELEMENT",5X,"GRAIN ANGLE",5X,
     2"RING ANGLE"//)
  41  DO 33 J=1,NE
C
C  IF NSGR IS NOT EQUAL TO ZERO, IT IS THE NO.
C  OF ELEMENT WITH SAME ANGLES AND MECH. PROP.
C  AS THE CURRENT ELEMENT
C
      IF(JSIM.EQ.1)GO TO 49
      READ(5,*)N,NSGR
      IF(NSGR.NE.0)GO TO 45
      READ(5,*)GR(J),RING
  45  IF(I1.NE.0)GO TO 29
      IF(NSGR.NE.0)GO TO 46
      WRITE(21,312)N,GR(J),RING
      GO TO 29
  46  WRITE(21,313)N,NSGR
 313  FORMAT(3X,I3,1X,I6)
 312  FORMAT(3X,I3,10X,F5.2,11X,F5.2)
  29  IF(NSGR.EQ.0)GO TO 42
      GR(J)=GR(NSGR)
      ORT(J,1)=ORT(NSGR,1)
      ORT(J,2)=ORT(NSGR,2)
      ORT(J,3)=ORT(NSGR,3)
      ORT(J,4)=ORT(NSGR,4)
      ORT(J,5)=ORT(NSGR,5)
      GO TO 33
C
C       N=ELEMENT NO.
C       GR=GRAIN ANGLE
C       RING = RING ANGLE
C
C
C              Y(R)    ..........
C               .    .        ..
C               .   .        . .
C               .  .        . /.
C               . .        . / .            G=GRAIN ANGLE
C               ..        . / /.            R=RING ANGLE
C               ......... G=0 .
C               . - - - ./ / .
C               . - - - . / .
C               .  R=0  ./ .
C               . - - - . .
C               . - - - ..
C               ................ Z(T)
C              .
C             .
C            .
C           .
C          X(L)
C
C
  49  IF(JSIM.NE.1)GO TO 42
      IF(I1.NE.0)GO TO 42
      WRITE(21,312)J,GR(J),RING
  42  GG=GR(J)*0.0174533
      RM=RING*0.0174533
      CG=(COS(GG))**2
      SG=(SIN(GG))**2
      CR=(COS(RM))**2
      SR=(SIN(RM))**2
      NT=NI(J)
      EL=ORTHO(NT,1)/100000.
      ER=ORTHO(NT,2)/100000.
      ULR=ORTHO(NT,3)
      URL=ORTHO(NT,4)
      GRL=ORTHO(NT,5)/100000.
      ET=ORTHO(NT,6)/100000.
      GLT=ORTHO(NT,7)/100000.
      GTR=ORTHO(NT,8)/100000.
      ULT=ORTHO(NT,9)
      UTL=ORTHO(NT,10)
      URT=ORTHO(NT,11)
      UTR=ORTHO(NT,12)
      S11=(CG**2)/EL+(SG**2)/ER+SG*CG*(1./GRL-2.*ULR/EL)
      S13=SG*CR*(CG/EL-(URL*SG-CG)/ER-CG/GRL)-(CG/EL)*
     2(ULT*SR+ULR*CG*CR)-URT*SG*SR/ER
      S33=(SG*CR)**2/EL+SR**2/ET+SR*SG*CR*(1./GLT-2.*ULT
     2/EL)+CR*CG*(CR*CG/ER-2.*ULR*CR*SG/EL-2.*UTR*SR/ET
     3+SR/GTR+SG/GRL)
```

```
      S55=4.*CG*CR*SG*((1.+2.*ULR)/EL+1./ER)+SR*(SG/GTR+
     2CG/GLT)+(CR/GRL)*(CG-SG)**2
      ORT(J,1)=100000./S11
      ORT(J,2)=100000./S33
      ORT(J,3)=(-1)*ORT(J,1)*S13/100000.
      ORT(J,4)=(-1)*ORT(J,2)*S13/100000.
      ORT(J,5)=100000./S55
   33 CONTINUE
C
C     READ BOUNDARY CONDITIONS
C     NBC=RESTRAINED BOUNDARY NODE NO.
C     NFIX(I)=BOUNDARY CONDITION TYPE
C     NFIX= 01 - FIXED IN Y-DIRECTION
C     NFIX = 10 - FIXED IN X-DIRECTION
C     NFIX = 11 - FIXED IN BOTH X AND Y DIRECTIONS
C
      IF(JSIM.NE.1)GO TO 99
      NFIX(1)=11
      NFIX(2)=1
      R(1)=0.0
      R(2)=PINC
      IF(I6.GT.1)GO TO 91
      NQ(1)=84
      NQ(2)=144
      NBC(1)=8
   97 NBC(2)=184
      GO TO 90
   91 NBC(1)=3
      IF(I6.GT.11)GO TO 92
      NQ(1)=89
      NQ(2)=149
   98 NBC(2)=189
      GO TO 90
   92 IF(I6.GT.12)GO TO 93
      NQ(1)=79
      NQ(2)=147
   96 NBC(2)=187
      GO TO 90
   93 IF(I6.GT.13)GO TO 85
      NQ(1)=42
      NQ(2)=145
   87 NBC(2)=185
      GO TO 90
   85 NQ(1)=37
      IF(I6.GT.23)GO TO 86
      NQ(2)=145
      GO TO 87
   86 IF(I6.GT.24)GO TO 94
      NQ(2)=137
      GO TO 87
   94 IF(I6.GT.25)GO TO 95
      NQ(2)=102
      GO TO 96
   95 NQ(2)=97
      IF(I6.GT.35)GO TO 97
      GO TO 98
   99 READ(5,*)(NBC(I),NFIX(I),I=1,NB)
      DO 209 I=1,NLNP
  209 READ(5,*)NQ(I),(R(K),K=1,NDF)
   90 WRITE(15)(NBC(I),NFIX(I),I=1,NB)
      IF(I1.NE.0)GO TO 500
C
C       PRINT INPUT DATA
C
      WRITE(21,108)
      WRITE(21,8)(N,(ORT(N,I),I=1,5),N=1,NE)
      WRITE(21,80)
   80 FORMAT(//1X,"ELEMENT",3X,"SPL",5X,"STR2",4X,"MOR",
     26X,"E2",8X,"E3"//)
      DO 81 I=1,NE
      N=NI(I)
   81 WRITE(21,82)I,SPL(N),STR2(N),XMOR(N),ORT(I,6),
     2ORT(I,7)
   82 FORMAT(3X,I3,2X,3(2X,F6.0),2(2X,F8.0))
      WRITE(21,102)
      WRITE(21,2)(N,(CORD(N,M),M=1,2),N=1,NP)
      WRITE(21,103)
      WRITE(21,3)(N,(NOP(N,M),M=1,4),NODES(N),IMAT(N),NI(N),
     2N=1,NE)
      WRITE(21,104)
      WRITE(21,6)(NBC(I),NFIX(I),I=1,NB)
  500 CONTINUE
      WRITE(21,100)TITLE
      WRITE(21,109)
      WRITE(21,110)
      DO 208 I=1,NLNP
  208 WRITE(21,9)NQ(I),(R(K),K=1,NDF)
    9 FORMAT(I5,2F10.2)
  109 FORMAT(2X,"LOADS"/)
  110 FORMAT(2X,"NODE",7X,"X",7X,"Y")
    2 FORMAT(I5,2F10.5)
    3 FORMAT(8I5)
    6 FORMAT(I5,I8)
    8 FORMAT(I5,2F13.2,2F9.5,F13.2)
  102 FORMAT(//"  NODAL POINTS COORDINATES"//)
  103 FORMAT(//"  ELEMENTS"//)
  104 FORMAT(//" BOUNDARY CONDITIONS"//)
  108 FORMAT(//"  MATERIAL PROPERTIES"//)
      RETURN
```

```
      END
C
      SUBROUTINE SIM1
C
C  GENERATES VALUES FOR NP, NE AND NMP
C
      COMMON/DATA/TITLE(8),NP,NE,NB,NDF,NMAT,NSZF,NLD,IP
     1,CD,PINC,NMP,DMAX,NLNP,IV,I6,JSIM,NSIM
     2,ISTD,IENDD,JSTS,JENDS,EAV,ESD,AMOR,SDMOR
     3,AST2,ASPL,E12,E13,RING,ADEF,ISEED
      COMMON CORD(190,2),NOP(170,4),IMAT(170),ORT(171,7)
     1,NBC(10),NFIX(10),R1(380),SK(380,20),NODES(170)
     2,KP(170),LD(170),IK(170),EST(170,36),BDATA(170,24)
     3,R(3),ESTIFM(12,12),A(8,6),B(3,8),RS(8),SMAX(170)
     4,NQ(10),LB(170),RR(10,2),SMIN(170),ANG(170)
     5,ERAT(12,2),SPL(12),STR2(12),XMOR(12),NI(170)
     6,ST(170),IX(170),ORTHO(12,14),GR(170),STGRN(170)
     7,FORC(170,3),DISP(2,190),RAND(5),COORD(190,2)
     8,NOPP(170,4),ASMAX(170)
      IF(ISEED.NE.1)GO TO 201
      VX=RANF(A)
      GO TO 200
201   XT=RANSET(TIME(A))
      VX=RANF(B)
      XT1=RANGET(XT)
200   IV=VX*10000
156   IF(IV.LT.1261)GO TO 155
      IV=IV-1260
      GO TO 156
155   I6=(IV+34)/35
      IF(I6.GT.1)GO TO 157
      NP=184
      NE=152
      NMP=114
      GO TO 151
157   IF(I6.GT.11)GO TO 167
      NP=189
      NMP=119
      IF(I6.GT.10)GO TO 158
      NE=167
      GO TO 151
158   NE=165
      GO TO 151
167   IF(I6.GT.12)GO TO 168
      NP=187
      NE=163
      NMP=117
      GO TO 151
168   IF(I6.GT.13)GO TO 169
      NP=185
      NE=161
      NMP=115
      GO TO 151
169   IF(I6.GT.19)GO TO 173
      NP=185
      NE=165
      IF(I6.GT.16)GO TO 170
      NMP=115
      GO TO 151
170   IF(I6.GT.17)GO TO 174
      NMP=115
      GO TO 151
174   IF(I6.GT.18)GO TO 175
      NMP=107
      GO TO 151
175   NMP=72
      GO TO 151
173   NMP=67
      IF(I6.GT.24)GO TO 180
      NP=185
      IF(I6.GT.23)GO TO 176
      NE=165
      GO TO 151
176   NE=161
      GO TO 151
180   IF(I6.GT.25)GO TO 181
      NP=187
      NE=163
      GO TO 151
181   IF(I6.GT.35)GO TO 183
      NP=189
      IF(I6.GT.26)GO TO 182
      NE=165
      GO TO 151
182   NE=167
      GO TO 151
183   NP=184
      NE=152
151   RETURN
      END
C
      SUBROUTINE SIM2
C
C  GENERATES NODAL COORDINATES AND ELEMENT NODE NOS.
C
      COMMON/DATA/TITLE(8),NP,NE,NB,NDF,NMAT,NSZF,NLD,IP
     1,CD,PINC,NMP,DMAX,NLNP,IV,I6,JSIM,NSIM
```

```
      2,ISTD,IENOD,JSTS,JENOS,EAV,ESD,AMOR,SDMOR
      3,AST2,ASPL,E12,E13,RING,ADEF,ISEED
       COMMON CORD(190,2),NOP(170,4),IMAT(170),ORT(171,7)
      1,NBC(10),NFIX(10),RI(380),SK(380,23),NODES(170)
      2,KP(170),LD(170),IK(170),EST(170,36),BDATA(170,24)
      3,R(3),ESTIFM(12,12),A(8,6),B(3,8),RS(8),SMAX(170)
      4,NQ(10),LB(170),RR(10,2),SMIN(170),ANG(170)
      5,ERAT(12,2),SPL(12),STR2(12),XMOR(12),NI(170)
      6,ST(170),IX(170),ORTHO(12,14),GR(170),STGRN(170)
      7,FORC(170,3),DISP(2,190),RAND(5),COORD(190,2)
      8,NOPP(170,4),ASMAX(170)
       DIMENSION COOR(5)
       COOR(1)=3.5
       COOR(2)=2.5
       COOR(3)=1.75
       COOR(4)=1.
       COOR(5)=0.
       IF(I6.GT.1)GO TO 228
       B1=-0.5
       M9=M7=0
       IM=6
       GO TO 291
  228  IF(I6.GT.10)GO TO 235
       IM=6
       M7=3+3*(I6-2)
  239  DO 245 I=1,M7
       CORD(I,1)=COORD(I,1)
  245  CORD(I,2)=COORD(I,2)
       DO 250 I=1,5
       M8=M7+I
       CORD(M8,1)=CORD(M7,1)+1.25
  250  CORD(M8,2)=COOR(I)
       M9=M7+5
       B1=CORD(M8,1)+0.75
  291  DO 251 I=1,6
       B1=B1+0.5
       B2=4.
       DO 251 J=1,8
       B2=B2-0.5
       M9=M9+1
       CORD(M9,1)=B1
  251  CORD(M9,2)=B2
       IF(I6.EQ.36)GO TO 290
       DO 252 I=1,5
       N1=M9+I
       CORD(N1,1)=CORD(M9,1)+1.25
  252  CORD(N1,2)=COOR(I)
       N2=137-M7-IM
       DO 260 I=1,N2
       N3=N1+I
       N4=M7+IM+I
       CORD(N3,1)=COORD(N4,1)
  260  CORD(N3,2)=COORD(N4,2)
       GO TO 290
  235  IF(I6.GT.13)GO TO 261
       M7=30+3*(I6-11)
       IM=6+2*(I6-11)
       GO TO 239
  261  IF(I6.GT.23)GO TO 265
       IM=10
       M7=41+5*(I6-14)
       GO TO 239
  265  IF(I6.GT.26)GO TO 275
       M7=91+5*(I6-24)
       IM=10-2*(I6-24)
       GO TO 239
  275  IM=6
       M7=104+3*(I6-27)
       GO TO 239
  290  IX=0
       IF(I6.GT.1)GO TO 108
       J5=0
       J2=-8
       GO TO 106
  108  IF(I6.GT.2)GO TO 112
       KA=1
       IG=J2=MQ=MN=0
       J5=IH=17
       GO TO 124
  112  LK=1
       LC=LT=0
       IF(I6.GT.13)GO TO 320
       MQ=MN=0
       LX=2+2*(I6-3)
       IH=J5=LX+17
       IG=J2=3+3*(I6-3)
       GO TO 322
  320  IF(I6.GT.26)GO TO 324
       MQ=1
       LX=28+4*(I6-14)
       IH=J5=LX+19
       IG=36+5*(I6-14)
       J2=IG+2
       GO TO 322
  324  MN=MQ=0
       LX=82+2*(I6-27)
       IH=J5=LX+17
       IG=J2=101+3*(I6-27)
```

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322   KA=LX+1
      GO TO 302
124   KB=KA+1
      KC=KA+2
      KD=KA+3
      KE=KA+4
      KF=KA+5
      KG=KA+6
      KH=KA+7
      KI=KA+8
      KJ=KA+9
      KK=KA+10
      KL=KA+11
      KM=KA+12
      KN=KA+13
      KO=KA+14
      KP=KA+15
      KQ=KA+16
      KR=KA+17
      KS=KA+13
      IF(MQ.EQ.1)GO TO 356
      IF(MN.EQ.1)GO TO 340
      IF(IX.EQ.1)GO TO 130
      NOP(KA,1)=NOP(KB,1)=1+IG
      NOP(KA,2)=NOP(KB,3)=NOP(KC,3)=NOP(KH,2)=NOP(KI,1)
     2=NOP(KJ,1)=NOP(KK,1)=5+IG
      NOP(KA,3)=NOP(KG,1)=NOP(KH,1)=4+IG
      NOP(KB,2)=NOP(KC,1)=NOP(KD,1)=NOP(KE,1)=2+IG
      NOP(KC,2)=NOP(KD,3)=NOP(KK,2)=NOP(KL,1)=NOP(KM,1)
     2=6+IG
      NOP(KD,2)=NOP(KE,3)=NOP(KF,3)=NOP(KM,2)=NOP(KN,1)
     2=NOP(KO,1)=NOP(KP,1)=7+IG
      NOP(KE,2)=NOP(KF,1)=3+IG
      NOP(KF,2)=NOP(KP,2)=NOP(KQ,1)=8+IG
      NOP(KG,2)=NOP(KH,3)=NOP(KI,3)=10+IG
      NOP(KG,3)=9+IG
      NOP(KI,2)=NOP(KJ,3)=11+IG
      NOP(KJ,2)=NOP(KK,3)=NOP(KL,3)=12+IG
      NOP(KL,2)=NOP(KM,3)=NOP(KN,3)=13+IG
      NOP(KN,2)=NOP(KO,3)=14+IG
      NOP(KO,2)=NOP(KP,3)=NOP(KQ,3)=15+IG
      NOP(KQ,2)=16+IG
800   DO 102 I=KA,IH
      NOP(I,4)=0
102   NODES(I)=3
106   DO 104 I=1,5
      J2=J2+8
      DO 104 J=1,7
      J5=J5+1
      J1=J+J2
      NOP(J5,1)=J1+1
      NOP(J5,2)=J1+9
      NOP(J5,3)=J1+8
      NOP(J5,4)=J1
104   NODES(J5)=4
      IX=1
      IF(I6.EQ.36)GO TO 700
      LX=104
      IF(I6.GT.1)GO TO 400
      LT=47
      IG=40
      IH=LC=52
      LK=5
      KA=36
      MN=MQ=0
      GO TO 124
400   IF(I6.GT.13)GO TO 402
      LT=52
      IF(I6.GT.10)GO TO 404
      KA=53+2*(I6-2)
      IH=LC=KA+16
      LK=KA-46
      IG=48+3*(I6-2)
      GO TO 124
404   MN=1
      KA=71+2*(I6-11)
      IH=LC=KA+18
      LK=29+4*(I6-11)
      IG=75+3*(I6-11)
      GO TO 124
402   IF(I6.GT.26)GO TO 406
      MN=1
      KA=83+4*(I6-14)
      IH=LC=KA+18
      IG=86+5*(I6-14)
      IF(I6.GT.23)GO TO 408
      LK=41+4*(I6-14)
      GO TO 413
408   MN=MQ=0
      LK=83+2*(I6-24)
413   IF(I6.GT.24)GO TO 411
      LT=48
      GO TO 124
411   IF(I6.GT.25)GO TO 412
      LT=50
      GO TO 124
412   LT=52
      GO TO 124
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406   KA=135+2*(IG-27)
      IH=LC=KA+16
      LI=52
      LK=83+2*(IG-24)
      IG=149+3*(IG-27)
      GO TO 124
133   NOP(KA,1)=1+IG
      NOP(KA,2)=NOP(KB,1)=NOP(KC,1)=2+IG
      NOP(KA,3)=NOP(KB,3)=NOP(KL,1)=9+IG
      NOP(KB,2)=NOP(KC,3)=NOP(KD,3)=NOP(KF,3)=NOP(KL,2)
     2=NOP(KM,1)=NOP(KN,1)=10+IG
      NOP(KC,2)=NOP(KD,1)=3+IG
      NOP(KD,2)=NOP(KE,1)=NOP(KF,1)=4+IG
      NOP(KE,2)=NOP(KF,3)=NOP(KG,3)=NOP(KN,2)=NOP(KO,1)
     2=11+IG
      NOP(KF,2)=NOP(KG,1)=NOP(KH,1)=5+IG
      NOP(KG,2)=NOP(KH,3)=NOP(KI,3)=NOP(KJ,3)=NOP(KO,2)
     2=NOP(KP,1)=NOP(KQ,1)=12+IG
      NOP(KH,2)=NOP(KI,1)=6+IG
      NOP(KI,2)=NOP(KJ,1)=NOP(KK,1)=7+IG
      NOP(KJ,2)=NOP(KK,3)=NOP(KQ,2)=13+IG
      NOP(KK,2)=8+IG
      NOP(KL,3)=NOP(KM,3)=14+IG
      NOP(KM,2)=NOP(KN,3)=NOP(KO,3)=NOP(KP,3)=15+IG
      NOP(KP,2)=NOP(KQ,3)=16+IG
      DO 132 I=KA,IH
      NOP(I,4)=0
132   NODES(I)=3
      GO TO 302
300   NOP(KA,1)=1+IG
      NOP(KA,2)=NOP(KB,1)=NOP(KC,1)=2+IG
      NOP(KA,3)=NOP(KB,3)=NOP(KL,1)=NOP(KM,1)=9+IG
      NOP(KB,2)=NOP(KC,3)=NOP(KD,3)=NOP(KE,3)=NOP(KM,2)
     2=NOP(KN,1)=NOP(KO,1)=10+IG
      NOP(KC,2)=NOP(KD,1)=3+IG
      NOP(KD,2)=NOP(KE,1)=NOP(KF,1)=4+IG
      NOP(KE,2)=NOP(KF,3)=NOP(KG,3)=NOP(KO,2)=NOP(KP,1)
     2=11+IG
      NOP(KF,2)=NOP(KG,1)=NOP(KH,1)=5+IG
      NOP(KG,2)=NOP(KH,3)=NOP(KI,3)=NOP(KJ,3)=NOP(KP,2)
     2=NOP(KQ,1)=NOP(KR,1)=12+IG
      NOP(KH,2)=NOP(KI,1)=6+IG
      NOP(KI,2)=NOP(KJ,1)=NOP(KK,1)=7+IG
      NOP(KJ,2)=NOP(KK,3)=NOP(KR,2)=NOP(KS,1)=13+IG
      NOP(KK,2)=8+IG
      NOP(KL,2)=NOP(KM,3)=NOP(KN,3)=15+IG
      NOP(KL,3)=14+IG
      NOP(KN,2)=NOP(KO,3)=NOP(KP,3)=NOP(KQ,3)=16+IG
      NOP(KQ,2)=NOP(KR,3)=NOP(KS,3)=17+IG
      NOP(KS,2)=18+IG
      DO 348 I=KA,IH
      NOP(I,4)=0
348   NODES(I)=3
      GO TO 302
356   NOP(KA,1)=1+IG
      NOP(KA,2)=NOP(KB,1)=NOP(KC,1)=2+IG
      NOP(KA,3)=NOP(KB,3)=NOP(KI,1)=NOP(KJ,1)=6+IG
      NOP(KB,2)=NOP(KC,3)=NOP(KD,3)=NOP(KJ,2)=NOP(KK,1)
     2=NOP(KL,1)=NOP(KM,1)=7+IG
      NOP(KC,2)=NOP(KD,1)=NOP(KE,1)=NOP(KF,1)=3+IG
      NOP(KD,2)=NOP(KE,3)=NOP(KM,2)=NOP(KN,1)=NOP(KO,1)
     2=8+IG
      NOP(KE,2)=NOP(KF,3)=NOP(KG,3)=NOP(KO,2)=NOP(KP,1)
     2=NOP(KQ,1)=NOP(KR,1)=9+IG
      NOP(KF,2)=NOP(KG,1)=NOP(KH,1)=4+IG
      NOP(KG,2)=NOP(KH,3)=NOP(KR,2)=NOP(KS,1)=10+IG
      NOP(KH,2)=5+IG
      NOP(KI,2)=NOP(KJ,3)=NOP(KK,3)=12+IG
      NOP(KI,3)=11+IG
      NOP(KK,2)=NOP(KL,3)=13+IG
      NOP(KL,2)=NOP(KM,3)=NOP(KN,3)=14+IG
      NOP(KN,2)=NOP(KO,3)=NOP(KP,3)=15+IG
      NOP(KP,2)=NOP(KQ,3)=16+IG
      NOP(KQ,2)=NOP(KR,3)=NOP(KS,3)=17+IG
      NOP(KS,2)=18+IG
      DO 360 I=KA,IH
      NOP(I,4)=0
360   NODES(I)=3
      MQ=0
      GO TO 106
302   DO 150 I=LK,LX
      LC=LC+1
      NOP(LC,1)=NOPP(I,1)+LT
      NOP(LC,2)=NOPP(I,2)+LT
      NOP(LC,3)=NOPP(I,3)+LT
      IF(NOPP(I,4).EQ.0)GO TO 151
      NOP(LC,4)=NOPP(I,4)+LT
      NODES(LC)=4
      GO TO 150
151   NOP(LC,4)=0
      NODES(LC)=3
150   CONTINUE
      IF(IX.EQ.0)GO TO 124
700   RETURN
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      END
C
      SUBROUTINE SIM4
C
C  GENERATES KNOT DIA., GRAIN AND RING ANGLES FOR EACH
C  ELEMENT AND DETERMINES WHAT MATERIAL PROPERTIES ARE
C  TO BE USED BY EACH ELEMENT
C
      COMMON/DATA/TITLE(8),NP,NE,NB,NDF,NMAT,NSZF,NLD,IP
     1,CD,PINC,NMP,LMAX,NLNP,IV,I6,JSIM,NSIM
     2,ISTD,IENDL,JSTS,JENDS,FAV,ESD,AMOR,SDMOR
     3,AST2,ASPL,F12,F13,RING,ADEF,ISEEL
      COMMON CORD(190,2),NOP(170,4),IMAT(170),ORT(171,7)
     1,NBC(10),NFIX(10),R1(380),SK(380,20),NODES(170)
     2,KP(170),LL(170),IR(170),EST(170,36),PDATA(170,24)
     3,R(3),ESTIFF(12,12),A(8,6),B(3,8),RS(8),SMAX(170)
     4,NQ(10),LP(170),RR(10,2),SMIN(170),ANG(170)
     5,ERAT(12,2),SPL(12),STR2(12),XMOR(12),NI(170)
     6,ST(170),IX(170),ORTHO(12,14),GR(170),STGRN(170)
     7,FORC(170,3),DISP(2,190),RAND(5),COORD(190,2)
     8,NOPP(170,4),ASMAX(170)
108   IF(ISEED.NE.1)GO TO 920
      DO 100 I=1,2
100   RAND(I)=RANF(A)
      GO TO 921
920   XT=RANSET(TIME(A))
      RAND(1)=RANF(B)
      XTI=RANGET(XT)
      RAND(2)=RANF(C)
921   DKNT=RAND(1)*10.
931   IF(DKNT.GT.2.75)GO TO 930
      GO TO 932
930   DKNT=DKNT-2.75
      GO TO 931
932   RING=RAND(1)*100.
      IF(RING.GT.90.)GO TO 101
      GO TO 102
101   RING=RING-90.
102   GRN=RAND(2)*100.
937   IF(GRN.GT.14.0)GO TO 935
      GO TO 936
935   GRN=GRN-14.
      GO TO 937
936   DO 110 I=1,NE
110   GR(I)=GRN
      IF(DKNT.GT.0.25)GO TO 115
      GO TO 3
115   IF(DKNT.GT.0.75)GO TO 120
      IF(IP.LT.4.OR.IP.EQ.7)GO TO 108
      JA=IV
130   IF(JA.LT.36)GO TO 125
      JA=JA-35
      GO TO 130
125   JB=JA
140   IF(JB.LT.8)GO TO 135
      JB=JB-7
      GO TO 140
135   IF(I6.GT.1)GO TO 145
320   NI(IV)=2
      IF(JB.GT.1)GO TO 155
160   IF(JB.EQ.7)GO TO 165
      GR(IV+1)=GRN+10.
      IF(JA.GT.28)GO TO 165
      GR(IV+8)=GRN+5.
165   IF(JA.EQ.35)GO TO 220
      IF(I6.EQ.36)GO TO 185
      GR(IV+7)=GRN+15.
      IF(JA.EQ.28)GO TO 220
      IF(JA.GT.22)GO TO 185
      IF(I6.EQ.36)GO TO 420
      GR(IV+14)=GRN+5.
420   IF(JA.LT.8)GO TO 3
      IF(JB.EQ.7)GO TO 220
185   GR(IV-6)=GRN+5.
220   GR(IV-7)=GRN+15.
      IF(JA.LT.15)GO TO 3
      GR(IV-14)=GRN+5.
      IF(JA.EQ.29)GO TO 180
      GO TO 3
180   IF(I6.EQ.36)GO TO 3
      GR(IV+9)=GRN+5.
      GO TO 3
155   GR(IV-1)=GRN+10.
      IF(JA.EQ.35.OR.I6.EQ.36)GO TO 255
      GR(IV+6)=GRN+5.
      IF(JA.LT.8)GO TO 160
255   GR(IV-8)=GRN+5.
      IF(JA.LT.22.OR.I6.EQ.36)GO TO 160
      IF(JA.GT.28)GO TO 195
      IF(JB.GT.3)GO TO 190
      GR(IV+15)=GRN+5.
      GO TO 160
190   IF(JB.GT.4)GO TO 200
      IF(I6.EQ.36)GO TO 160
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      GR(IV+16)=GRN+5.
      GO TO 160
200   IF(JB.EQ.7)GO TO 215
      IF(JB.EQ.36)GO TO 160
      GR(IV+17)=GRN+5.
      GO TO 160
195   IF(JB.GT.3)GO TO 205
      IF(IG.EQ.36)GO TO 160
      GR(IV+8)=GRN+10.
      GO TO 160
205   IF(JB.GT.4)GO TO 210
      IF(IG.EQ.36)GO TO 160
      GR(IV+9)=GRN+10.
      GO TO 160
210   IF(IG.EQ.36)GO TO 160
      GR(IV+10)=GRN+10.
      IF(JA.EQ.35)GO TO 250
      GO TO 160
250   GR(IV+11)=GRN+15.
      GO TO 160
215   IF(IG.EQ.36)GO TO 160
      GR(IV+18)=GRN+5.
      GO TO 160
145   IF(IG.GT.13)GO TO 300
      IV=(IG-2)*2+JA+17
405   IF(JA.GT.7)GO TO 370
      IF(JB.EQ.4)GO TO 305
      GR(IV-9)=GRN+5.
      GO TO 345
305   GR(IV-9)=GRN+15.
345   IF(JB.GT.1)GO TO 310
      GR(IV-11)=GRN+15.
      GR(IV-10)=GRN+5.
      GO TO 320
310   IF(JB.GT.3)GO TO 315
      GR(IV-10)=GRN+15.
      IF(JB.EQ.3)GO TO 350
      GR(IV-12)=GRN+5.
350   GR(IV-11)=GRN+5.
      IF(JB.EQ.2)GO TO 320
360   GR(IV-8)=GRN+5.
      GO TO 320
315   IF(JB.GT.5)GO TO 325
      GR(IV-7)=GR(IV-10)=GRN+5.
      IF(JB.EQ.5)GO TO 330
      GR(IV-11)=GRN+5.
      IF(JB.GT.4)GO TO 330
      GO TO 360
325   IF(JB.GT.6)GO TO 335
      GR(IV-7)=GR(IV-6)=GRN+5.
330   GR(IV-8)=GRN+15.
      GO TO 320
335   GR(IV-7)=GRN+15.
      GO TO 360
370   IF(JA.GT.14)GO TO 320
      IF(JB.GT.1)GO TO 375
      GR(IV-18)=GRN+5.
      GO TO 320
375   IF(JB.GT.3)GO TO 380
      GR(IV-17)=GRN+5.
      GO TO 320
380   IF(JB.GT.4)GO TO 385
      GR(IV-16)=GRN+5.
      GO TO 320
385   IF(JB.GT.6)GO TO 390
      GR(IV-15)=GRN+5.
      GO TO 320
390   GR(IV-14)=GRN+5.
      GO TO 320
300   IF(IG.GT.26)GO TO 400
      IV=(IG-12)*4+JA+47
      GO TO 405
400   IV=(IG-27)*2+JA+99
      GO TO 405
120   IF(DKNT.GT.1.25)GO TO 450
      IF(IP.LT.4)GO TO 108
      IF(IP.GT.1)GO TO 108
      IF(IG.GT.1)GO TO 455
      IF(JB.GT.2)GO TO 474
      IF(JA.GT.9)GO TO 475
      IV=JA-1
460   NI(IV)=NI(IV+1)=NI(IV+7)=NI(IV+8)=2
      IF(DKNT.GT.1.25)GO TO 793
      IF(JA.GT.25)GO TO 3
      GR(IV+15)=15.+GRN
      IF(JA.EQ.24)GO TO 463
      GR(IV+14)=15.+GRN
      IF(JA.EQ.20)GO TO 3
      IF(JA.GT.16)GO TO 463
      GR(IV+21)=GR(IV+22)=GRN+15.
      IF(JA.EQ.15)GO TO 463
      GR(IV+28)=GR(IV+29)=GRN+5.
      IF(JA.EQ.6)GO TO 3
463   GR(IV+2)=GR(IV+9)=GRN+10.
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      IF(JA.EQ.26)GO TO 460
      IF(JA.EQ.19)GO TO 464
      IF(JA.GT.14)GO TO 467
464   GR(IV+16)=GR(IV+23)=GRN+5.
      IF(JA.GT.4)GO TO 3
      GR(IV+17)=GR(IV+24)=GRN+5.
467   GR(IV+3)=GR(IV+10)=GRN+10.
      GO TO 3
475   IF(JA.GT.23)GO TO 478
      IV=JA=15
533   GR(IV-14)=GR(IV-13)=GR(IV-7)=GR(IV-6)=GRN+15.
      IF(JA.EQ.20.OR.JA.EQ.27)GO TO 476
      GR(IV-5)=GR(IV-12)=GRN+5.
      IF(JA.EQ.22)GO TO 535
      IF(JA.EQ.24)GO TO 537
      GR(IV+16)=GRN+5.
      IF(JA.GT.18)GO TO 476
535   GR(IV+17)=GRN+5.
537   GR(IV-4)=GR(IV-11)=GRN+5.
      IF(JA.EQ.22)GO TO 460
      IF(JA.EQ.24)GO TO 476
      GR(IV+23)=GRN+15.
      IF(JA.EQ.17)GO TO 476
      GO TO 460
478   IV=JA=22
602   GR(IV+16)=GRN+15.
      GR(IV+18)=GR(IV+19)=GRN+5.
      IF(JA.EQ.24)GO TO 549
      GR(IV-23)=GR(IV-21)=GRN+5.
      GO TO 533
474   IF(JB.GT.4)GO TO 477
      IF(JA.GT.11)GO TO 520
      IV=JA=3
476   GR(IV-1)=GR(IV-2)=GR(IV+5)=GR(IV+6)=GRN+10.
      IF(JA.EQ.26)GO TO 487
      IF(JA.EQ.27)GO TO 460
      GR(IV+12)=GR(IV+13)=GRN+5.
      IF(JA.EQ.24)GO TO 487
      IF(JA.GT.18)GO TO 463
487   GR(IV+19)=GR(IV+20)=GRN+5.
      IF(JA.EQ.26)GO TO 463
      GO TO 460
520   IF(JA.GT.25)GO TO 590
      IV=JA=17
547   GR(IV+24)=GRN+15.
549   GR(IV-8)=GR(IV-9)=GR(IV-15)=GR(IV-16)=GRN+5.
      IF(JA.GT.19)GO TO 533
      GR(IV+21)=GR(IV+22)=GR(IV+26)=GRN+5.
      IF(JA.EQ.19)GO TO 533
      GR(IV+25)=GRN+5.
      GO TO 533
590   IV=JA=24
607   GR(IV+17)=GRN+15.
      GR(IV+14)=GRN+5.
      IF(JA.GT.25)GO TO 549
      GO TO 602
477   IF(JB.GT.6)GO TO 480
      IF(JA.GT.13)GO TO 525
      IV=JA=5
      GO TO 476
525   IF(JA.GT.27)GO TO 595
      IV=JA=19
514   GR(IV+25)=GRN+15.
      GR(IV+27)=GRN+5.
      GO TO 547
595   IV=JA=26
596   GR(IV+18)=GRN+15.
      GR(IV+15)=GR(IV-20)=GR(IV-21)=GRN+5.
      GO TO 607
480   IF(JA.GT.14)GO TO 530
      IV=JA=6
      GO TO 476
530   IF(JA.GT.28)GO TO 600
      IV=JA=20
578   GR(IV+25)=GR(IV+26)=GRN+15.
      GO TO 547
600   IV=JA=27
659   GR(IV+18)=GR(IV+19)=GRN+15.
      GR(IV+15)=GR(IV+16)=GRN+5.
      GO TO 607
455   IF(JB.GT.2)GO TO 456
      IF(JA.GT.9)GO TO 625
      JA=1
623   IF(I6.GT.13)GO TO 481
      IV=(I6-2)*2+JA+17
      GO TO 624
481   IF(I6.GT.26)GO TO 710
      IV=(I6-12)*4+JA+47
      GO TO 624
710   IV=(I6-27)*2+JA+99
624   IF(JB.GT.2)GO TO 629
      IF(JA.GT.1)GO TO 649
      GR(IV-11)=GR(IV-10)=GR(IV-9)=GRN+15.
      GR(IV-8)=GR(IV-7)=GR(IV-6)=GRN+5.
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      GO TO 460
 625  IF(JA.GT.23)GO TO 683
      JA=15
      GO TO 623
 649  IF(JA.GT.15)GO TO 602
      GR(IV-25)=GR(IV-24)=GR(IV-23)=GRN+5.
      GO TO 533
 683  JA=22
      GO TO 623
 456  IF(JB.GT.4)GO TO 526
      IF(JA.GT.11)GO TO 642
      JA=3
      GO TO 623
 629  IF(JB.GT.4)GO TO 591
      IF(JA.GT.3)GO TO 652
      GR(IV-10)=GR(IV-9)=GR(IV-8)=GRN+15.
      GR(IV-13)=GR(IV-12)=GR(IV-11)=GR(IV-8)=GR(IV-7)
     2=GR(IV-6)=GRN+5.
      GO TO 476
 642  IF(JA.GT.25)GO TO 689
      JA=17
      GO TO 623
 652  IF(JA.GT.17)GO TO 607
      GR(IV-24)=GR(IV-23)=GR(IV-22)=GRN+5.
      GO TO 547
 689  JA=24
      GO TO 623
 526  IF(JB.GT.6)GO TO 608
      IF(JA.GT.13)GO TO 645
      JA=5
      GO TO 623
 591  IF(JB.GT.6)GOTO 635
      IF(JA.GT.5)GO TO 512
      GR(IV-8)=GR(IV-7)=GRN+15.
      GR(IV-10)=GR(IV-9)=GR(IV-6)=GR(IV-5)=GRN+5.
      GO TO 476
 645  IF(JA.GT.27)GO TO 516
      JA=19
      GO TO 623
 512  IF(JA.GT.19)GO TO 596
      GR(IV-22)=GR(IV-21)=GRN+5.
      GO TO 514
 516  JA=26
      GO TO 623
 608  IF(JA.GT.14)GO TO 581
      JA=6
      GO TO 623
 635  IF(JA.GT.6)GO TO 658
      GR(IV-8)=GR(IV-7)=GR(IV-6)=GRN+15.
      GR(IV-9)=GR(IV-8)=GR(IV-7)=GRN+5.
      GO TO 476
 581  IF(JA.GT.28)GO TO 583
      JA=20
      GO TO 623
 658  IF(JA.GT.20)GO TO 659
      GR(IV-22)=GR(IV-21)=GR(IV-20)=GRN+5.
      GO TO 578
 583  JA=27
      GO TO 623
 450  IF(IP.EQ.6)GO TO 108
      IF(DRNT.GT.1.75)GO TO 790
      IF(IP.EQ.3)GO TO 108
      IF(I6.GT.1)GO TO 792
      IF(JB.GT.3)GO TO 451
      IF(JA.GT.17)GO TO 452
      IV=JA=1
      GO TO 460
 793  NI(IV+2)=NI(IV+9)=NI(IV+15)=NI(IV+14)=NI(IV+16)=2
      IF(DRNT.GT.1.75)GO TO 750
      IF(JA.EQ.18)GO TO 796
      IF(JA.EQ.19)GO TO 3
      GR(IV+21)=GR(IV+22)=GR(IV+23)=GRN+15.
      IF(JA.EQ.15)GO TO 796
      GR(IV+28)=GR(IV+29)=GR(IV+30)=GRN+15.
      IF(JA.EQ.5)GO TO 3
 796  GR(IV+3)=GR(IV+10)=GR(IV+17)=GRN+10.
      IF(JA.EQ.15)GO TO 798
      IF(JA.EQ.18)GO TO 3
      GR(IV+24)=GR(IV+31)=GR(IV+37)=GRN+5.
      IF(JA.EQ.4)GO TO 3
 798  GR(IV+4)=GR(IV+11)=GR(IV+18)=GRN+10.
      IF(JA.EQ.15)GO TO 3
      GR(IV+25)=GR(IV+32)=GR(IV+35)=GR(IV+36)=5.+GRN
      GO TO 3
 452  IV=JA=15
 724  GR(IV-7)=GR(IV-6)=GR(IV-5)=GR(IV-14)=GR(IV-13)
     2=GR(IV-12)=GR(IV+24)=GRN+15.
      IF(JA.EQ.19)GO TO 803
      GR(IV-4)=GR(IV-11)=GR(IV+28)=GRN+5.
      IF(JA.EQ.18)GO TO 803
      GR(IV-3)=GR(IV-10)=GRN+5.
      GO TO 460
 451  IF(JB.GT.6)GO TO 453
      IF(JA.GT.20)GO TO 694
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      IV=JA=4
  803 GR(IV-1)=GR(IV-2)=GR(IV+5)=GR(IV+6)=GR(IV+12)
     2=GR(IV+13)=GRN+10.
      IF(JA.EQ.19)GO TO 460
      GR(IV+27)=GR(IV+20)=GRN+5.
      IF(JA.EQ.18)GO TO 460
      GR(IV+26)=GR(IV+19)=GR(IV+39)=GRN+5.
      IF(JA.EQ.5)GO TO 460
      GR(IV+38)=GRN+5.
      GO TO 460
  604 IV=JA=18
  831 GR(IV+23)=GRN+15.
  832 GR(IV+25)=GR(IV+26)=GRN+15.
      GR(IV-9)=GR(IV-8)=GR(IV-16)=GR(IV-15)=GR(IV+21)
     2=GR(IV+22)=GRN+5.
      GO TO 724
  453 IF(JA.GT.21)GO TO 461
      IV=JA=5
  738 GR(IV+40)=GR(IV+41)=GRN+5.
      GO TO 803
  461 IV=JA=19
  740 GR(IV+27)=GRN+15.
      GR(IV+20)=GR(IV+23)=GRN+5.
      GO TO 832
  792 IF(JB.GT.3)GO TO 462
      IF(JA.GT.17)GO TO 846
      JA=1
  722 IF(I6.GT.13)GO TO 712
      IV=(I6-2)*2+JA+17
      GO TO 714
  712 IF(I6.GT.26)GO TO 716
      IV=(I6-12)*4+JA+47
      GO TO 714
  716 IV=(I6-27)*2+JA+99
  714 IF(JB.GT.3)GO TO 718
      IF(JA.GT.1)GO TO 720
      GR(IV-8)=GR(IV-9)=GR(IV-11)=GR(IV-10)=GRN+15.
      GR(IV-5)=GR(IV-4)=GR(IV-7)=GR(IV-6)=GRN+5.
      GO TO 460
  846 JA=15
      GO TO 722
  720 GR(IV-25)=GR(IV-24)=GR(IV-23)=GR(IV-22)=GRN+5.
      GO TO 724
  462 IF(JB.GT.6)GO TO 726
      IF(JA.GT.20)GO TO 728
      JA=4
      GO TO 722
  718 IF(JB.GT.6)GO TO 730
      IF(JA.GT.4)GO TO 732
      GR(IV-9)=GR(IV-8)=GR(IV-7)=GR(IV-6)=GRN+15.
      GR(IV-5)=GR(IV-4)=GR(IV-12)=GR(IV-11)=GR(IV-10)
     2=GRN+5.
      GO TO 803
  728 JA=18
      GO TO 722
  732 GR(IV-23)=GR(IV-22)=GR(IV-21)=GR(IV-20)=GRN+5.
      GO TO 831
  726 IF(JA.GT.21)GO TO 734
      JA=5
      GO TO 722
  730 IF(JA.GT.5)GO TO 736
      GR(IV-8)=GR(IV-7)=GR(IV-6)=GR(IV-5)=GRN+15.
      GR(IV-12)=GR(IV-11)=GR(IV-10)=GR(IV-9)=GRN+5.
      GO TO 738
  734 JA=19
      GO TO 722
  736 GR(IV-22)=GR(IV-21)=GR(IV-20)=GR(IV-19)=GRN+5.
      GO TO 740
  790 IF(IP.EQ.5)GO TO 108
      IF(DKNT.GT.2.25)GO TO 742
      IF(I6.GT.1)GO TO 744
      IF(JB.GT.4)GO TO 746
      IF(JA.GT.25)GO TO 748
      IV=JA=1
      GO TO 460
  750 NI(IV+3)=NI(IV+10)=NI(IV+17)=NI(IV+21)=NI(IV+22)
     2=NI(IV+23)=NI(IV+24)=2
      IF(DKNT.GT.2.25)GO TO 860
      IF(JA.EQ.11)GO TO 764
      GR(IV+28)=GR(IV+29)=GRN+15.
      GR(IV+34)=GRN+5.
  764 GR(IV+30)=GR(IV+31)=GRN+15.
      GR(IV+4)=GR(IV+5)=GR(IV+6)=GR(IV+11)=GR(IV+12)
     2=GR(IV+13)=GR(IV+18)=GR(IV+19)=GR(IV+20)=GRN+10.
      IF(JA.EQ.4)GO TO 756
      IF(JA.EQ.8)GO TO 3
      GR(IV+25)=GR(IV+26)=GR(IV+27)=GRN+10.
      IF(JA.EQ.8)GO TO 3
      GR(IV+41)=GR(IV+42)=GR(IV+43)=GR(IV+44)=GR(IV+45)
     2=GRN+5.
      GR(IV+35)=GR(IV+36)=GRN+15.
  756 GR(IV+37)=GR(IV+38)=GR(IV+39)=GR(IV+40)=GRN+15.
      GR(IV+32)=GR(IV+33)=GRN+5.
      GO TO 3
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748   IV=JA=6
754   GR(IV+35)=GR(IV+36)=GRN+5.
      IF(JA.EQ.4)GO TO 460
      GR(IV-3)=GR(IV-2)=GR(IV-1)=GR(IV+37)=GR(IV+38)
     2=GRN+5.
762   GR(IV-7)=GR(IV-6)=GR(IV-5)=GR(IV-4)=GR(IV+32)
     2=GR(IV+33)=GRN+15.
      GO TO 460
746   IF(JA.GT.28)GO TO 752
      IV=JA=4
810   GR(IV+41)=GR(IV+42)=GRN+15.
760   GR(IV-1)=GR(IV-2)=GR(IV-3)=GRN+10.
      GR(IV+25)=GR(IV+26)=GR(IV+27)=GRN+5.
      IF(JA.EQ.11)GO TO 762
      GO TO 754
752   IV=JA=11
795   GR(IV+34)=GR(IV+35)=GRN+15.
      GR(IV-8)=GR(IV-9)=GR(IV-10)=GR(IV+28)=GR(IV+29)
     2=GRN+5.
      GO TO 760
744   IF(JB.GT.4)GO TO 766
      IF(JA.GT.25)GO TO 768
      JA=1
780   IF(IG.GT.13)GO TO 770
      IV=(IG-2)*2+JA+17
      GO TO 772
770   IF(IG.GT.26)GO TO 774
      IV=(IG-12)*4+JA+47
      GO TO 772
774   IV=(IG-27)*2+JA+99
772   IF(JB.GT.4)GO TO 776
      IF(JA.GT.1)GO TO 778
782   GR(IV-6)=GR(IV-7)=GRN+15.
      IF(JA.EQ.4)GO TO 788
      IF(JA.EQ.11)GO TO 795
      GR(IV-1)=GR(IV-2)=GR(IV-3)=GRN+5.
      IF(JA.EQ.8)GO TO 754
788   GR(IV-8)=GR(IV-9)=GRN+15.
      IF(JA.EQ.4)GO TO 810
      GR(IV-11)=GR(IV-13)=GRN+15.
      GR(IV-4)=GR(IV-5)=GRN+5.
      GO TO 460
768   JA=8
      GO TO 780
778   GR(IV-5)=GR(IV-4)=GRN+15.
      IF(JA.EQ.11)GO TO 815
      GR(IV-12)=GR(IV-11)=GR(IV-10)=GRN+5.
      IF(JA.EQ.4)GO TO 782
      GR(IV-18)=GR(IV-17)=GR(IV-16)=GRN+15.
815   GR(IV-15)=GR(IV-14)=GR(IV-13)=GR(IV-16)=GRN+15.
      GR(IV-9)=GR(IV-8)=GRN+5.
      GO TO 782
766   IF(JA.GT.28)GO TO 784
      JA=4
      GO TO 780
776   IF(JA.GT.4)GO TO 786
      GR(IV-14)=GR(IV-13)=GRN+5.
      GO TO 778
784   JA=11
      GO TO 780
786   GR(IV-12)=GR(IV-11)=GRN+15.
      GR(IV-10)=GR(IV-21)=GR(IV-20)=GR(IV-19)=GR(IV-18)
     2=GR(IV-17)=GRN+5.
      GO TO 778
742   IF(IP.GT.6)GO TO 108
      IF(IG.GT.1)GO TO 850
      IF(JB.GT.5)GO TO 852
      IV=JA=1
      GO TO 460
860   NI(IV+4)=NI(IV+11)=NI(IV+18)=NI(IV+25)=NI(IV+28)
     2=NI(IV+29)=NI(IV+30)=NI(IV+31)=NI(IV+32)=2
      GR(IV+36)=GR(IV+37)=GR(IV+38)=GR(IV+39)=GR(IV+40)
     2=GR(IV+41)=GR(IV+42)=GRN+15.
      GR(IV+5)=GR(IV+6)=GR(IV+12)=GR(IV+13)=GR(IV+19)
     2=GR(IV+20)=GR(IV+26)=GR(IV+27)=GRN+10.
      IF(JA.EQ.3)GO TO 3
      GR(IV+35)=GRN+15.
      GR(IV+33)=GR(IV+34)=GRN+10.
      GR(IV+43)=GR(IV+44)=GR(IV+45)=GRN+5.
      GO TO 3
852   IV=JA=3
880   GR(IV+43)=GRN+15.
      GR(IV-1)=GR(IV-2)=GRN+10.
      GR(IV+33)=GR(IV+34)=GR(IV+35)=GRN+5.
      GO TO 460
850   IF(JB.GT.5)GO TO 862
      JA=1
875   IF(IG.GT.13)GO TO 864
      IV=(IG-2)*2+JA+17
      GO TO 866
864   IF(IG.GT.26)GO TO 868
      IV=(IG-12)*4+JA+47
      GO TO 866
868   IV=(IG-27)*2+JA+99
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 866  GR(IV-10)=GR(IV-9)=GR(IV-8)=GR(IV-7)=GR(IV-6)
     2=GR(IV-5)=GR(IV-4)=GRN+15.
      IF(JA.EQ.3)GO TO 870
      GR(IV-11)=GRN+15.
      GR(IV-3)=GR(IV-2)=GR(IV-1)=GRN+5.
      GO TO 469
 862  JA=3
      GO TO 875
 870  GR(IV-3)=GRN+15.
      GR(IV-13)=GR(IV-12)=GR(IV-11)=GRN+5.
      GO TO 880
 3    WRITE(21,917)DKNT,16,JA
 917  FORMAT(//1X,"KNOT DIA.=",F5.3,5X,
     2"LOCATED AT SECTION",I4,5X,"NO.",I3//)
      RETURN
      END
C
      SUBROUTINE LOAD(LI)
      COMMON/DATA/TITLE(8),NP,NE,NB,NDF,NMAT,NSZF,NLD,IP
     1,CD,PINC,NMP,DMAX,NLNP,IV,16,JSIM,NSIM
     2,ISTD,IENDD,JSTS,JENDS,EAV,ESD,AMOR,SDMOR
     3,AST2,ASPL,E12,E13,RING,ADEF,ISEED
      COMMON CORD(190,2),NOP(170,4),IMAT(170),ORT(171,7)
     1,NBC(10),NFIX(10),RI(380),SK(380,20),NODES(170)
     2,KP(170),LD(170),IK(170),EST(170,36),BDATA(170,24)
     3,R(3),ESTIFM(12,12),A(8,6),B(3,8),RS(8),SMAX(170)
     4,NQ(10),LB(170),RR(10,2),SMIN(170),ANG(170)
     5,ERAT(12,2),SPL(12),STR2(12),XMOR(12),NI(170)
     6,ST(170),IX(170),ORTHO(12,14),GR(170),STGRN(170)
     7,FORC(170,3),DISP(2,190),RAND(5),COORD(190,2)
     8,NOPP(170,4),ASMAX(170)
C
C   ZERO  LOAD  ARRAY
C
      DO 160 J=1,NSZF
 160  RI(J)=0.
      IF(LI.EQ.1)GO TO 200
      DO 340 I=1,NLNP
      IF(RR(I,1).EQ.0.)GO TO 310
      RR(I,1)=RR(I,1)+PINC
 310  IF(RR(I,2).EQ.0.)GO TO 340
      RR(I,2)=RR(I,2)+PINC
 340  CONTINUE
C
C  READ, PRINT AND STORE LOAD CARD
C  NQ=NODAL POINT NUMBER WHERE LOAD ACTS
C  R(1)=HORIZONTAL LOAD COMPONENT (POSITIVE TO THE
C        RIGHT)
C  R(2)=VERTICAL LOAD COMPONENT (POSITIVE UPWARD)
C  RI=LOAD VECTOR
C
 200  DO 400 I=1,NLNP
      IF(LI.GT.1)GO TO 202
      RR(I,1)=R(1)
      RR(I,2)=R(2)
 202  DO 170  K=1,NDF
      IC=(NQ(I)-1)*NDF+K
 170  RI(IC)=R(K)+RI(IC)
 400  CONTINUE
      RETURN
      END

      SUBROUTINE FORMK(LI)
C
C       FORMS STIFFNESS MATRIX IN UPPER TRIANGULAR FORM
C
      COMMON/DATA/TITLE(8),NP,NE,NB,NDF,NMAT,NSZF,NLD,IP
     1,CD,PINC,NMP,DMAX,NLNP,IV,16,JSIM,NSIM
     2,ISTD,IENDD,JSTS,JENDS,EAV,ESD,AMOR,SDMOR
     3,AST2,ASPL,E12,E13,RING,ADEF,ISEED
      COMMON CORD(190,2),NOP(170,4),IMAT(170),ORT(171,7)
     1,NBC(10),NFIX(10),RI(380),SK(380,20),NODES(170)
     2,KP(170),LD(170),IK(170),EST(170,36),BDATA(170,24)
     3,R(3),ESTIFM(12,12),A(8,6),B(3,8),RS(8),SMAX(170)
     4,NQ(10),LB(170),RR(10,2),SMIN(170),ANG(170)
     5,ERAT(12,2),SPL(12),STR2(12),XMOR(12),NI(170)
     6,ST(170),IX(170),ORTHO(12,14),GR(170),STGRN(170)
     7,FORC(170,3),DISP(2,190),RAND(5),COORD(190,2)
     8,NOPP(170,4),ASMAX(170)
      REWIND 15
C
C  SET BANDMAX AND NO. OF EQUATIONS
C
C  NBAND = (D+1)F   WHERE
C              NBAND=HALF-BANDWIDTH
C              F=NUMBER OF DEGREES OF FREEDOM AT EACH NODE.
C              D=MAX. LARGEST DIFFERENCE OF NODAL NUMBERS
C                OCCURING FOR ALL ELEMENTS.
C
      NBAND=20
C
C        ZERO STIFFNESS MATRIX
C
      DO 300  N=1,NSZF
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      DO 300  M=1,NBAND
  300 SK(N,M)=0.
C
C        SCAN ELEMENTS
C
      DO 400 N=1,NE
      IF(LI.EQ.1)GO TO 620
      IF(KP(N).EQ.0)GO TO 600
  620 IF(NODES(N).EQ.4)GO TO 605
      CALL STIFT3(N)
      GO TO 650
  605 CALL STIFT4(N)
      GO TO 650
  600 IF(NODES(N).EQ.4)GO TO 610
      M=0
      DO 770 I=1,6
      DO 770 J=1,6
      M=M+1
      ESTIFM(I,J)=EST(N,M)
      IF(I.EQ.J)GO TO 770
      ESTIFM(J,I)=ESTIFM(I,J)
  770 CONTINUE
      GO TO 650
  610 M=0
      DO 777 I=1,8
      DO 777 J=1,8
      M=M+1
      ESTIFM(I,J)=EST(N,M)
      IF(I.EQ.J)GO TO 777
      ESTIFM(J,I)=ESTIFM(I,J)
  777 CONTINUE
  650 NCN=NODES(N)
C
C RETURNS ESTIFM AS STIFFNESS MATRIX, STORE ESTIFM IN SK
C
C       FIRST, ROWS
C
      DO 350 JJ=1,NCN
      NROWB=(NOP(N,JJ)-1)*NDF
      DO 350  J=1,NDF
      NROWB=NROWB+1
      I=(JJ-1)*NDF+J
C
C    THEN COLUMNS
C
      DO 330  KK=1,NCN
      NCOLB=(NOP(N,KK)-1)*NDF
      DO 320 K=1,NDF
      L=(KK-1)*NDF+K
      NCOL=NCOLB+K+1-NROWB
C
C SKIP STORING IF BELOW BAND
C
      IF(NCOL)320,320,310
  310 SK(NROWB,NCOL)=SK(NROWB,NCOL)+ESTIFM(I,L)
  320 CONTINUE
  330 CONTINUE
  350 CONTINUE
  400 CONTINUE
C
C  INSERT BOUNDARY CONDITIONS
C
      READ(15)(NBC(I),NFIX(I),I=1,NB)
      DO 500 N=1,NB
      NX=10**(NDF-1)
      I=NBC(N)
      NROWB=(I-1)*NDF
C
C  EXAMINE EACH DEGREE OF FREEDOM
C
      DO 490 M=1,NDF
      NROWB=NROWB+1
      ICON=NFIX(N)/NX
      IF(ICON)450,450,420
  420 SK(NROWB,1)=1.
      DO 430 J=2,NBAND
      SK(NROWB,J)=0.
      NR=NROWB+1-J
      IF(NR)430,430,425
  425 SK(NR,J)=0.
  430 CONTINUE
      NFIX(N)=NFIX(N)-NX*ICON
  450 NX=NX/10
  490 CONTINUE
  500 CONTINUE
      RETURN
      END

      SUBROUTINE STIFT3(N)
C
C          TRIANGULAR ELEMENTS  -   PLANE  STRESS
C
      COMMON/DATA/TITLE(8),NP,NE,NB,NDF,NMAT,NSZF,NLD,IP
     1,CD,PINC,NEP,EMAX,NENP,IV,I6,JSIN,NSIM
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     2,ISTD,IENDD,JSTS,JENDS,EAV,ESD,AMOR,SIMOR
     3,AST2,ASPL,E12,E13,RING,ADEF,ISEED
      COMMON CORD(190,2),NOP(170,4),IMAT(170),ORT(171,7)
     1,NBC(10),NFIX(10),R1(380),SK(380,20),NODES(170)
     2,KP(170),LD(170),IR(170),EST(170,36),BDATA(170,24)
     3,R(3),ESTIFM(12,12),A(8,6),B(3,8),RS(8),SMAX(170)
     4,NO(10),LB(170),ER(10,2),SMIN(170),ANG(170)
     5,EMAT(12,2),SPL(12),STR2(12),XMOR(12),NI(170)
     6,SF(170),IX(170),ORTHO(12,14),GR(170),STGRN(170)
     7,FORC(170,3),DISP(2,190),RAND(5),COORD(190,2)
     8,NOPP(170,4),ASMAX(170)
C
C     DETERMINE ELEMENTS CONNECTIONS
C
      I=NOP(N,1)
      J=NOP(N,2)
      K=NOP(N,3)
      L=IMAT(N)
C
C   NUMBER THE NODES COUNTER-CLOCKWISE
C
C   SET UP LOCAL COORDINATE SYSTEM
C
      AJ=CORD(J,1)-CORD(I,1)
      AK=CORD(K,1)-CORD(I,1)
      BJ=CORD(J,2)-CORD(I,2)
      BK=CORD(K,2)-CORD(I,2)
      AREA=(AJ*BK-AK*BJ)/2.
      IF(AREA.LE.0.)GO TO 220
C
C   FORM STRAIN DISP. MATRIX
C
      A(1,1)=A(3,2)=BJ-BK
      A(1,2)=A(1,4)=A(1,6)=A(2,1)=0.
      A(2,3)=A(2,5)=0.
      A(1,3)=A(3,4)=BK
      A(1,5)=A(3,6)=-BJ
      A(2,2)=A(3,1)=AK-AJ
      A(2,4)=A(3,3)=-AK
      A(2,6)=A(3,5)=AJ
C
C   FORM STRESS STRAIN MATRIX FOR ORTHOTROPIC ELEMENT
C
      COMM=1./((1.-ORT(L,3)*ORT(L,4))*AREA)
      ESTIFM(1,1)=COMM*ORT(L,1)
      ESTIFM(2,2)=COMM*ORT(L,2)
      ESTIFM(1,2)=ESTIFM(2,1)=COMM*ORT(L,1)*ORT(L,4)
      ESTIFM(1,3)=ESTIFM(2,3)=ESTIFM(3,1)=ESTIFM(3,2)=0.
      ESTIFM(3,3)=ORT(L,5)/AREA
C
C  B IS THE STRESS BACKSUBSTITUTION MATRIX AND IS
C     SAVED ON TAPE
C
      DO 205 I=1,3
      DO 205  J=1,6
      B(I,J)=0.
      DO 205 K=1,3
  205 B(I,J)=B(I,J)+ESTIFM(I,K)/2.*A(K,J)
      M=0
      DO 600 I=1,3
      DO 600 J=1,6
      M=M+1
  600 BDATA(N,M)=B(I,J)
C
C    ESTIFM IS STIFFNESS MATRIX
C
      DO 210 I=1,6
      DO 210 J=1,6
      ESTIFM(I,J)=0.
      DO 210 K=1,3
  210 ESTIFM(I,J)=ESTIFM(I,J)+B(K,I)/2.*A(K,J)
      M=0
      DO 300 I=1,6
      DO 300 J=1,6
      M=M+1
  300 EST(N,M)=ESTIFM(I,J)
      RETURN
C
C    ERROR EXIT FOR BAD CONNECTIONS
C
  220 WRITE(21,101)N
  101 FORMAT("1ZERO OR NEGATIVE AREA ELEMENT NO.",I4/
     1"EXECUTION","TERMINATED")
      STOP
      END

      SUBROUTINE STIFT4(N)
C
C        BENDING RECTANGULAR ELEMENT TAKEN FROM IMPROVED
C        TWO-DIMENSIONAL FINITE ELEMENT BY R. D. COOK IN
C        JOUR. OF STRUCT. DIV., SEPT. 1974.
C
      COMMON/DATA/TITLE(8),NP,NE,NB,DIF,NMAT,NSZF,NLD,IP
     1,CD,PINC,NMP,DMAX,NLNP,IV,IG,JSTM,JSTP
```

```
2,ISTD,IEND,JSTS,JENDS,EAV,ESL,AMOR,SDMOR
3,AST2,ASPL,E12,E13,RING,ADFF,ISEED
 COMMON CORD(190,2),NOP(170,4),IMAT(170),ORT(171,7)
1,NBC(10),NFIX(10),R1(380),SK(380,20),NODES(170)
2,EP(170),LD(170),IK(170),EST(170,36),BDATA(170,24)
3,R(3),ESTIFM(12,12),A(8,6),B(3,8),RS(8),SMAX(170)
4,NJ(10),LB(170),RR(10,2),SMIN(170),ANG(170)
5,EMAT(12,2),SPL(12),STR2(12),XMOM(12),NI(170)
6,SI(170),IX(170),ORTHO(12,14),GR(170),STGRN(170)
7,FORC(170,3),LISF(2,190),RAND(5),CCORD(190,2)
8,NOPP(170,4),ASMAX(170)
 DIMENSION T(5,8),P(3,5),H(5,5),C(3,8)
C
C      BENDING RECTANGULAR ELEMENTS STIFFNESS MATRIX
C
C      DETERMINE ELEMENTS CONNECTIONS(NODES NUMBERED
C      COUNTER-CLOCKWISE)
C
C      POSITIONS OF NODES:
C
C          L------------K
C          .            .
C          .            .
C          .            .
C          .            .
C          I------------J
C
      I=NOP(N,1)
      J=NOP(N,2)
      K=NOP(N,3)
      L=NOP(N,4)
      M=IMAT(N)
C
C  FORM T MATRIX
C
      DO 101 IA=1,8
      DO 101 IB=1,5
 101  T(IB,IA)=0.0
      T(5,2)=T(1,1)=((CORD(J,2)-CORD(L,2))/2.)
      T(5,4)=T(1,3)=((CORD(K,2)-CORD(I,2))/2.)
      T(5,6)=T(1,5)=(-1.)*T(1,1)
      T(5,8)=T(1,7)=(-1.)*T(1,3)
      G=CORD(J,2)+CORD(I,2)
      D=CORD(L,2)+CORD(I,2)
      E=CORD(K,2)+CORD(J,2)
      F=CORD(L,2)+CORD(K,2)
      T(2,1)=((CORD(J,2)*G-CORD(L,2)*D)/6.)
      T(2,3)=((CORD(K,2)*E-CORD(I,2)*G)/6.)
      T(2,5)=((CORD(L,2)*F-CORD(J,2)*E)/6.)
      T(2,7)=((CORD(I,2)*D-CORD(L,2)*F)/6.)
      T(5,1)=T(3,2)=((CORD(L,1)-CORD(J,1))/2.)
      T(5,3)=T(3,4)=((CORD(I,1)-CORD(K,1))/2.)
      T(5,5)=T(3,6)=(-1.)*T(3,2)
      T(5,7)=T(3,8)=(-1.)*T(3,4)
      G=CORD(L,1)+CORD(I,1)
      D=CORD(J,1)+CORD(I,1)
      E=CORD(J,1)+CORD(K,1)
      F=CORD(K,1)+CORD(L,1)
      T(4,2)=((CORD(L,1)*G-CORD(J,1)*D)/6.)
      T(4,4)=((CORD(I,1)*D-CORD(K,1)*E)/6.)
      T(4,6)=((CORD(J,1)*E-CORD(L,1)*F)/6.)
      T(4,8)=((CORD(K,1)*F-CORD(I,1)*G)/6.)
C
C  FORM P MATRIX
C
      DO 100 IA=1,3
      DO 100 IB=1,5
 100  P(IA,IB)=0.0
      X=Y=0.5
      P(1,1)=P(2,3)=P(3,5)=1.
      P(2,4)=((CORD(J,1)-CORD(I,1))*X)+CORD(I,1)
      P(1,2)=((CORD(K,2)-CORD(J,2))*Y)+CORD(J,2)
C
C  FORM H-INVERSE MATRIX
C
      AB=ABS(CORD(K,1)-CORD(I,1))
      BA=ABS(CORD(K,2)-CORD(I,2))
      DO 102 IA=1,5
      DO 102 IB=1,5
 102  H(IA,IB)=0.0
      CA=AB**5
      CB=BA**5
      COMM=144./((ORT(M,1)*ORT(M,2)-((ORT(M,3)*ORT(M,2))
     2**2))*(BA**6)*(AB**6))
      H(1,1)=COMM*(((ORT(M,1)**2)*ORT(M,2)*(CB)*CA/36.)-
     2(ORT(M,1)*((ORT(M,3)*ORT(M,2))**2)*CA*CB/48.))
      H(2,1)=H(1,2)=COMM*(((ORT(M,1)*((ORT(M,3)*ORT(M,2))
     2**2)*CA*(BA**4))-(ORT(M,1)**2)*ORT(M,2)*CA*(BA**4))/
     324.)
      H(3,1)=H(1,3)=COMM*(ORT(M,1)*ORT(M,2)*(ORT(M,3)*
     2ORT(M,2))*CA*CB/144.)
      H(2,2)=COMM*(((ORT(M,1)**2)*ORT(M,2)*CA*(BA**3))-
     2ORT(M,1)*((ORT(M,3)*ORT(M,2))**2)*CA*(BA**3))/12.
      H(3,3)=COMM*((ORT(M,1)*(ORT(M,2)**2)*CA*CB/36.)-
```

```
     2(ORT(M,2)*((ORT(M,3)*ORT(M,2))**2)*CA*CB)/48.)
      H(4,3)=H(3,4)=((ORT(M,2)*((ORT(M,3)*ORT(M,2))**2)*
     2(AB**4)*CB-ORT(M,1)*(ORT(M,2)**2)*(AB**4)*CB)/24.)*
     3COMM
      H(4,4)=COMM*(ORT(M,1)*(ORT(M,2)**2)*CB*(AB**3)-
     2ORT(M,2)*((ORT(M,3)*ORT(M,2))**2)*(AB**3)*CB)/12.
      H(5,5)=COMM*(ORT(M,5)/144.)*(ORT(M,1)*ORT(M,2)*CA*CB-
     2((ORT(M,3)*ORT(M,2))**2)*CA*CB)
C
C   FORM ELEMENT STIFFNESS MATRIX
C
      DO 103 NA=1,8
      DO 103 NC=1,5
      A(NA,NC)=0.0
      DO 103 JA=1,5
  103 A(NA,NC)=T(JA,NA)*H(JA,NC)+A(NA,NC)
      DO 104 NA=1,8
      DO 104 NC=1,8
      ESTIFM(NA,NC)=0.0
      DO 104 JA=1,5
  104 ESTIFM(NA,NC)=A(NA,JA)*T(JA,NC)+ESTIFM(NA,NC)
      M=0
      DO 300 I=1,8
      DO 300 J=1,8
      M=M+1
  300 EST(N,M)=ESTIFM(I,J)
C
C   FORM STRESS-DISPLACEMENT MATRIX AND SAVE ON BDATA
C
      DO 106 NA=1,3
      DO 106 NC=1,5
      B(NA,NC)=0.0
      DO 106 JA=1,5
  106 B(NA,NC)=P(NA,JA)*H(JA,NC)+B(NA,NC)
      DO 107 NA=1,3
      DO 107 NC=1,8
      C(NA,NC)=0.0
      DO 107 JA=1,5
  107 C(NA,NC)=B(NA,JA)*T(JA,NC)+C(NA,NC)
      M=0
      DO 600 I=1,3
      DO 600 J=1,8
      M=M+1
  600 BDATA(N,M)=C(I,J)
      RETURN
      END
C
```

```
      SUBROUTINE SOLVE
C
C   DIRECT SOLUTION BY THE GAUSS ELIMINATION PROCEDURE
C   AND BAND MATRIX TECHNIQUE.
C
      COMMON/DATA/TITLE(8),NP,NE,NB,NDF,NMAT,NSZF,NLD,IP
     1,CD,PINC,NMP,DMAX,NLNF,IV,I6,JSIM,NSIM
     2,ISTD,IENDD,JSTS,JENDS,FAC,ESD,AMOR,SDMOR
     3,AST2,ASPL,E12,E13,RING,ADFF,ISEED
      COMMON CORD(190,2),NOP(170,4),IMAT(170),ORT(171,7)
     1,NBC(10),NFIX(10),RI(380),SK(380,20),NODES(170)
     2,KP(170),LD(170),IK(170),EST(170,36),BDATA(170,24)
     3,R(3),ESTIFM(12,12),A(8,6),B(3,8),RS(8),SMAX(170)
     4,NQ(10),LE(170),RR(10,2),SMIN(170),ANG(170)
     5,ERAT(12,2),SPL(12),STR2(12),XMOR(12),NI(170)
     6,ST(170),IX(170),ORTHO(12,14),GR(170),STGRN(170)
     7,FORC(170,3),DISP(2,190),BAND(5),COORL(190,2)
     8,NOPP(170,4),ASMAX(170)
      NBAND=20
C
C   REDUCE MATRIX
C
      DO 300 N=1,NSZF
      I=N
      DO 290 L=2,NBAND
      I=I+1
      IF(SK(N,L))240,290,240
  240 C=SK(N,L)/SK(N,1)
      J=0
      DO 270 K=L,NBAND
      J=J+1
      IF(SK(N,K))260,270,260
  260 SK(I,J)=SK(I,J)-C*SK(N,K)
  270 CONTINUE
      SK(N,L)=C
C
C   AND LOAD VECTOR FOR EACH EQUATION
C
      RI(I)=RI(I)-C*RI(N)
  290 CONTINUE
  300 RI(N)=RI(N)/SK(N,1)
C
C   BACK-SUBSTITUTION
C
      N=NSZF
  350 N=N-1
      IF(N)500,500,360
```

```
  360 L=N
      DO 400  K=2,NBAND
      L=L+1
      IF(SK(N,K))370,400,370
  370 RI(N)=RI(N)-SK(N,K)*RI(L)
  400 CONTINUE
      GO TO 350
  500 RETURN
      END

      SUBROUTINE STRESS(LI,JN)
      COMMON/DATA/TITLE(8),NP,NE,NB,NDF,NMAT,NSZF,NLD,IP
     1,CB,PINC,NMP,EMAX,NENP,IV,I6,JSIM,NSIM
     2,ISTD,IENDD,JSTS,JENDS,EAV,ESD,AMOR,SIMOR
     3,AST2,ASPL,E12,E13,RING,ALEF,ISEED
      COMMON CORD(190,2),NOP(170,4),IMAT(170),ORT(171,7)
     1,NPC(10),NFIX(10),RI(380),SK(380,20),NODES(170)
     2,KP(170),LD(170),IK(170),EST(170,36),BDATA(170,24)
     3,R(3),ESTIFM(12,12),A(8,6),B(3,8),RS(8),SMAX(170)
     4,NO(10),LB(170),RR(10,2),SMIN(170),ANG(170)
     5,EMAT(12,2),SPL(12),STR2(12),XMOR(12),NI(170)
     6,ST(170),IX(170),ORTHO(12,14),GR(170),STGRN(170)
     7,FORC(170,3),DISP(2,190),RAND(5),COORD(190,2)
     8,NOPP(170,4),ASMAX(170)
      DIMENSION DIS(2,200),FORCE(200,3)
      EQUIVALENCE(DIS(1),RI(1)),(SK(1),FORCE(1))
C
C  PRINT DISPLACEMENTS
C
      IF(LI.GT.1)GO TO 50
      WRITE(21,100)
      WRITE(21,110)(M,(DIS(J,M),J=1,NDF),M=ISTD,IENDD)
  100 FORMAT(///,15X,"DISPLACEMENTS"//5X,"NODE",10X,"X",
     115X,"Y")
  110 FORMAT(I10,2E15.5)
C
C  CALCULATE RECTANGULAR ELEMENTS STRESSES
C
   50 DO 200 NC=1,NE
      IF(NODES(NC).EQ.3)GO TO 222
      MX=0
      DO 922 I=1,3
      DO 922 J=1,8
      MX=MX+1
  922 B(I,J)=BDATA(NC,MX)
      DO 260 I=1,4
      M=NOP(NC,I)
      IF(M.EQ.0)GO TO 260
      K=(I-1)*2
      DO 240 J=1,2
      IJ=J+K
  240 RS(IJ)=DIS(J,M)
  260 CONTINUE
      IA=K+2
      DO 300 I=1,3
      FORCE(NC,I)=0.0
      DO 300 J=1,IA
  300 FORCE(NC,I)=FORCE(NC,I)+B(I,J)*RS(J)
      GO TO 200
C
C  CALCULATE TRIANGULAR ELEMENTS STRESSES
C
  222 MZ=0
      DO 923 I=1,3
      DO 923 J=1,6
      MZ=MZ+1
  923 B(I,J)=BDATA(NC,MZ)
      DO 460 I=1,3
      M=NOP(NC,I)
      IF(M.EQ.0)GO TO 460
      K=(I-1)*NDF
      DO 440  J=1,NDF
      IJ=J+K
  440 RS(IJ)=DIS(J,M)
  460 CONTINUE
      IA=K+NDF
      DO 500 I=1,3
      FORCE(NC,I)=0.
      DO 500 J=1,IA
  500 FORCE(NC,I)=FORCE(NC,I)+B(I,J)*RS(J)
  200 CONTINUE
      DO 555 I=1,NE
      DO 555 J=1,3
  555 FORC(I,J)=FORC(I,J)+FORCE(I,J)
C
C  CALCULATE PRINCIPAL STRESSES AND DIRECTIONS
C
      DO 600 N=1,NE
      C=(FORCE(N,1)+FORCE(N,2))/2.
      XANG=GR(N)*2./57.29578
      STV1=(FORCE(N,1)-FORCE(N,2))/2.
      STG=STV1*COS(XANG)-FORCE(N,3)*SIN(XANG)+C
      STGRN(N)=STGRN(N)+STG
      AA=SQRT(STV1**2+FORCE(N,3)**2)
```

```
      STMAX=C+AA
      STMIN=C-AA
      SMAX(N)=SMAX(N)+STMAX
      SMIN(N)=SMIN(N)+STMIN
      IF(FORCE(N,2).EQ.SMIN(N))GO TO 700
      ANG(N)=57.29578*ATAN(FORCE(N,3)/(FORCE(N,2)-SMIN(N)))
      GO TO 210
 700  ANG(N)=90.
 210  CONTINUE
 600  CONTINUE
      IF(LI.GT.1)GO TO 610
      CD=SQRT((DIS(2,NMP)*4.)**2)
C
C  WRITE ALL STRESS COMPONENTS
C
      WRITE(21,101)
      WRITE(21,111)(N,(FORC(N,I),I=1,3),STGRN(N),N=JSTS
     2,JENDS)
      WRITE(21,790)
      WRITE(21,112)(N,SMAX(N),SMIN(N),ANG(N),N=JSTS,JENDS)
 610  DO 620 I=1,NP
      DO 620 J=1,NDF
      DISP(J,I)=DISP(J,I)+DIS(J,I)
 620  CONTINUE
      DEFL=DIS(2,NMP)
      ADEF=ABS(DEFL)
      IF(LI.EQ.1)GO TO 930
      IF(ADEF.LT.CD)GO TO 902
      WRITE(21,811)TITLE,LI
      WRITE(21,813)
      WRITE(21,814)
      WRITE(21,815)(NQ(I),(RR(I,K),K=1,NDF),I=1,NLNP)
      WRITE(21,100)
      WRITE(21,110)(M,(DISP(J,M),J=1,NDF),M=ISTD,IENDD)
      WRITE(21,101)
      WRITE(21,111)(N,(FORC(N,I),I=1,3),STGRN(N),N=JSTS
     2,JENDS)
      WRITE(21,790)
      WRITE(21,112)(N,SMAX(N),SMIN(N),ANG(N),N=JSTS,JENDS)
 811  FORMAT(//1X,8A6,"LOAD CASE",I3//)
 813  FORMAT(3X,"LOAD"/)
 814  FORMAT(2X,"NODE",7X,"X",7X,"Y")
 815  FORMAT(I5,2F10.2)
      GO TO 931
 930  IF(DEFL-DMAX)901,931,902
 790  FORMAT(//17X,"MAX-STRESS",6X,"MIN-STRESS",7X,"ANGLE")
 101  FORMAT(//3X,"ELEMENT",2X,"X-STRESS",5X,"Y-STRESS",3X,
     2"X-Y-STRESS",6X,"STGRN")
 111  FORMAT(I7,4E13.4)
 112  FORMAT(I10,2F17.4,F12.3)
 902  RETURN
 901  IF(JN.LT.NSIM)GO TO 902
      STOP
      END
C
      SUBROUTINE CHECK(LI)
C
C   THIS SUBROUTINE DETERMINES IF ANY OF THE ELEMENTS
C   SHOULD CHANGE THEIR STIFFNESS (K) MATRIX FOR THE
C   NEXT LOAD.
C
      COMMON/DATA/TITLE(8),NP,NE,NB,NDF,NMAT,NSZF,NLD,IP
     1,CD,PINC,NMP,DMAX,NLNP,IV,I6,JSIM,NSIM
     2,ISTD,IENDD,JSTS,JENDS,EAV,ESD,AMOR,SDMOR
     3,AST2,ASPL,E12,E13,RING,ADEF,ISEED
      COMMON CORD(190,2),NOP(170,4),IMAT(170),ORT(171,7)
     1,NBC(10),NFIX(10),RI(380),SK(380,20),NODES(170)
     2,KP(170),LD(170),IK(170),EST(170,36),BDATA(170,24)
     3,R(3),ESTIFM(12,12),A(8,6),B(3,8),RS(8),SMAX(170)
     4,NQ(10),LB(170),RR(10,2),SMIN(170),ANG(170)
     5,EMAT(12,2),SPL(12),STR2(12),XMOR(12),NI(170)
     6,ST(170),IX(170),ORTHO(12,14),GR(170),STGRN(170)
     7,FORC(170,3),DISP(2,190),RAND(5),COORD(190,2)
     8,NOPP(170,4),ASMAX(170)
      DIMENSION ST2(200),STT(200),STD(200),STL(200),STI(200)
     2,STDIF(200),STM(200),DIS(2,200),FORCE(200,3)
      EQUIVALENCE(DIS(1),RI(1)),(SK(1),FORCE(1))
      JB=0
      DO 500 I=1,NE
      KP(I)=0
      KQ=NI(I)
C
C   IF LB(I)=1, ELEMENT I HAS BEEN BROKEN. CHECK
C            NEXT ELEMENT.
C
      IF(LB(I).EQ.1)GO TO 500
      ASMAX(I)=ABS(STGRN(I))
      IF(SPL(KQ).GT.ASMAX(I)) GO TO 112
      IF(STR2(KQ).GT.ASMAX(I))GO TO 201
      IK(I)=IK(I)+1
C
C   IF ASMAX(I) IS GREATER THAN MODULUS OF RUPTURE
C   (XMOR),ELEMENT I HAS BEEN BROKEN. CHANGE STIFFNESS
C   PROPERTIES.
```

```
C
      IF(XNOR(KQ).GT.ASMAX(I))GO TO 114
 120  IMAT(I)=NF+1
      LB(I)=1
      KP(I)=1
      JB=1
      GO TO 500
C
C    IF IK(I)=1,IT IS THE FIRST LOADING OF ELEMENT I
C    BEYOND THE PROPORTIONAL LIMIT (PL).
C
 114  IF(IK(I).EQ.1) GO TO 116
      IF(IK(I).GT.2)GO TO 118
      ST2(I)=(ASMAX(I)-STT(I))/2.
 118  STD(I)=XNOR(KQ)-ASMAX(I)
      IF(STD(I)-ST2(I))120,120,500
 116  STT(I)=ASMAX(I)
C
C    IF LD(I)=1,THE K-MATRIX OF ELEMENT I HAVE ALREADY
C    BEEN USING PROPERTIES BEYOND PL.
C
      IF(LD(I).EQ.2)GO TO 500
      GO TO 207
 201  IX(I)=IX(I)+1
      IF(IX(I).EQ.1)GO TO 203
      IF(IX(I).GT.2)GO TO 205
      ST1(I)=(ASMAX(I)-STL(I))/2.
 205  STM(I)=STR2(KQ)-ASMAX(I)
      IF(STM(I)-ST1(I))207,207,500
 207  KP(I)=1
      ORT(1,1)=ORT(1,1)*ERAT(KQ,2)
      ORT(1,2)=ORT(1,1)*0.068
      ORT(1,5)=ORT(1,1)*0.064
      JB=1
      LD(I)=2
      GO TO 500
 203  STL(I)=ASMAX(I)
      IF(LD(I).EQ.1)GO TO 500
 112  IF(LI.GT.2)GO TO 124
      ST(I)=(ASMAX(I)-ST(I))/2.
 124  STDIF(I)=SPL(KQ)-ASMAX(I)
      IF(STDIF(I)-ST(I))122,122,500
 122  KP(I)=1
C
C    CHANGE STIFFNESS PROPERTIES
C
      ORT(1,1)=ORT(1,1)*ERAT(KQ,1)
      ORT(1,2)=ORT(1,1)*0.068
      ORT(1,5)=ORT(1,1)*0.064
      LD(I)=1
      JB=1
 500  CONTINUE
C
C    IF JB=0,RESULTS WILL NOT BE PRINTED.
C    IF JB=1,THE K-MATRIX OF ONE OR MORE OF THE
C    ELEMENTS WILL CHANGE NEXT LOADING. RESULTS
C    WILL BE PRINTED.
C
 550  IF(JB.EQ.0)GO TO 600
      IF(LI.EQ.1)GO TO 600
      WRITE(21,811)TITLE,LI
      WRITE(21,813)
      WRITE(21,814)
      WRITE(21,815)(NQ(I),(RR(I,K),K=1,NDF),I=1,NLNP)
      WRITE(21,820)
      WRITE(21,821)(M,(DISP(J,M),J=1,NDF),M=ISTD,IENDD)
      WRITE(21,101)
      WRITE(21,111)(N,(FORC(N,I),I=1,3),STGRN(N),N=JSTS
     2,JENDS)
      WRITE(21,790)
      WRITE(21,793)(N,SMAX(N),SMIN(N),ANG(N),N=JSTS,JENDS)
 811  FORMAT(//1X,8A6,"LOAD CASE",I3//)
 813  FORMAT(2X,"LOADS"/)
 814  FORMAT(2X,"NODE",7X,"X",7X,"Y")
 815  FORMAT(I5,2F10.2)
 820  FORMAT(///,15X,"DISPLACEMENTS"//5X,"NODE",10X,"X",
     115X,"Y")
 821  FORMAT(I10,2E15.5)
 101  FORMAT(//3X,"ELEMENT",2X,"X-STRESS",5X,"Y-STRESS",3X,
     1"X-Y-STRESS",6X,"STGRN")
 111  FORMAT(I7,4F13.4)
 790  FORMAT(//17X,"MAX-STRESS",6X,"MIN-STRESS",7X,"ANGLE")
 793  FORMAT(I10,2F17.4,F12.3)
 600  RETURN
      END
```

APPENDIX B: INPUT FILE FOR STUD NO. 1

```
1  0  0  0
FINITE ELEMENT ANALYSIS (SPEC 1,MESS B)
135 156 2 2 10 0 67 -2. -25. 2 60
 1 135 1 156
 1 1933000. 131400. .292 .020 123700. 96700. 150800.
     13500. .449 .022 .390 .287 1484500. 723800.
 2 1723300. 117200. .292 .020 110300. 86200. 134400.
     12100. .449 .022 .390 .287 1418300. 1406600.
 3 2752800. 187200. .292 .020 176200. 137600. 214700.
     19300. .449 .022 .390 .287 1744300. 708400.
 4 1668800. 113500. .292 .020 106800. 83400. 130200.
     11700. .449 .022 .390 .287 1438100. 1438100.
 5 2341400. 159200. .292 .020 149800. 117100. 182600.
     16400. .449 .022 .390 .287 1838800. 1312100.
 6 1890100. 128500. .292 .020 121000. 94500. 147400.
     13200. .449 .022 .390 .287 1631000. 1485300.
 7 2342300. 159300. .292 .020 149900. 117100. 182700.
     16400. .449 .022 .390 .287 1710600. 971500.
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 4  10620. 11160. 11700.
 5   5250.  6460.  8490.
 6  10040. 11160. 11920.
 7   5220.  6460.  8340.
 8  10240. 11050. 11870.
 9   5220.  6460.  8340.
10  10160. 12480. 13640.
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  11  14.    1.71
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  24  27.5   0.
  25  30.    3.42
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  27  30.    0.
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  31  31.25  0.
  32  32.5   3.42
  33  32.5   1.71
  34  32.5   0.
  35  33.75  3.42
  36  33.75  2.565
  37  33.75   .855
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  41  35.    0.
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133	90.	3.42
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148	146		
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153	151		
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156	154		
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APPENDIX C: INPUT FILE FOR STUD NO. 2

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FINITE ELEMENT ANALYSIS (SPEC 2,MESS B)
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 3 1839800. 125100. .292 .020 117700. 92000. 143500.
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 4 1776900. 120800. .292 .020 113700. 88800. 138600.
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10 1725700. 117300. .292 .020 110400. 86300. 134600.
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 27  30.     0.
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 29  31.25   2.587
 30  31.25    .862
 31  31.25   0.
 32  32.5    3.45
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133	90.	3.45
134	90.	1.725
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 92  Ø   .5   17.9
 93  92
 94  Ø   Ø.   15.3
 95  Ø   .5   15.3
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147  Ø  1.   18.8
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154  152
155  149
156  Ø  1.   14.4
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APPENDIX D: INPUT FILE FOR STUD NO. 3

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 3 2102600. 142800. .292 .020 134400. 105000. 163800.
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 5   6590.   7840.   8520.
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    32  32.5   3.42
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    34  32.5   0.
    35  33.75  3.42
    36  33.75  2.565
    37  33.75   .855
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149	0	4.	46.5
150	0	3.25	70.5
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152	0	2.18	66.95
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109	0.0	-25.	

APPENDIX E: INPUT FILE FOR STUD NO. 4

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FINITE ELEMENT ANALYSIS (SPEC 4)
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 2 1640600. 113200. .292 .020 106600. 83300. 129900.
    11700. .449 .022 .390 .287 1528400. 1501300.
 3 2372500. 161300. .292 .020 151800. 116600. 185100.
    16600. .449 .022 .390 .287 1762900. 573300.
 4 1936900. 131700. .292 .020 124000. 96800. 151100.
    13600. .449 .022 .390 .287 1585400. 753700.
 5 1885700. 128200. .292 .020 120700. 94300. 147100.
    13200. .449 .022 .390 .287 1239500. 410400.
 6 1796000. 122100. .292 .020 114900. 89800. 140100.
    12600. .449 .022 .390 .287 1316400. 315000.
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    .390 .257 700. 500.
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 3  5340.  6850. 8200.
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 5  5230. 6860. 7930.
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  7  5.  3.4
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  9  4.75  1.9
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 12  5.25  1.9
 13  7.  3.4
14  7.  1.7
15  7.  0.
16  11.  3.4
17  11.  1.7
18  11.  0.
19  15.  3.4
20  15.  1.7
21  15.  0.
22  16.67  3.4
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27  17.67  3.15
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38  28.5  3.4
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40  28.5  0.
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43  30.  1.7
44  30.  .5
45  30.  0.
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48  31.  2.57
49  31.  1.7
50  31.  .5
51  31.  0.
52  31.56  3.4
53  31.56  2.98
54  31.56  2.57
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64	33.	3.4
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85	39.	3.4
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87	39.	1.7
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92	40.5	1.7
93	40.5	.5
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96	41.5	2.9
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175	0	10.	54.
176	0	20.	89.
177	176		
178	0	15.	54.
179	175		
180	9		
181	179		
182	176		
183	176		
184	178		
185	179		
186	174		
187	175		
188	0	5.	89.
189	0	5.	54.
3	11		
199	1		
41	0.0	-25.	
165	0.0	-25.	

APPENDIX F: INPUT FILE FOR STUD NO. 5

```
FINITE ELEMENT ANALYSIS (SPEC 5)
184 173 2 2 12 0 99 -2. -25. 2 60
 1 184 1 173
 1 2516800. 171300. .292 .020 161200. 125900. 196500.
    17600. .449 .022 .390 .287 1489900. 414600.
 2 1541100. 104800. .292 .020 98600. 77100. 120200.
    10800. .449 .022 .390 .287 1467000. 1467000.
 3 1614200. 109800. .292 .020 103300. 80700. 125900.
    11300. .449 .022 .390 .287 1378000. 435000.
 4 1540000. 104700. .292 .020 98600. 77000. 120100.
    10800. .449 .022 .390 .287 1475200. 1332800.
 5 1790000. 121700. .292 .020 114600. 89500. 139600.
    12500. .449 .022 .390 .267 1286800. 315200.
 6 1562100. 106200. .292 .020 100000. 78100. 121800.
    10900. .449 .022 .390 .287 1434000. 1098800.
 7 1642900. 111700. .292 .020 105100. 82100. 128100.
    11500. .449 .022 .390 .287 1035700. 232100.
 8 1612400. 109600. .292 .020 103200. 80600. 125800.
    11300. .449 .022 .390 .287 1510000. 1369000.
 9 1743400. 118900. .292 .020 111900. 87400. 136400.
    12200. .449 .022 .390 .287 1345100. 228700.
10 1714900. 116600. .292 .020 109800. 85700. 133800.
    12000. .449 .022 .390 .287 1576700. 1414600.
11 89500. 89500. .449 .449 12500. 89500. 12500. 12500.
    .449 .449 .449 .449 64300. 15800.
12 1000.  68. .292 .020 64. 50. 78. 7.
    .449 .022 .390 .287 700. 500.
174 1000. 68. .292 .020 64.
 1   5290.   6970.   8920.
 2   7020.   8980.   10950.
 3   5620.   7250.   8960.
 4   4950.   8820.   11120.
 5   5330.  7210.   9130.
 6   4880.   7939.   10610.
 7   5430.   7460.   9330.
 8   6610.   9090.   11270.
 9   4960.   7020.   9190.
10   8473.   10090.   11710.
11   1000.   2000.   3000.
12   1000.   2000.   3000.
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   2  0.    1.73
   3  0.    0.
   4  3.    3.45
   5  3.    2.78
   6  3.    1.73
   7  3.    0.
   8  4.    3.45
   9  4.    2.78
  10  4.    1.73
  11  4.    0.
  12  6.5   3.45
  13  6.5   1.73
  14  6.5   0.
  15  10.   3.45
  16  10.   1.73
  17  10.   0.
  18  13.5   3.45
  19  13.5   1.73
  20  13.5   0.
  21  16.   3.45
  22  16.   2.78
  23  16.   1.73
  24  16.   .67
  25  16.   0.
  26  17.   3.45
  27  17.   2.78
  28  17.   1.73
  29  17.   .67
  30  17.   0.
  31  20.   3.45
  32  20.   1.73
  33  20.   0.
  34  24.   3.45
  35  24.   1.73
  36  24.   0.
  37  27.5   3.45
  38  27.5   1.73
  39  27.5   0.
  40  30.   3.45
  41  30.   2.95
  42  30.   1.73
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43	30.	.5
44	30.	0.
45	32.	3.45
46	32.	2.95
47	32.	1.73
48	32.	.5
49	32.	0.
50	33.5	3.45
51	33.5	2.95
52	33.5	1.73
53	33.5	.5
54	33.5	0.
55	35.	3.45
56	35.	2.95
57	35.	1.73
58	35.	.5
59	35.	0.
60	36.	3.45
61	36.	2.95
62	36.	2.28
63	36.	1.73
64	36.	.5
65	36.	0.
66	37.08	3.45
67	37.08	2.95
68	37.08	1.73
69	37.08	1.33
70	37.08	.5
71	37.08	0.
72	38.33	3.45
73	38.33	2.95
74	38.33	1.73
75	38.33	1.33
76	38.33	.5
77	38.33	0.
78	39.33	3.45
79	39.33	2.95
80	39.33	2.28
81	39.33	1.73
82	39.33	.5
83	39.33	0.
84	40.5	3.45
85	40.5	2.95
86	40.5	1.73
87	40.5	.5
88	40.5	0.
89	42.	3.45
90	42.	2.95
91	42.	1.73
92	42.	.5
93	42.	0.
94	43.5	3.45
95	43.5	2.95
96	43.5	1.73
97	43.5	.5
98	43.5	0.
99	45.	3.45
100	45.	2.95
101	45.	1.73
102	45.	.5
103	45.	0.
104	46.5	3.45
105	46.5	2.95
106	46.5	1.73
107	46.5	.5
108	46.5	0.
109	48.	3.45
110	48.	2.95
111	48.	1.73
112	48.	.5
113	48.	0.
114	49.5	3.45
115	49.5	2.95
116	49.5	1.73
117	49.5	.5
118	49.5	0.
119	51.	3.45
120	51.	2.95
121	51.	1.73
122	51.	.5
123	51.	0.
124	52.5	3.45
125	52.5	2.95
126	52.5	1.73
127	52.5	.5
128	52.5	0.
129	54.	3.45
130	54.	2.95
131	54.	1.73
132	54.	.5
133	54.	0.
134	55.5	3.45
135	55.5	2.95
136	55.5	1.73

137	55.5	.5
138	55.5	0.
139	57.	3.45
140	57.	2.95
141	57.	1.73
142	57.	.5
143	57.	0.
144	58.5	3.45
145	58.5	2.95
146	58.5	2.17
147	58.5	1.73
148	58.5	.5
149	58.5	0.
150	60.	3.45
151	60.	2.95
152	60.	2.17
153	60.	1.73
154	60.	.3
155	60.	0.
156	61.92	3.45
157	61.92	2.95
158	61.92	2.17
159	61.92	1.73
160	61.92	.3
161	61.92	0.
162	63.5	3.45
163	63.5	2.95
164	63.5	1.73
165	63.5	.3
166	63.5	0.
167	66.	3.45
168	66.	1.73
169	66.	0.
170	70.	3.45
171	70.	1.73
172	70.	0.
173	75.	3.45
174	75.	1.73
175	75.	0.
176	80.	3.45
177	80.	1.73
178	80.	0.
179	85.	3.45
180	85.	1.73
181	85.	0.
182	90.	3.45
183	90.	1.73

184 90. 0.

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6	6	10	9	5	4	6	11
7	7	11	10	6	4	7	2
8	8	9	12	0	3	8	1
9	9	13	12	0	3	9	1
10	9	10	13	0	3	10	1
11	11	14	13	10	4	11	2
12	13	16	15	12	4	12	1
13	14	17	16	13	4	13	2
14	16	19	18	15	4	14	1
15	17	20	19	16	4	15	2
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20	19	20	24	0	3	20	2
21	20	25	24	0	3	21	2
22	22	27	26	21	4	22	1
23	23	28	27	22	4	23	11
24	24	29	28	23	4	24	2
25	25	30	29	24	4	25	2
26	26	27	31	0	3	26	3
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66	64	70	69	0	3	66	6
67	65	71	70	64	4	67	6
68	67	73	72	66	4	68	5
69	68	74	73	67	4	69	11
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71	70	76	75	69	4	71	6
72	71	77	76	70	4	72	6
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74	73	80	79	0	3	74	5
75	73	74	80	0	3	75	5
76	74	81	80	0	3	76	5
77	74	75	81	0	3	77	6
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93	92	97	96	91	4	93	6
94	93	98	97	92	4	94	6

95	95	100	99	94	4	95	5
96	96	101	100	95	4	96	5
97	97	102	101	96	4	97	6
98	98	103	102	97	4	98	6
99	100	105	104	99	4	99	5
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101	102	107	106	101	4	101	6
102	103	108	107	102	4	102	6
103	105	110	109	104	4	103	5
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105	107	112	111	106	4	105	6
106	108	113	112	107	4	106	6
107	110	115	114	109	4	107	5
108	111	116	115	110	4	108	5
109	112	117	116	111	4	109	6
110	113	118	117	112	4	110	6
111	115	120	119	114	4	111	5
112	116	121	120	115	4	112	5
113	117	122	121	116	4	113	6
114	118	123	122	117	4	114	6
115	120	125	124	119	4	115	5
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118	123	128	127	122	4	118	6
119	125	130	129	124	4	119	5
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122	128	133	132	127	4	122	6
123	130	135	134	129	4	123	7
124	131	136	135	130	4	124	7
125	132	137	136	131	4	125	8
126	133	138	137	132	4	126	8
127	135	140	139	134	4	127	7
128	136	141	140	135	4	128	7
129	137	142	141	136	4	129	8
130	138	143	142	137	4	130	8
131	140	145	144	139	4	131	7
132	140	146	145	0	3	132	7
133	140	141	146	0	3	133	7
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137	142	143	148	0	3	137	8
138	143	149	148	0	3	138	8
139	145	151	150	144	4	139	7
140	146	152	151	145	4	140	7
141	147	153	152	146	4	141	7

142	147	148	153	0	3	142	8
143	148	154	153	0	3	143	8
144	148	149	154	0	3	144	8
145	149	155	154	0	3	145	8
146	151	157	156	150	4	146	7
147	152	158	157	151	4	147	7
148	153	159	158	152	4	148	11
149	154	160	159	153	4	149	12
150	155	161	160	154	4	150	8
151	157	163	162	156	4	151	7
152	157	158	163	0	3	152	7
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159	163	164	168	0	3	159	7
160	163	168	167	0	3	160	7
161	164	165	168	0	3	161	8
162	165	166	169	0	3	162	8
163	165	169	168	0	3	163	8
164	168	171	170	167	4	164	7
165	169	172	171	168	4	165	8
166	171	174	173	170	4	166	9
167	172	175	174	171	4	167	10
168	174	177	176	173	4	168	9
169	175	178	177	174	4	169	10
170	177	180	179	176	4	170	9
171	178	181	180	177	4	171	10
172	180	183	182	179	4	172	9
173	181	184	183	180	4	173	10

1	0	3.	73.
2	0	4.	73.
3	0	5.5	73.
4	0	4.2	28.
5	0	4.	70.4
6	0	45.	45.
7	0	4.	27.
8	5		
9	0	3.	70.4
10	0	5.5	70.4
11	7		
12	0	5.	70.4
13	0	5.	27.
14	0	8.	70.4
15	0	8.	27.
16	0	15.	70.4
17	0	12.	70.4
18	0	24.	70.4
19	0	24.	27.
20	0	15.	27.
21	0	10.	27.
22	17		
23	6		
24	0	20.	27.
25	21		
26	0	12.	67.8
27	0	15.	67.8
28	0	24.	67.8
29	0	24.	26.
30	0	15.	26.
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36	0	10.	63.2
37	0	12.5	63.2
38	36		
39	33		
40	0	6.	34.
41	40		
42	34		
43	34		
44	0	10.	34.
45	44		
46	34		
47	34		
48	44		
49	44		
50	36		
51	32		
52	39		
53	39		
54	0	12.	58.6
55	54		
56	0	10.	58.6
57	56		
58	0	8.	42.
59	58		
60	0	15.	58.6
61	60		
62	60		

63	60		
64	0	12.	42.
65	0	10.	42.
66	65		
67	0	6.	58.6
68	0	12.	59.5
69	0	45.	45.
70	0	12.	42.9
71	0	10.	42.9
72	0	6.	42.9
73	0	15.	59.5
74	73		
75	73		
76	73		
77	70		
78	71		
79	71		
80	72		
81	0	10.	59.5
82	68		
83	81		
84	81		
85	0	8.	42.9
86	85		
87	0	6.	59.5
88	87		
89	0	6.	42.9
90	89		
91	87		
92	87		
93	89		
94	89		
95	0	3.	59.5
96	95		
97	0	4.	42.9
98	97		
99	95		
100	95		
101	97		
102	97		
103	0	1.	59.5
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105	101		
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107	103		
108	103		
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111	0	2.	59.5
112	111		
113	0	3.	42.9
114	113		
115	99		
116	99		
117	113		
118	113		
119	0	4.	60.3
120	119		
121	0	4.	43.8
122	121		
123	0	5.	60.3
124	123		
125	0	5.	60.3
126	125		
127	0	8.	63.4
128	127		
129	0	8.	40.4
130	129		
131	0	10.	63.4
132	0	12.	63.4
133	132		
134	0	12.	40.4
135	134		
136	134		
137	134		
138	131		
139	0	15.	63.4
140	0	19.	63.4
141	140		
142	0	19.	40.4
143	142		
144	142		
145	0	15.	40.4
146	138		
147	138		
148	0	45.	45.
149	0	45.	45.
150	0	10.	40.4
151	132		
152	139		
153	140		
154	153		
155	144		
156	144		
157	145		
158	146		
159	151		
160	158		
161	134		
162	150		
163	150		
164	127		
165	129		
166	0	6.	66.5
167	0	6.	37.
168	0	4.	67.1
169	0	4.	38.8
170	0	2.	67.1
171	0	2.	38.8
172	0	2.	67.6
173	0	2.	40.6
3	11		
184	1		
40	0.0	-25.	
150	0.0	-25.	

APPENDIX G: INPUT FILE FOR SIMULATION ANALYSIS

```
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FINITE ELEMENT ANALYSIS
1519400. 345000. 11370. 2280. 10440. 7950. .651 .372
137 104 2 2 2 0 67 -2. -25. 2 50 1 137 1 104
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  2  0.    1.75
  3  0.    0.
  4  2.5   3.5
  5  2.5   1.75
  6  2.5   0.
  7  5.    3.5
  8  5.    1.75
  9  5.    0.
 10  7.5   3.5
 11  7.5   1.75
 12  7.5   0.
 13  10.   3.5
 14  10.   1.75
 15  10.   0.
 16  12.5  3.5
 17  12.5  1.75
 18  12.5  0.
 19  15.   3.5
 20  15.   1.75
 21  15.   0.
 22  17.5  3.5
 23  17.5  1.75
 24  17.5  0.
 25  20.   3.5
 26  20.   1.75
 27  20.   0.
 28  22.5  3.5
 29  22.5  1.75
 30  22.5  0.
 31  25.   3.5
 32  25.   1.75
 33  25.   0.
 34  27.5  3.5
 35  27.5  1.75
 36  27.5  0.
 37  30.   3.5
 38  30.   3.
 39  30.   1.75
 40  30.   .5
 41  30.   0.
 42  32.5  3.5
 43  32.5  3.
 44  32.5  1.75
 45  32.5  .5
 46  32.5  0.
 47  35.   3.5
 48  35.   3.
 49  35.   1.75
 50  35.   .5
 51  35.   0.
 52  37.5  3.5
 53  37.5  3.
 54  37.5  1.75
 55  37.5  .5
 56  37.5  0.
 57  40.   3.5
 58  40.   3.
 59  40.   1.75
 60  40.   .5
 61  40.   0.
 62  42.5  3.5
 63  42.5  3.
 64  42.5  1.75
 65  42.5  .5
 66  42.5  0.
 67  45.   3.5
 68  45.   3.
 69  45.   1.75
 70  45.   .5
 71  45.   0.
 72  47.5  3.5
 73  47.5  3.
 74  47.5  1.75
 75  47.5  .5
 76  47.5  0.
 77  50.   3.5
 78  50.   3.
 79  50.   1.75
 80  50.   .5
 81  50.   0.
 82  52.5  3.5
 83  52.5  3.
 84  52.5  1.75
 85  52.5  .5
 86  52.5  0.
 87  55.   3.5
 88  55.   3.
```

89	55.	1.75		
90	55.	.5		
91	55.	0.		
92	57.5	3.5		
93	57.5	3.		
94	57.5	1.75		
95	57.5	.5		
96	57.5	0.		
97	60.	3.5		
98	60.	3.		
99	60.	1.75		
100	60.	.5		
101	60.	0.		
102	62.5	3.5		
103	62.5	1.75		
104	62.5	0.		
105	65.	3.5		
106	65.	1.75		
107	65.	0.		
108	67.5	3.5		
109	67.5	1.75		
110	67.5	0.		
111	70.	3.5		
112	70.	1.75		
113	70.	0.		
114	72.5	3.5		
115	72.5	1.75		
116	72.5	0.		
117	75.	3.5		
118	75.	1.75		
119	75.	0.		
120	77.5	3.5		
121	77.5	1.75		
122	77.5	0.		
123	80.	3.5		
124	80.	1.75		
125	80.	0.		
126	82.5	3.5		
127	82.5	1.75		
128	82.5	0.		
129	85.	3.5		
130	85.	1.75		
131	85.	0.		
132	87.5	3.5		
133	87.5	1.75		
134	87.5	0.		
135	90.	3.5		
136	90.	1.75		
137	90.	0.		
1	2	5	4	1
2	3	6	5	2

3	5	8	7	4
4	6	9	8	5
5	8	11	10	7
6	9	12	11	8
7	11	14	13	10
8	12	15	14	11
9	14	17	16	13
10	15	18	17	14
11	17	20	19	16
12	18	21	20	17
13	20	23	22	19
14	21	24	23	20
15	23	26	25	22
16	24	27	26	23
17	26	29	28	25
18	27	30	29	26
19	29	32	31	28
20	30	33	32	29
21	32	35	34	31
22	33	36	35	32
23	34	35	38	0
24	34	38	37	0
25	35	39	38	0
26	35	40	39	0
27	35	36	40	0
28	36	41	40	0
29	38	43	42	37
30	39	44	43	38
31	40	45	44	39
32	41	46	45	40
33	43	48	47	42
34	44	49	48	43
35	45	50	49	44
36	46	51	50	45
37	48	53	52	47
38	49	54	53	48
39	50	55	54	49
40	51	56	55	50
41	53	58	57	52
42	54	59	58	53
43	55	60	59	54
44	56	61	60	55
45	58	63	62	57
46	59	64	63	58
47	60	65	64	59
48	61	66	65	60
49	63	68	67	62
50	64	69	68	63
51	65	70	69	64
52	66	71	70	65
53	68	73	72	67

54	69	74	73	68
55	70	75	74	69
56	71	76	75	70
57	73	78	77	72
58	74	79	78	73
59	75	80	79	74
60	76	81	80	75
61	78	83	82	77
62	79	84	83	78
63	80	85	84	79
64	81	86	85	80
65	83	88	87	82
66	84	89	88	83
67	85	90	89	84
68	86	91	90	85
69	88	93	92	87
70	89	94	93	88
71	90	95	94	89
72	91	96	95	90
73	93	98	97	92
74	94	99	98	93
75	95	100	99	94
76	96	101	100	95
77	97	98	102	0
78	98	103	102	0
79	98	99	103	0
80	99	100	103	0
81	100	104	103	0
82	100	101	104	0
83	103	106	105	102
84	104	107	106	103
85	106	109	108	105
86	107	110	109	106
87	109	112	111	108
88	110	113	112	109
89	112	115	114	111
90	113	116	115	112
91	115	118	117	114
92	116	119	118	115
93	118	121	120	117
94	119	122	121	118
95	121	124	123	120
96	122	125	124	121
97	124	127	126	123
98	125	128	127	124
99	127	130	129	126
100	128	131	130	127
101	130	133	132	129
102	131	134	133	130
103	133	136	135	132
104	134	137	136	133

APPENDIX H: FIRST PART OF COMPUTER OUTPUT FOR ANALYSIS OF STUD NO. 2

FINITE ELEMENT ANALYSIS (SPEC 2,MESS B)

LOADS

NODE	X	Y
25	0.00	-25.00
109	0.00	-25.00

DISPLACEMENTS

NODE	X	Y
67	.52087E-02	-.78595E-01
68	.52716E-02	-.78659E-01
69	.53345E-02	-.78588E-01

ELEMENT	X-STRESS	Y-STRESS	X-Y-STRESS	STGRN
79	-.1644E+03	.1264E+01	.7003E+01	-.1644E+03
80	-.3453E+03	.3596E+01	-.5174E+01	-.3453E+03
81	.1475E+02	-.6023E+01	.2430E-01	.1475E+02
82	-.3452E+03	.3597E+01	.5245E+01	-.3452E+03
83	-.1644E+03	.1280E+01	-.6939E+01	-.1644E+03
84	.1646E+03	-.1116E+01	.5990E+01	.1646E+03
85	.1538E+02	.5321E+01	-.2525E-01	.1538E+02
86	.3150E+03	-.2990E+01	-.4369E+01	.3150E+03
87	.3151E+03	-.2989E+01	.4300E+01	.3151E+03
88	.1646E+03	-.1100E+01	-.6054E+01	.1646E+03

	MAX-STRESS	MIN-STRESS	ANGLE
79	.1559E+01	-.1647E+03	2.417
80	.3673E+01	-.3454E+03	-.849
81	.1475E+02	-.6023E+01	89.933
82	.3676E+01	-.3453E+03	.861
83	.1571E+01	-.1647E+03	-2.394
84	.1648E+03	-.1332E+01	87.933
85	.1538E+02	.5321E+01	-89.856
86	.3151E+03	-.3050E+01	-89.213
87	.3152E+03	-.3047E+01	89.226
88	.1648E+03	-.1320E+01	-87.911

FINITE ELEMENT ANALYSIS (SPEC 2,MESS B) LOAD CASE 15

LOADS

NODE	X	Y
25	0.00	-375.00
109	0.00	-375.00

DISPLACEMENTS

NODE	X	Y
67	.78131E-01	-.11789E+01
68	.79075E-01	-.11799E+01
69	.80017E-01	-.11788E+01

ELEMENT	X-STRESS	Y-STRESS	X-Y-STRESS	STGRN
79	-.2466E+04	.1895E+02	.1050E+03	-.2466E+04
80	-.5180E+04	.5394E+02	-.7761E+02	-.5180E+04
81	.2212E+03	-.9035E+02	.3645E+00	.2212E+03
82	-.5178E+04	.5396E+02	.7867E+02	-.5178E+04
83	-.2466E+04	.1921E+02	-.1041E+03	-.2466E+04
84	.2469E+04	-.1674E+02	.8984E+02	.2469E+04
85	.2308E+03	.7981E+02	-.3787E+00	.2308E+03
86	.4725E+04	-.4485E+02	-.6554E+02	.4725E+04
87	.4727E+04	-.4483E+02	.6450E+02	.4727E+04
88	.2469E+04	-.1649E+02	-.9081E+02	.2469E+04

	MAX-STRESS	MIN-STRESS	ANGLE
79	.2339E+02	-.2470E+04	.162
80	.5509E+02	-.5181E+04	-.057
81	.2212E+03	-.9035E+02	.017
82	.5514E+02	-.5179E+04	.058
83	.2356E+02	-.2470E+04	-.161
84	.2473E+04	-.1998E+02	17.616
85	.2308E+03	.7981E+02	.019
86	.4726E+04	-.4575E+02	-5.834
87	.4728E+04	-.4570E+02	5.749
88	.2473E+04	-.1981E+02	-17.932

APPENDIX I: Moisture Content and Specific Gravity of the Studs Used in the Study

Specimen Number	Moisture Content (%)	Specific Gravity
1	7.84	0.493
2	7.32	0.470
3	7.86	0.523
4	7.06	0.516
5	7.84	0.582

APPENDIX J: MODULI OF ELASTICITY AND STRESSES OF SMALL CLEAR SPECIMENS CUT FROM THE FIVE STUDS AFTER TEST

Specimen number*	Moduli of elasticity (psi) E_1	E_2	E_3	Stresses (psi) S_1	S_2	S_3
1-C-A-1	1,735,800	1,263,500	372,800	4,630	5,740	7,990
1-C-A-2	2,130,200	1,705,400	1,074,800	4,990	6,020	8,060
Average (1-C-A)	1,933,000	1,484,500	723,800	4,810	5,880	8,030
1-C-B-1	2,408,500	1,627,100	626,100	4,930	6,680	8,490
1-C-B-2	3,097,000	1,861,500	790,700	6,260	7,380	8,360
Average (1-C-B)	2,752,800	1,744,300	708,400	5,600	7,030	8,430
1-C-C-1	2,758,800	1,959,900	1,111,000	4,270	6,220	8,580
1-C-C-2	2,490,200	2,018,100	1,998,000	5,720	6,830	8,420
1-C-C-3	1,775,200	1,538,500	827,200	5,760	6,340	8,460
Average (1-C-C)	2,341,400	1,838,800	1,312,100	5,250	6,460	8,490
Average (1-C)	2,342,300	1,710,600	971,500	5,220	6,460	8,340
1-T-A-1	1,609,100	1,609,100	1,609,100	10,990	10,990	10,990
1-T-A-2	1,923,800	1,559,100	1,559,100	8,510	9,240	9,970
1-T-A-3	1,636,800	1,086,800	1,033,700	8,920	9,390	10,100
Average (1-T-A)	1,723,300	1,418,300	1,400,600	9,470	9,870	10,350

Specimen number	Moduli of elasticity (psi) E_1	E_2	E_3	Stresses (psi) S_1	S_2	S_3
1-T-B-1	1,896,300	1,620,600	1,620,600	11,120	11,440	11,760
1-T-B-2	1,441,300	1,255,500	1,255,500	10,110	10,870	11,630
Average (1-T-B)	1,668,800	1,438,100	1,438,100	10,620	11,160	11,700
1-T-D	1,833,300	1,787,200	1,787,200	10,240	11,050	11,870
1-T-E-1	2,215,500	1,927,000	1,462,000	8,630	13,640	15,500
1-T-E-2	2,313,100	1,831,100	1,037,500	12,310	13,380	14,080
1-T-E-3	2,142,000	2,002,900	2,002,900	9,530	10,430	11,340
Average (1-T-E)	2,223,500	1,920,300	1,500,800	10,160	12,480	13,640
Average (1-T)	1,890,100	1,631,000	1,485,300	10,040	11,160	11,920
2-C-A	2,102,000	1,492,900	671,400	6,830	7,430	7,930
2-C-B	1,839,800	1,334,300	287,900	5,140	6,710	7,910
2-C-D	2,115,200	1,670,900	1,037,400	3,250	6,250	7,710
2-C-E	2,594,000	1,884,200	383,000	5,310	6,960	7,880
Average (2-C)	2,162,700	1,595,600	594,900	5,130	6,840	7,860

Specimen number	Moduli of elasticity (psi) E_1	E_2	E_3	Stresses (psi) S_1	S_2	S_3
2-T-A	1,787,600	1,582,600	1,582,600	6,130	7,410	8,700
2-T-D	1,919,600	753,500	753,500	7,660	8,390	9,140
2-T-E-1	1,687,700	1,584,600	1,584,600	5,810	6,870	7,930
2-T-E-2	1,712,000	1,616,500	1,616,500	8,720	9,130	9,540
2-T-E-3	1,777,400	1,777,400	1,777,400	9,140	9,140	9,140
Average (2-T-E)	1,725,700	1,659,500	1,659,500	7,890	8,380	8,870
Average (2-T)	1,776,900	1,462,900	1,462,900	7,490	8,190	8,890
3-C-A-1	2,507,900	1,469,900	458,100	6,960	7,660	8,330
3-C-A-2	2,439,800	1,665,300	333,900	4,690	6,810	8,280
Average (3-C-A)	2,473,800	1,567,600	396,000	5,820	7,240	8,300
3-C-B-1	1,734,600	1,548,800	618,200	5,190	6,440	8,540
3-C-B-2	2,466,500	1,773,200	434,200	7,420	8,730	9,730
Average (3-C-B)	2,100,600	1,661,000	526,200	6,310	7,590	9,140
3-C-C-1	2,515,700	1,794,500	680,700	6,730	7,810	8,300
3-C-C-2	2,757,800	2,127,900	1,369,700	6,270	7,750	8,740
3-C-C-3	1,826,500	1,399,900	507,600	6,760	7,950	8,530
Average (3-C-C)	2,366,700	1,774,100	852,700	6,590	7,840	8,520

Specimen number	Moduli of elasticity (psi) E_1	E_2	E_3	Stresses (psi) S_1	S_2	S_3
3-C-D-1	2,635,000	1,799,800	373,300	4,930	6,810	8,680
3-C-D-2	2,056,300	1,804,800	1,746,600	6,260	7,210	8,560
Average (3-C-D)	2,345,700	1,802,300	1,060,000	5,600	7,010	8,620
3-C-E-1	2,009,800	1,678,200	425,000	6,030	7,410	8,730
3-C-E-2	1,896,200	1,405,700	267,300	7,110	8,170	8,790
Average (3-C-E)	1,953,000	1,541,900	346,100	6,570	7,790	8,760
Average (3-C)	2,258,800	1,678,900	655,900	6,220	7,530	8,650
3-T-A-1	2,542,700	2,316,600	1,464,600	10,910	14,820	16,370
3-T-A-2	2,205,000	1,933,300	1,769,100	11,150	13,280	17,660
3-T-A-3	2,109,400	2,018,200	1,740,500	9,640	12,800	18,090
Average (3-T-A)	2,285,700	2,089,400	1,658,100	10,570	13,630	17,370
3-T-B-1	2,288,800	1,917,800	1,917,800	8,090	11,140	14,190
3-T-B-2	2,209,100	1,849,900	1,849,900	8,770	12,160	15,560
Average (3-T-B)	2,248,900	1,883,800	1,883,800	8,430	11,650	14,870
3-T-C	2,134,900	1,991,900	1,652,900	7,290	11,140	16,640
3-T-E-1	2,018,900	1,915,200	1,915,200	6,630	11,180	15,730

Specimen number	Moduli of elasticity (psi) E_1	E_2	E_3	Stresses (psi) S_1	S_2	S_3
3-T-E-2	2,441,400	1,363,300	1,363,300	14,020	14,730	15,460
Average (3-T-E)	2,230,100	1,639,200	1,639,200	10,320	12,950	15,590
Average (3-T)	2,243,700	1,913,300	1,709,100	9,560	12,650	16,210
4-C-A	1,820,600	1,341,000	363,000	4,010	6,020	7,920
4-C-B-1	2,319,000	1,698,400	542,400	4,870	6,610	8,200
4-C-B-2	2,426,100	1,827,500	604,300	5,820	7,100	8,200
Average (4-C-B)	2,372,500	1,762,900	573,300	5,340	6,850	8,200
4-C-C	1,936,900	1,585,400	753,700	4,010	5,560	6,970
4-C-D-1	2,329,600	1,458,800	510,300	5,770	7,040	7,920
4-C-D-2	1,441,800	1,020,200	310,600	4,690	6,680	7,950
Average (4-C-D)	1,885,700	1,239,500	410,400	5,230	6,860	7,930
4-C-E	1,796,000	1,316,400	315,000	3,860	5,700	7,550
Average (4-C)	2,010,000	1,463,900	485,600	4,720	6,390	7,810
4-T-B-1	1,580,100	1,429,700	1,348,500	6,630	9,610	13,300
4-T-B-2	1,662,200	1,649,000	1,649,000	4,050	7,430	10,810

Specimen number	Moduli of elasticity (psi) E_1	E_2	E_3	Stresses (psi) S_1	S_2	S_3
4-T-B-3	1,679,400	1,506,500	1,506,500	6,750	9,340	11,940
Average (4-T)	1,640,600	1,528,400	1,501,300	5,810	8,790	12,020
5-C-A	2,518,800	1,489,900	414,600	5,290	6,970	8,920
5-C-B-1	1,598,200	1,362,700	335,600	5,910	7,450	9,130
5-C-B-2	1,630,300	1,393,300	534,500	5,340	7,050	8,800
Average (5-C-B)	1,614,200	1,378,000	435,000	5,620	7,250	8,960
5-C-D-1	1,632,600	897,200	151,100	6,330	7,920	9,080
5-C-D-2	1,653,200	1,174,300	313,200	4,540	7,030	9,580
Average (5-C-D)	1,642,900	1,035,700	232,100	5,430	7,480	9,330
5-C-E-1	1,551,700	1,286,300	283,100	4,530	6,910	9,640
5-C-E-2	1,945,200	1,403,900	174,300	5,390	7,140	8,730
Average (5-C-E)	1,748,400	1,345,100	228,700	4,960	7,020	9,190
Average (5-C)	1,790,000	1,286,800	315,200	5,330	7,210	9,130
5-T-A-1	1,570,600	1,463,300	1,463,300	8,650	10,260	11,880
5-T-A-2	1,511,600	1,470,700	1,470,700	5,400	7,710	10,020
Average (5-T-A)	1,541,100	1,467,000	1,467,000	7,020	8,980	10,950