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A STUDY OF RSI UNDER COMBINED STRESSES

By J. J. Kibler and B. W. Rosen

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SYMBOLS LIST

A,B,C,A_i,a_i,b_i,c_i	Constants as defined in text.
a,b,c,	RSI cell edge dimensions.
e	Eccentricity of fiber distribution
E_i	Young's Modulus in i^{th} direction.
f_i	Normalized number of fiber intersections per scanning line length per orientation of scanning line on photomicrograph.
$f(\theta)$	Continuous distribution function for fiber distribution in RSI.
$g(\phi)$	Discrete fiber distribution function for representing $f(\theta)$.
G	Shear modulus.
L	Total length of each fiber in cell.
N,S,T	Coordinate System for RSI tile N = through-the-thickness S,T = in the plane of tile.
V	Least squares - sum of squared residuals.
S	Variance of fiber distribution.
α	Orientation of vertical planes of trusses.
$\bar{\alpha}$	Locator of discrete angle within constant area interval for $f(\theta)$.
β	Orientation of fiber pairs in each plane.
$\Delta L/L$	Thermal expansion per unit length per degree Kelvin.
θ	Fiber orientation within continuous fiber distribution.
$\bar{\theta}$	Mean orientation of fiber distribution.
σ	Stress component.
ϕ	Fiber orientation within discrete fiber distribution.
ν	Poisson's ratio.
1,2,3	SPACE cell axes.

INTRODUCTION

Analytical techniques for predicting the mechanical behavior of rigidized surface insulation materials (RSI) under generalized states of stress were developed by Materials Sciences Corporation (MSC) under contract NAS1-11819 (the results are in Ref. 1). Initial computations indicated that the model was sufficiently realistic to be able to predict the properties of RSI material with reasonable accuracy, given only photomicrographs of the material and some basic fiber material properties. The previous work also demonstrated the ability of the RSI model to predict the sensitivity of various mechanical properties of RSI to changes in the numerous geometric parameters contributing to the final RSI material.

The current effort has been applied to determining how a typical RSI material would behave under combined loading states. In particular, the thermal stress states induced during re-entry of the Space Shuttle were of prime concern. A typical RSI tile was analyzed for re-entry thermal stresses under computed thermal gradients for a model of the RSI material. The results of the thermal stress analyses were then used to aid in defining typical combined stress states for the failure analysis of RSI using the MSC-SPACE Program.

An additional objective of this study was to modify the program described in Ref. 1 to make it more user-oriented. A complete listing of the program and supporting documentation are provided in the Appendices to enable others to utilize the program.

METHOD OF ANALYSIS

The Reusable Surface Insulation (RSI) Materials studied are rigidized fiber networks. The analysis of RSI materials as developed in Refs. 1 and 2 is based upon the modeling of the actual material by a space frame structure in which each section of fiber between nodes is treated as a beam having some initial curvature. The model utilizes a series of different, regular arrays of trusses, having various orientations, to represent the actual three dimensional fiber array, see Fig. 1. This may be regarded as representing a continuous statistical distribution function by a series of discrete delta functions of differing magnitude (i.e., approximating a curve with a bar graph). The analysis of RSI materials requires treatment of nonhomogeneous materials. When this material is subjected to any loading, the average deformation of the material depends both on the physical and geometrical variabilities of its constituents. The theory of deformation of heterogeneous media, considering physical variability from phase to phase has been reviewed in Ref. 2 and will not be repeated here.

The micromechanical RSI model follows the concept that the three-dimensional random network of fibers can be represented by a basic set of truss elements oriented in different planes, as introduced by Rosen and Bagchi [2]. Results obtained from the analysis of that model have shown encouraging agreement when compared with experimental values. This agreement has motivated the present development of a general model to evaluate the characteristics of RSI material exhibiting both geometrical and material variability. The geometrical and material variabilities of the actual material are represented by a number of trusses oriented in different planes with variable material and geometrical properties. The concept of parallel trusses is introduced to represent such geometric factors as orientation, fiber aspect ratio, eccentricity, volume fraction, etc.

Basically, the approach is to represent the continuous statistical distribution function defining fiber geometry by a series of elements having discrete values of each of the variables. This may be viewed physically as an approximate model, or it may be viewed mathematically as a discrete representation of a continuous function.

Details of the analytical model are available in Refs. 1 and 2. A description of how photomicrograph data of RSI material may be reduced to a useable form, and a description of the input variables required for utilization of the RSI computer program, "SPACE", are provided in the Appendices of this report.

The design and analysis of RSI tiles consist of several major aspects. Design studies require average RSI mechanical properties and a suitable understanding of the failure mechanisms under various loading conditions. Micromechanical analyses can provide average properties based on an understanding of the microstructure of the material and fiber properties. In addition, micromechanical analyses can be utilized to develop a suitable failure criteria to be applied during design studies utilizing average properties and finite element analyses.

Previous studies concentrated upon the mathematical development of the RSI model and subsequent justification of the validity of the model and computer program. During the current study several additional steps have been taken towards utilizing the SPACE program to develop design criteria for RSI materials. A finite element model of an RSI tile was utilized with average RSI properties to determine critical stress states existing in the RSI under a typical set of re-entry heating conditions. Photomicrographs of the RSI were analyzed to generate input for the SPACE Program to develop a micromechanical model of the RSI. The resulting predicted properties of the RSI which were generated from the photomicrograph data and fiber data from Ref. 1, were then compared with experimentally measured properties and excellent agreement was obtained. The RSI model generated by the SPACE Program was then utilized along with the critical stress states as determined by the finite element analyses to develop a set of failure surfaces for the RSI under combined stresses. The results, as described below, represent the first predictions of the behavior of RSI under combined stress states, based on the micromechanical model.

RSI TILE ANALYSIS

A typical RSI tile subjected to re-entry heating was analyzed using finite elements and average mechanical properties. The results of the finite element analyses were subsequently used to define both critical stress levels and typical combined stress states existing within the RSI during re-entry heating conditions.

The RSI tile modeled with finite elements is shown in Fig. 2. The model consisted of thirty-one elements along the tile and twenty-four elements through-the-thickness, with symmetry boundary conditions applied along the centerline of the model. An aluminum substrate 3.81 mm thick was assumed, along with a 6.25 mm thick foam pad bonding the RSI material to the aluminum. The properties of the aluminum and foam did not significantly influence the analytical results because only heat-up of the tile was considered and the base of the tile never exceeded 75F.

The average mechanical properties of the RSI and ceramic coating materials, obtained from Ref. 3, are listed in Table 1 as functions of temperature. Through-the-thickness temperature gradients for a typical re-entry heat-up period were also obtained from Ref. 3 and are listed in Table 2.

Several re-entry gradients were analyzed, and it was found that the 240 second gradient yielded the worst stress states in the tile. The highest stresses in the center of the tile were found to be the in-plane stresses several elements under the coating at the centerline, see Fig. 2. The stress state at that location was nearly unidirectional with a magnitude to approximately 0.1 MN/m^2 in-plane, see Table 3. At the outer edge of the tile (Area 2 of Fig. 2) combined stresses existed with typical magnitudes of 0.014MN/m^2, in the through-the-thickness direction, 0.07 MN/m^2 in the in-plane direction, and 0.02 MN/m^2 shear stresses, see also Table 3.

The results of the finite element study of RSI under re-entry heatup conditions indicate that the most useful combined stress failure surface data would be for combined loading conditions of positive tension in both the in-plane and through-the-thickness directions, plus shear stresses. Consequently, the studies with the SPACE Program for combined stress failure were concentrated upon these types of loading conditions.

ANALYSIS OF RSI UNDER COMBINED STRESSES

Before attempting to predict the behavior of RSI under combined stresses, it was necessary to define a suitable material model for the SPACE Program. An estimate of the fiber properties was available from Ref. 1, and photomicrographs of a typical RSI material were obtained from Ref. 4. In addition, measured mechanical properties of the RSI were available through Ref. 3, thus providing an experimental check on the predicted moduli and strengths in the in-plane and through-the-thickness directions. Assuming that reasonable agreement could be obtained between the predicted and measured properties, one could then place a reasonable degree of confidence in the predicted behavior under combined stress states.

The photomicrographs of RSI were studied to determine fiber distributions in each of the principal planes of the material. The raw photomicrograph data consisted of number of fiber intersections per given line length versus line orientation. The fiber distribution function was assumed to be of the form:

$$\frac{f(\theta)}{\bar{R}} = \frac{1+e\cos 2(\theta - \bar{\theta})}{1 + \frac{2e}{\pi}\sin 2\bar{\theta}} \tag{1}$$

where $\bar{\theta}$ gives the orientation of the distribution and e controls the eccentricity, or strength of orientation of the fiber distribution. The method of reducing the photomicrograph data to a fiber distribution function given by equation 1 with e and $\bar{\theta}$ known, is given in Appendix A.

Very interesting results were obtained for the fiber distribution functions as obtained from the photomicrograph data. The fiber distributions for the two through-the-thickness sections, the N-S and N-T planes of Fig. 2, were surprisingly similar. The distribution functions for both planes showed $\bar{\theta} \simeq 90°$ and distribution eccentricities of 0.35 and 0.43. In contrast, the third plane photomicrograph, the S-T plane, showed a circular fiber distribution, indicating no preferential fiber orientation.

Figs. 3 through 5 present the photomicrograph data and best fit distribution function, equation 1, to the data for the three planes examined, namely, the N-S, N-T and S-T planes. The data points plotted in Figs. 3 through 5 represent the data obtained from the photomicrographs. That is, each point represents the number of fibers which intersected a given length scanning line which was oriented at an angle of $\theta + 90°$ at a given location on the photomicrograph. A fixed length scanning line was oriented at θ degrees at twenty different locations on each photomicrograph and the number of fibers intersecting the line was determined. The ninety degree shift in the data was required since the highest orientation of fibers would show the largest number of intersections when the scanning line was oriented at 90° to that direction.

Based on the above, an in-plane fiber distribution with an eccentricity of 0.40 and mean fiber angle of 90° was assumed representative of the material in the N-S and N-T planes with no preferential orientation in the S-T plane. Fiber truss angles could thus be defined as in Appendix A. Appendix B provides the data supplied to the SPACE Program to represent the RSI material, and an example of the program input and output are provided in Appendix C.

A comparison of the measured mechanical properties of RSI and those predicted using the SPACE Program and above described model is provided in Table 4. As can be seen, a large variation occurs in the measured properties. Large experimental variations in properties preclude a critical comparison between the analytical model and experimentally determined properties. This does not prove to be a severe shortcoming for the current program, however, because as seen in Table 3, the predicted properties fall well within the range of measured values. The shear modulus is the only property which is out of the range of the experimental data. This difference could arise for several reasons. First, the SPACE Program assumes that the fibers intersect at rigid joints, which would over predict the shear stiffness. Secondly, although test methods do exist, shear properties are difficult to obtain. In the case of RSI, it could be that edge effects may have significantly reduced the effective cross-sectional area of the test specimen, resulting in a substantial reduction in measured shear modulus.

It is significant to note that the model accurately predicts the in-plane and through-the-thickness properties, which are very different in each direction. This result is significant in that the differences between the in-plane and through-the-thickness properties in the SPACE model have a direct correlation to the fiber distributions chosen to represent the spatial distribution of fibers. Consequently, the reasonable agreement between the model and measurement indicates that there is merit in the current method of obtaining fiber distribution data from photomicrographs and reducing the continuous distribution to a discrete distribution.

Given a valid model for the RSI material, various sets of combined stress states were applied to the model to develop an understanding of the behavior of the material under combined stresses. Although the SPACE Program employs incremental loading, the loading increments are applied to all stress components such that the initial stress ratios are maintained. That is, the initial stress tensor is increased in magnitude to failure of the material. Since the finite element analyses indicated that the most severe stress states were combinations of tension through-the-thickness and in-plane, along with shear, the SPACE analyses were concentrated on these cases. Namely, the intersection of the failure surface with the $\sigma_n - \sigma_s$, $\sigma_n - \sigma_{ns}$, and $\sigma_s - \sigma_{ns}$ planes for room temperature material were determined since these contours would reveal the basic characteristics of the failure surface. Figs. 6 through 8 present the intersections of the failure surface with the above-mentioned planes. Note that the regions of high stresses as defined by the finite element analyses and indicated in Figs. 6 through 8 fall well below the predicted failure surface for re-entry heat-up conditions.

DISCUSSION

The correlation between the analytical model for RSI and the measured elastic constants and strengths of the RSI in the two principal material directions indicates the validity of the analytical model. In particular, the agreement in elastic moduli in the two principal material directions lends credibility to the method of defining the fiber distributions using photomicrograph data.

The thermal stress analyses of the typical RSI tile provided some critical stress states to be evaluated using the SPACE Program. Since only one re-entry heating cycle was analyzed, one can only assume that the stress states obtained were typical and not necessarily "worst case". However, the intent of the thermal stress analyses was to provide some typical combined stress states, and not as an exercise to determine a "worst case" condition for a typical shuttle mission. The results of the analyses indicated that the most severe combined stresses were tension and shear in the tile.

A large range of combined stresses did not result from the thermal stress analyses. Consequently, those critical stresses were evaluated (in-plane tension and combined tension and shear). In addition, the intersection of the failure surface with the principal stress planes was determined to provide a better indication of the capability of the RSI under combined stresses. These results indicate that a great deal of interaction between stress components occurs for combined stress states, requiring careful consideration of the failure criteria to be used for design purposes.

The overall design of RSI tiles can now incorporate a reasonable failure criteria. That is, the SPACE Program can be utilized to develop a basic RSI model of a current material such that the SPACE Program agrees with experimental data in the principal material planes. One can then perform a series of computations using SPACE to develop an overall failure surface for the RSI, or the program could be utilized as a post analysis program for finite element results. The stress state at each finite element could be used as input to the program and a failure analysis performed for each RSI element. The end result would be a minimum margin of safety or contours of margins of safety.

Many modifications have been made to the SPACE Program, during the study, to make the program user oriented. The primary revisions to the program included changing the formatted input to namelist input, providing multiple case capability within each run, choosing suitable default values for many variables, to simplify choice of input for most RSI analyses, and improved documentation of the output data printed by the program. A description of the input to the program is provided in Appendix B, with a sample case input and output in Appendix C and a complete CDC 6600 listing of the program in Appendix D.

CONCLUSIONS

The analytical model for RSI material incorporated in the SPACE Program has been shown to be capable of predicting the mechanical properties of RSI material with good accuracy. This achievement is significant because the RSI model is based on the microstructural properties of the RSI as obtained from basic fiber property data and fiber geometry and distribution data obtainable from photomicrographs of the RSI. Thus, given some basic understanding of the material, one can predict mechanical properties, or conversely one can use the SPACE Program to provide some guidelines or goals for the RSI material development.

The combined stress failure study described earlier represents the first attempt to generate a failure criterion for RSI which is based upon the microstructure of the RSI and yet applicable to the design of RSI tiles from a macroscopic, average property, point of view. It is significant to note that no thermal stress cracking of the RSI studied had been observed during testing, and the combined stress study showed that, at least for the re-entry gradients examined, no failures of the RSI would be predicted.

Due to continuing developments in the RSI material, the thermostructural design of RSI tiles should include a model for the failure analysis. The SPACE Program provides such a model which can be used as a post processor to finite element studies, consequently, a complete CDC 6600 listing of the program and its subroutines is included as an Appendix to this report. Given satisfactory agreement between a SPACE model and one dimensional test data on a given RSI material, one can simply attach that RSI model and the SPACE Program to a post processor for finite element analyses to develop a complete design tool for RSI tiles.

REFERENCES

1. Rosen, B.W., Bagchi, D.K., and Kibler, J.J., "Analytical Study of Ridigized Fibrous Materials", NASA CR-2371, February 1974.

2. Rosen, B.W. and Bagchi, D.K., "Material Model Studies", NASA CR-112038 (R.A. Tanzilli, Editor).

3. Pigg, O., NASA Johnson Spacecraft Center, Private Communication to L. Vosteen, NASA Langley Center.

4. Chapman, A., NASA Langley, Private Communication.

TABLE 1

MATERIAL PROPERTIES

A - RSI MATERIAL

Temp K	E_N MN/m^2	$E_S = E_T$ MN/m^2	G_{NS} MN/m^2	$\nu_{NS} = \nu_{NT} = \nu_{ST}$	$\Delta L/L_N = \Delta L/L_S = \Delta L/L_T$ cm/cm/K
116.	40.0	137.8	24.1	0.10	-2.78E-5
200.	40.0	144.7	25.5		-2.22E-5
297.	41.3	165.4	27.5		0.
478.	46.8	227.4	27.5		0.61E-4
700.	53.7	254.9	27.5		1.56
922.	56.5	268.7	27.5		2.39
1144.	55.8	261.8	27.5		2.89

B - COATING MATERIAL - ISOTROPIC

Temp K	E_N MN/m^2	ν_{NS}	$\Delta L/L$ cm/cm/K
144.	6.89E4	0.20	-0.67E-4
200.	6.54		-5.00E-5
297.	6.20		0.
478.	6.20		1.06E-4
700.	6.20		2.28E-4
922.	4.82		3.39E-4
1144.	3.44E4		4.06E-4
1422.	6.89E2		-2.22E-5
1533.	6.89E1		-2.22E-5

TABLE 2

TEMPERATURE DISTRIBUTION THROUGH RSI FOR VARIOUS RE-ENTRY HEATING TIMES

Distance From Outer Surface mm	Temperature, K, at Time 120sec	160sec	200sec	240sec	300sec
0.00	711	810	939	1102	1340
2.50	624	696	804	941	1182
4.75	521	560	621	711	901
8.50	416	433	456	489	569
14.12	346	355	365	378	404
21.62	315	320	325	331	342
29.12	300	301	302	304	306
40.37	297	298	298	298	298
55.37	↓	297	297	297	298
66.62		↓	↓	↓	297
74.12					↓
↓ ∞	297	297	297	297	297

TABLE 3

SUMMARY OF MAXIMUM STRESSES FOR RE-ENTRY HEATING GRADIENTS IN TABLE 2

Area of Stresses See Figure 2	In-Plane Stress MN/m^2	Through Thickness Stress MN/m^2	Shear Stress MN/m^2
Area 1 Center of Tile	0.10	0.	0.
Area 2 Edge of Tile	0.07	0.014	0.02

TABLE 4

MEASURED AND PREDICTED PROPERTIES OF RSI
AT ROOM TEMPERATURE

Property	Measured Value (MN/m^2) Mean	Range	Predicted by SPACE (MN/m^2)
In-Plane Modulus $=E_S=E_T$	227	124→275	144.
Through Thickness Modulus $= E_N$	46.8	26→60.6	48.2
Shear Modulus = GNS	27.5	6.9→34.4	82.7
In-Plane Tensile Strength	.200	*	.205
Through Thickness Tensile Strength	.055	*	.069
Shear Strength	.103	*	.117

*Design Allowable Value

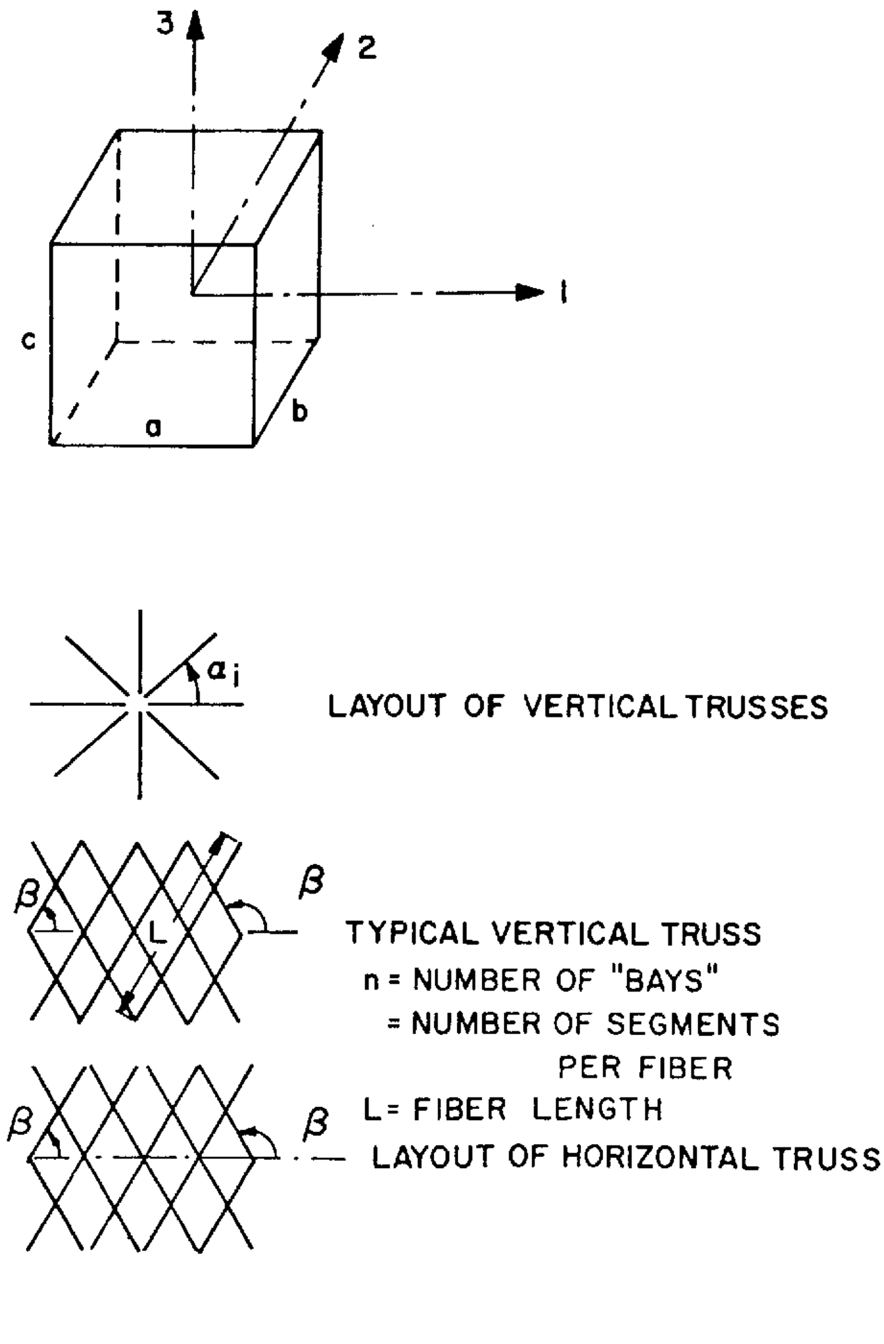


Figure 1. - A typical space model.

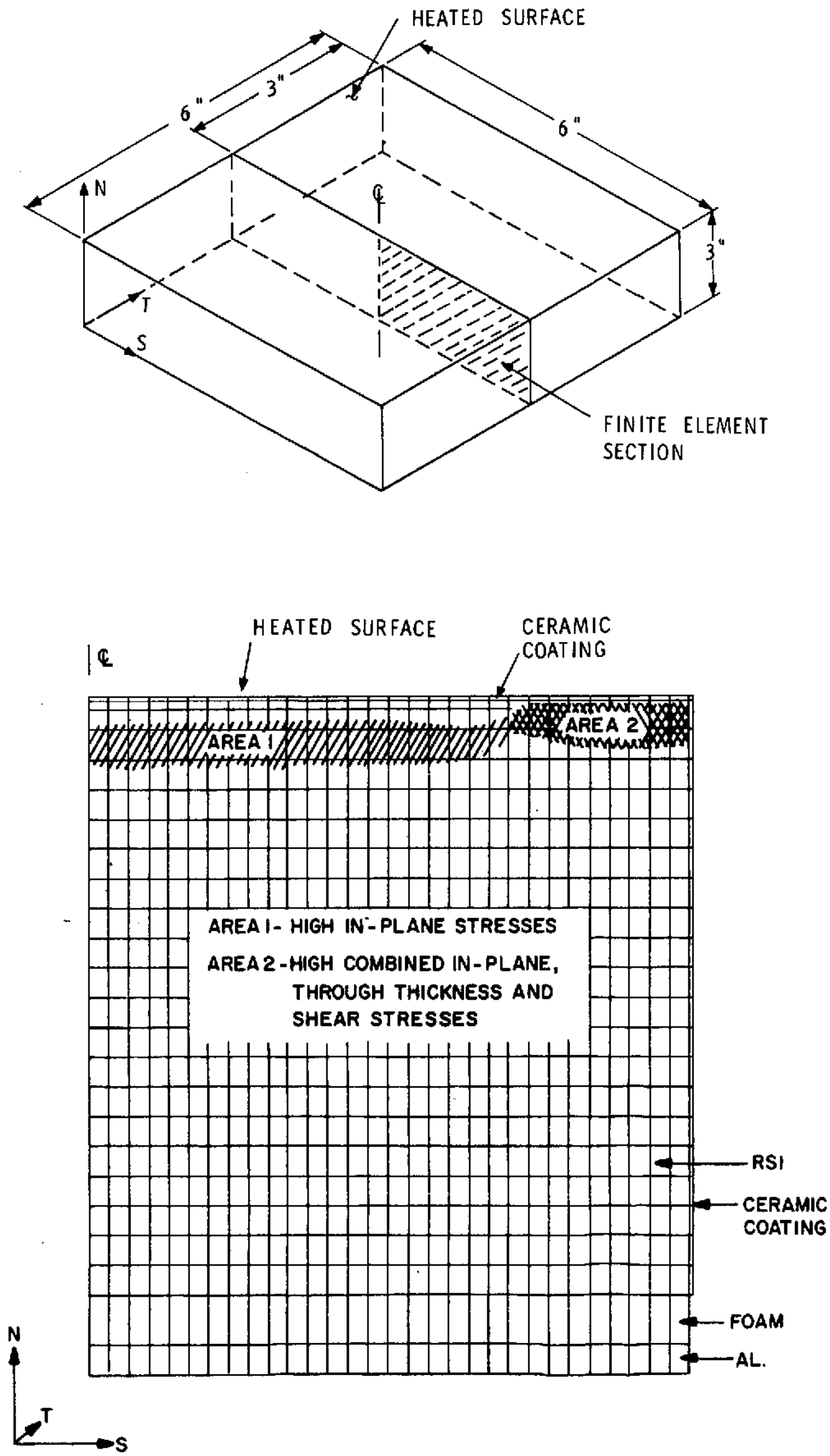


Figure 2 - Finite element model of RSI tile.

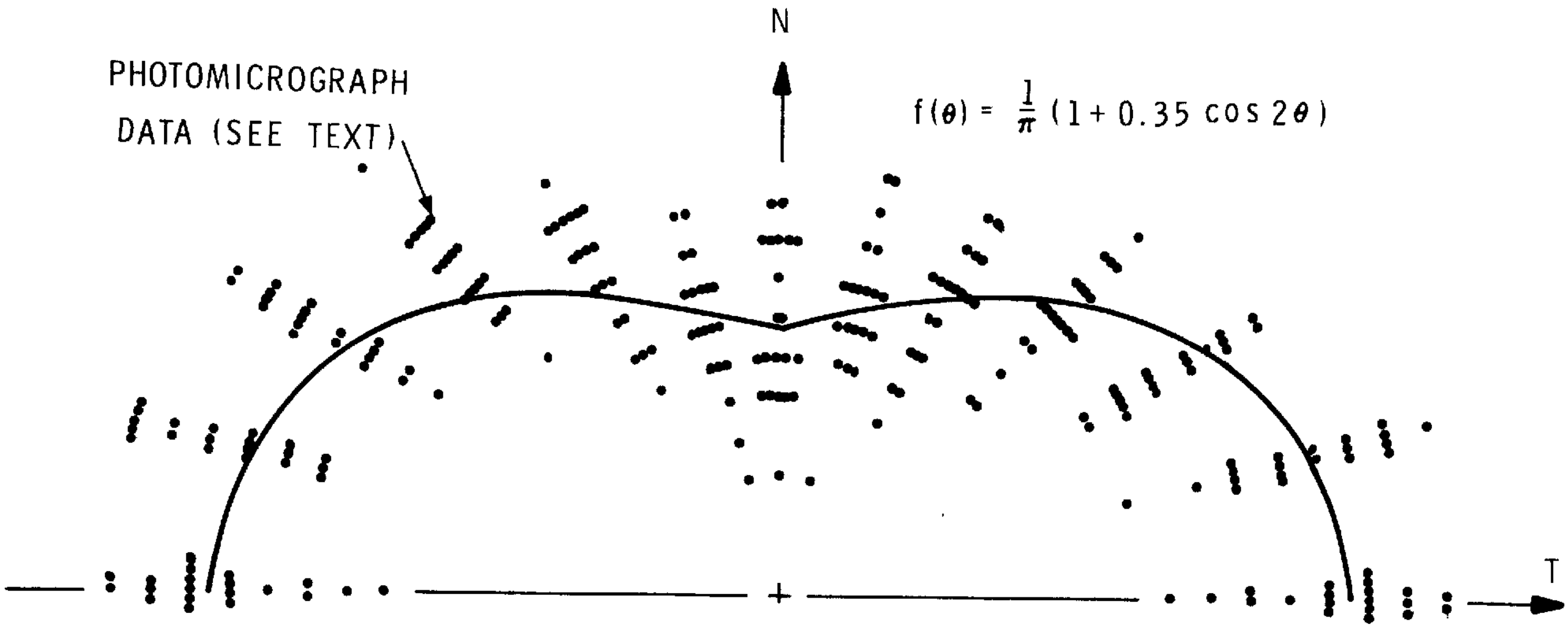


Figure 3. - RSI Fiber Distribution in the N-T plane of the tile.

$e = 0.35$

$\overline{\theta} = 90°$

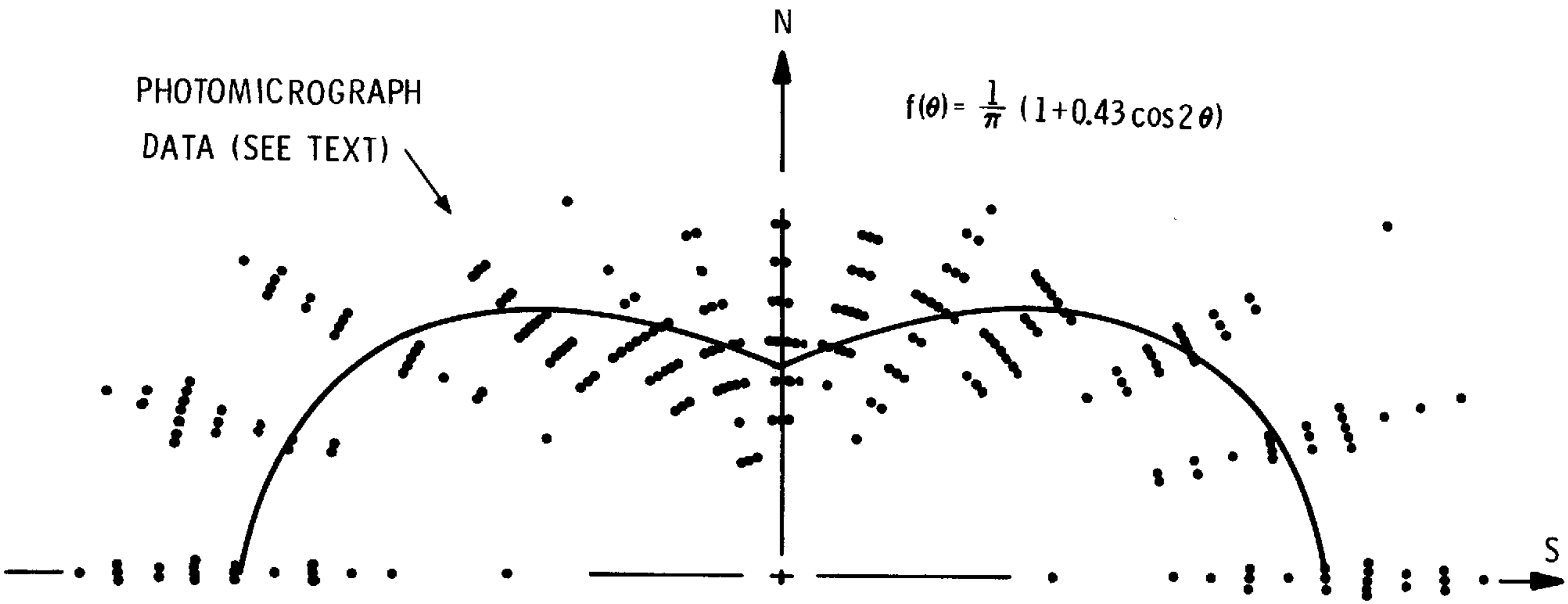


Figure 4. - RSI Fiber Distribution in N-S plane of the tile.

$e = 0.43$

$\bar{\theta} = 90°$

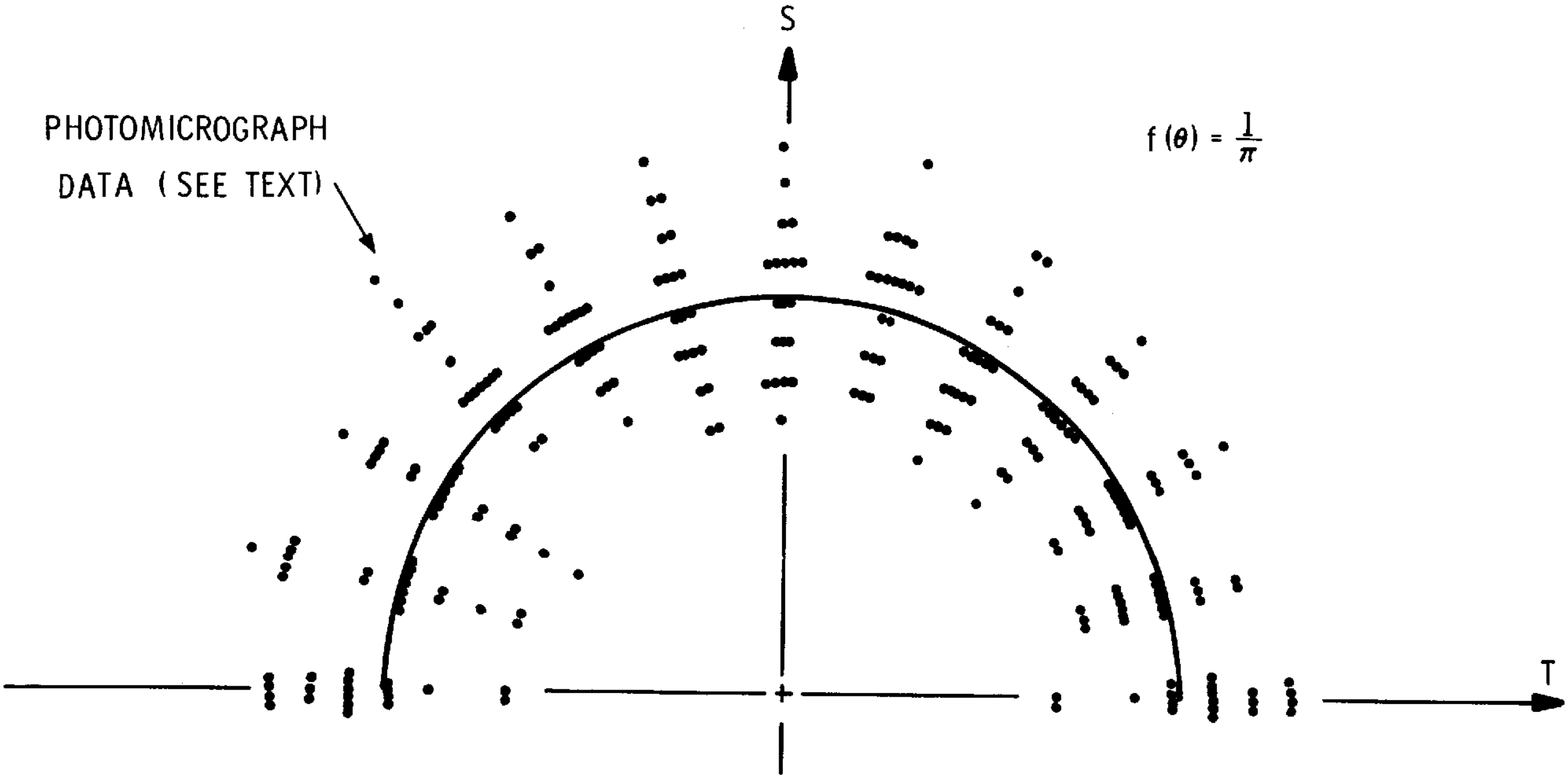


Figure 5. - RSI Fiber Distribution in the S-T plane.

$e = 0.0$

$\bar{\theta}$ = undefined - i.e., distribution circular

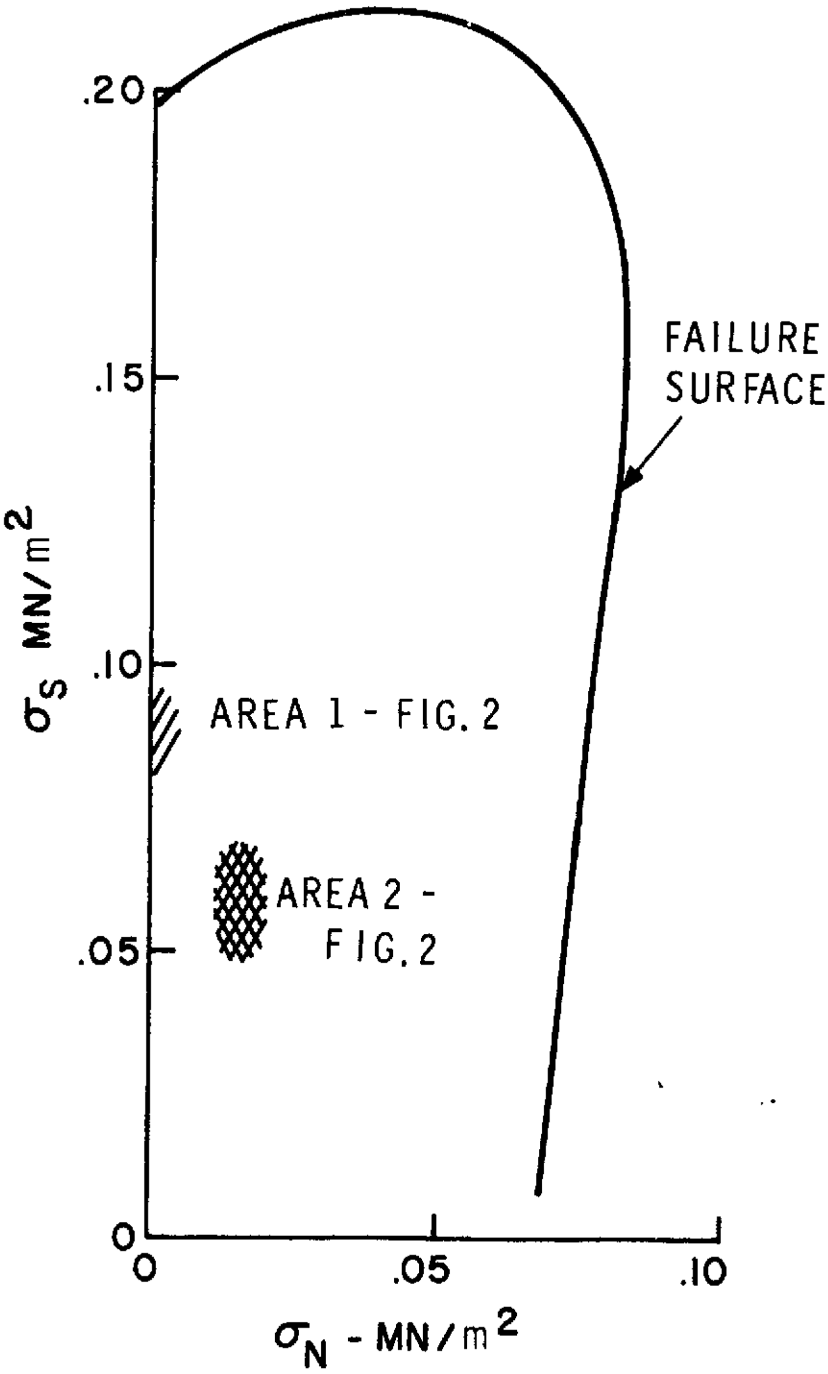


Figure 6 . - Failure surface in σ_N - σ_S plane.

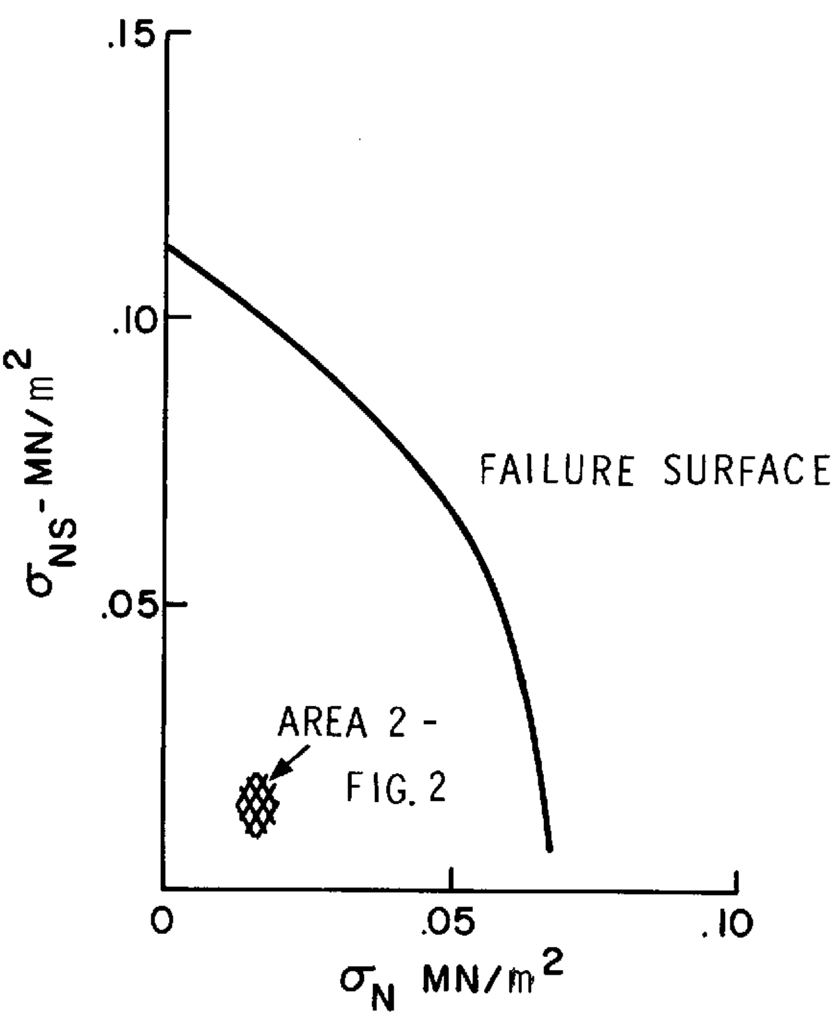


Figure 7. - Failure surface in $\sigma_{N'}$ - σ_{NS} plane.

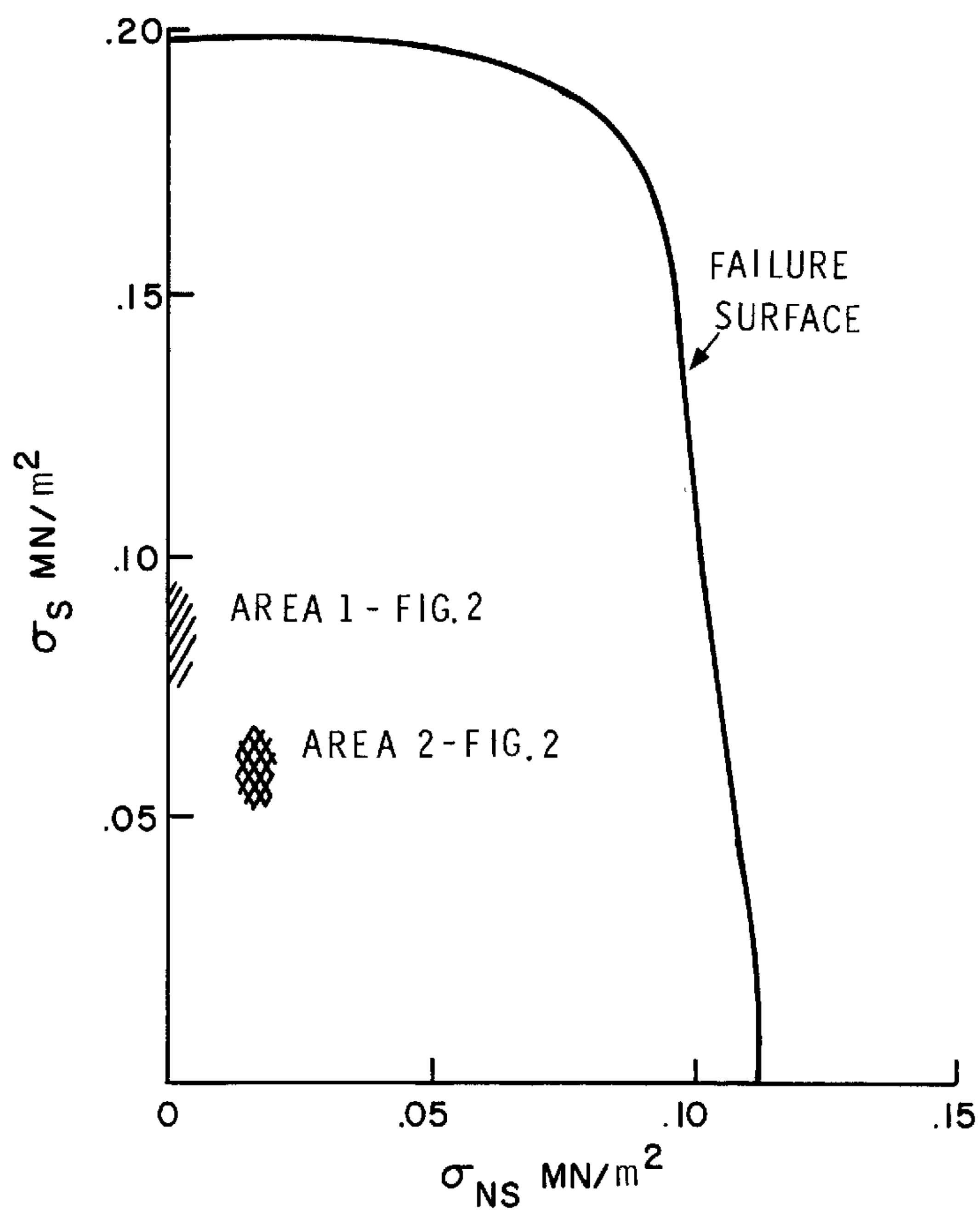


Figure 8. - Failure surface in σ_S - σ_{NS} plane.

APPENDIX A - REDUCTION OF PHOTOMICROGRAPH DATA

A.1 Discrete Representation of a Continuous Distribution Function:

The space frame analysis program requires representing continuous distribution functions with a discrete number of points. Spatial orientation of fibers, fiber diameters, length between fiber intersections, fiber eccentricities and fiber strengths all possess continuous distribution functions. Analytical representation of RSI material requires identifying a deterministic set of fiber properties which can be modeled with a finite number of trusses with fixed properties. The following section describes how a continuous distribution can be represented by a discrete distribution of finite number of samples. In particular, the spatial distribution of fibers in any given plane is considered. However, once the continuous distribution function for any of the variables is defined, the discrete representation of the variable can be determined in analogous fashion.

It is first assumed that the continuous distribution function of a variable is known, in this case the angular orientation of RSI fiber in a given plane. It has been assumed that the distribution can be represented as a first approximation by an elliptical distribution $f(\theta)$ such that

$$f(\theta) = \frac{1}{\pi} (1+e \cos 2\theta) \tag{A-1}$$

where e is a measure of the eccentricity of the ellipse and θ is understood to be the angle of a fiber as measured from the mean angle or preferred fiber orientation. In practice the mean angle, $\bar{\theta}$, and eccentricity can be determined by using scanning lines, on photomicrographs of RSI material. Namely, the number of fiber intersections with the scanning line, versus orientation of the scanning line will provide an experimental distribution of $f(\theta)$. A large number of scanning lines located at various areas of RSI material are employed to give a good representation of $f(\theta)$, the mean value of θ can be found and the eccentricity can be determined in a least squares sense, the results of which are described in the following section.

The discrete representation of $f(\theta)$ is given by

$$g(\phi) = \sum_{-N/2}^{N/2} \frac{1}{N} \phi_i \tag{A-2}$$

where N is the total number of points and $\phi_{-i} = \phi_i$ implying that ϕ_i is normalized with respect to the mean such that the mean values of $f(\theta)$ and $g(\phi)$ are zero. Specific values of ϕ_i are determined as follows:

$f(\theta)$ is divided into N regions such that

$$\int_{\theta_{n-1}}^{\theta_n} f(\theta)\, d\theta = \frac{1}{N}\, ; \quad n = 1, \ldots, N \qquad \text{(A-3)}$$

and one value of ϕ_i is located within each resulting interval. Each ϕ_i could be placed anywhere within the interval θ_{n-1} to θ_n, and the general solution requires satisfying the first N+1 moments of $f(\theta)$ in order to determine each ϕ_i location. However, a reasonable approximation of $f(\theta)$ can be made by placing all values of ϕ_i in the same relative position within θ_{n-1} and θ_n and minimizing the difference between the second moments of $f(\theta)$ and $g(\phi)$. One thus obtains the following expression to be solved for $\bar{\alpha}$, the position of the discrete variable ϕ_i between θ_{n-1} and θ_n

$$\sum_{\to 1}^{N/2} \frac{2}{N} \{\theta_{n-1} + \bar{\alpha}\ (\theta_n - \theta_{n-1})\ \}^2 - S = 0 \qquad \text{(A-4)}$$

where $S = \frac{1}{2}\ (\frac{\pi^2}{6} - e)$ is the variance of $f(\theta)$

$\theta_{n-1} \to \theta_n$ defines the equal area intervals of $f(\theta)$

N is the number of fibers = $\frac{1}{2}$ the number of discrete trusses (each truss has $\pm\theta$ fibers)

An example is tabulated in Table A-1 giving the desired positions of ϕ_i for various values of N. A graphical representation of two continuous distributions for e=0.3 and 0.95 along with the discrete representations of the distributions are given in Figures A-1 and A-2.

The above approach is valid for a standard elliptical distribution. However, when one consideres how a preferred mean value of fiber orientation may occur during manufacture, a slight modification to the elliptical distribution appears appropriate. Assuming that the manufacturing process starts with a slurry of completely randomly oriented fibers, and then pressure is applied to compress the slurry, it is reasonable to assume that the fiber distribution will be symmetric about both the in-plane and through-the-thickness directions. This can be accomplished by defining $f(\theta)$ such that

$$f(\theta) = \text{const.}\ (1 + e \cos 2(\theta - j\bar{\theta}) \qquad \text{(A-5)}$$

where

$$j = 1 \quad \text{if} \quad 0 \leq \theta \leq \pi/2$$
$$\pi < \theta \leq 3\pi/2$$

$$j = -1 \quad \text{if} \quad \pi/2 < \theta \leq \pi$$
$$3\pi/2 < \theta < 2\pi$$

and results in the distribution shown in Figure A-3. The function, $f(\theta)$, is normalized such that the mean value of $f(\theta)$ between 0 and $\pi/2$ is equal to the mean of the data, $\bar{R}$, i.e.

$$\int_0^{\pi/2} (\bar{R} - f(\theta))\, d\theta = 0 \qquad \text{(A-6)}$$

which results in

$$\frac{f(\theta)}{\bar{R}} = \frac{1 + e \cos 2(\theta - j\bar{\theta})}{1 + \frac{2e}{\pi} \sin 2\bar{\theta}} \qquad \text{(A-7)}$$

Note that, when normalized, the constant for $f(\theta)$ becomes a function of the orientation and eccentricity of the distribution. Although the process is slightly more involved algebraically, equal area intervals and discrete locations for placement of discrete points can be determined in the same manner as previously outlined. Substituting equation A-7 into equation A-3 one obtains

$$\theta_i + \frac{e}{2} \sin 2 (\theta_i - \bar{\theta}) =$$

$$\frac{i}{N} (1 + 2 \frac{e}{\pi} \sin 2\bar{\theta}) - \frac{e}{2} \sin 2\bar{\theta} \qquad \text{(A-8)}$$

where $i = 1, 2, \ldots N/2$

from which one can obtain θ_i and define the equal area intervals. For most applications one can locate ϕ_i midway between θ_i and θ_{i+1}. For a more accurate representation one can solve for $\bar{\alpha}$ in equation A-4, substituting the variance of equation A-7 for S in equation A-4. In addition, data points taken from RSI photomicrographs can be fit to equation A-7 in the least squares sense to define $\bar{\theta}$ and e; the solution involving solution of a pair of non-linear equations to determine $\bar{\theta}$ and e, as described below.

A.2 Least Squares Curve Fit to Distribution Functions

Given data from the photomicrographs of RSI material which can be tabulated as number of fiber intersections, f_i, with scanning line versus angular orientation, θ_i, of scanning line, one can determine the best fit values of e and $\bar{\theta}$ in the following manner.

Define the sum of the squared residuals for equation A-7 as

$$V = \sum_{1}^{N} \{f_i - \frac{1 + e \cos 2 (\theta_i - \bar{\theta})}{1 + \frac{2e}{\pi} \sin 2 \bar{\theta}}\}^2 \tag{A-9}$$

Note that here f_i represents the data points divided by the mean value of the data measurements.

Since it is desired to minimize V by proper selection of e and θ, we require

$$\frac{\partial V}{\partial e} = 0 \qquad \frac{\partial V}{\partial \bar{\theta}} = 0 \tag{A-10}$$

Taking the partial derivatives, and after some manipulation, one can solve each equation explicitly for e in terms of $\bar{0}$ as shown below:

From $\frac{\partial V}{\partial e} = 0$ one obtains

$$e = \frac{A_2 \cos 2\bar{\theta} + A_1 \sin 2 \bar{\theta}}{A_3 \sin^2 2\bar{\theta} + A_4 \cos^2 2\bar{\theta} + A_5 \sin 2\bar{\theta} \cos 2\bar{\theta}} \tag{A-11}$$

where

$$A_1 = \frac{\pi}{2} \Sigma (f_i - 1) \sin 2\theta_i$$

$$A_2 = \frac{\pi}{2} \Sigma (f_i - 1) \cos 2\theta_i$$

$$A_3 = \frac{\pi}{2} \Sigma \sin^2 2\theta_i + \frac{2}{\pi} \Sigma f_i - \Sigma (f_i + 1) \sin 2\theta_i$$

$$A_4 = \frac{\pi}{2} \Sigma \cos^2 2\theta_i$$

$$A_5 = \pi \Sigma \sin 2\theta_i \cos 2\theta_i - \Sigma (f_i + 1) \cos 2\theta_i$$

and where Σ represents summation over the number of experimental data pairs, N. Note also that the f_i values are divided by the mean value of f_i as required to maintain a normalized distribution function.

From $\frac{\partial V}{\partial \bar{\theta}} = 0$ one obtain

$$e = \{ - B \pm \sqrt{B^2 - 4\,AC} \} / (2A) \tag{A-12}$$

where

$$A = a_1 \sin 2\bar{\theta} + a_2 \cos 2\bar{\theta}$$

$$B = b_1 \sin 2\bar{\theta} \cos 2\bar{\theta} + b_2 \sin^2 2\bar{\theta} + b_3 \cos^2 2\bar{\theta} + b_4 \cos 4\bar{\theta} + b_5 \sin 4\bar{\theta} + b_6$$

$$C = c_1 \cos 2\bar{\theta} + c_2 \sin 2\bar{\theta}$$

and where

$$a_1 = \frac{2}{\pi} \Sigma f_i \cos 2\theta_i - \Sigma \sin 2\theta_i \cos 2\theta_i$$

$$a_2 = - \Sigma \cos^2 2\theta_i$$

$$b_1 = \frac{2}{\pi} \Sigma f_i - \Sigma (f_i+1) \sin 2\theta_i$$

$$b_2 = \Sigma f_i \cos 2\theta_i$$

$$b_3 = -\Sigma \cos 2\theta_i$$

$$b_4 = \frac{\pi}{4} \Sigma \sin 4\theta_i$$

$$b_5 = - \frac{\pi}{4} \Sigma \cos 4\theta_i$$

$$b_6 = \Sigma (f_i-1) \cos 2\theta_i$$

$$c_1 = \Sigma (f_i-1) - \frac{\pi}{2} \Sigma (f_i-1) \sin 2\theta_1$$

$$c_2 = \frac{\pi}{2} \Sigma (f_i-1) \cos 2\theta_i$$

Solution for e and $\bar{\theta}$ can be obtained from equations A-11 and A-12 by simply substituting various values of $\bar{\theta}$ and plotting the resultant values of e until an intersection of the two curves is obtained, noting the restrictions that the derivation requires $e \leq 1.0$, and $0 \leq \bar{\theta} \leq \pi/2$.

TABLE A-1

Values of ϕ_i for Representation of f (θ) Given by Equation A-1 at e = 0.95

ϕ_i \ N	2	4	6	8	10	12	16	20
1	33.96	8.52	5.54	4.19	3.40	2.88	2.22	1.93
2		47.26	22.44	16.32	12.94	10.75	8.08	6.60
3			54.08	30.37	23.30	19.07	14.10	11.36
4				58.36	35.72	28.34	20.47	16.28
5					61.38	39.70	27.41	21.45
6						63.65	35.35	27.01
7							45.34	33.18
8							66.93	40.35
9								49.56
10								70.11
α =	.3773	.3467	.3502	.3569	.3639	.3703	.3819	.4156

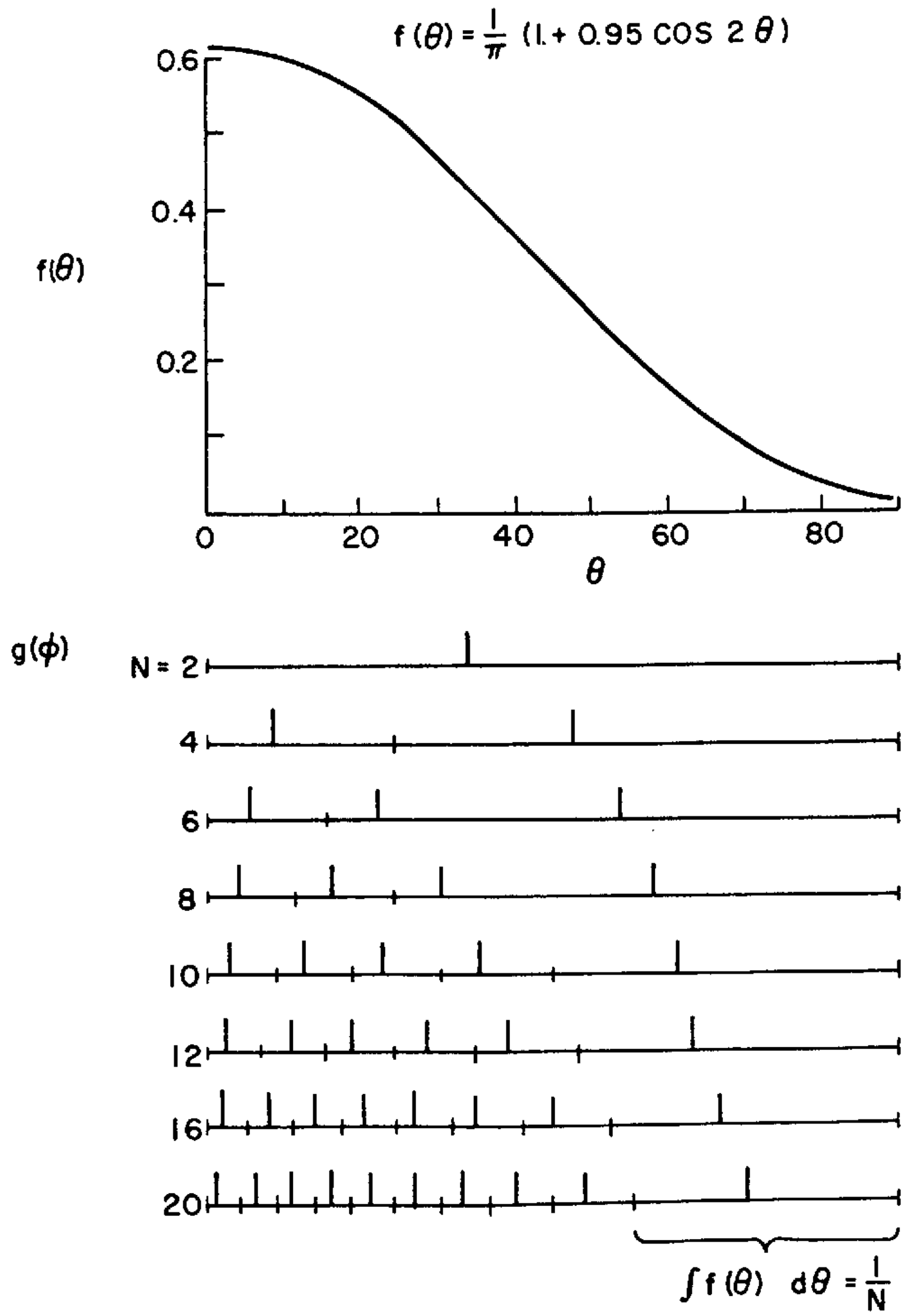


Figure A-1 - Continuous and Discrete Distributions.

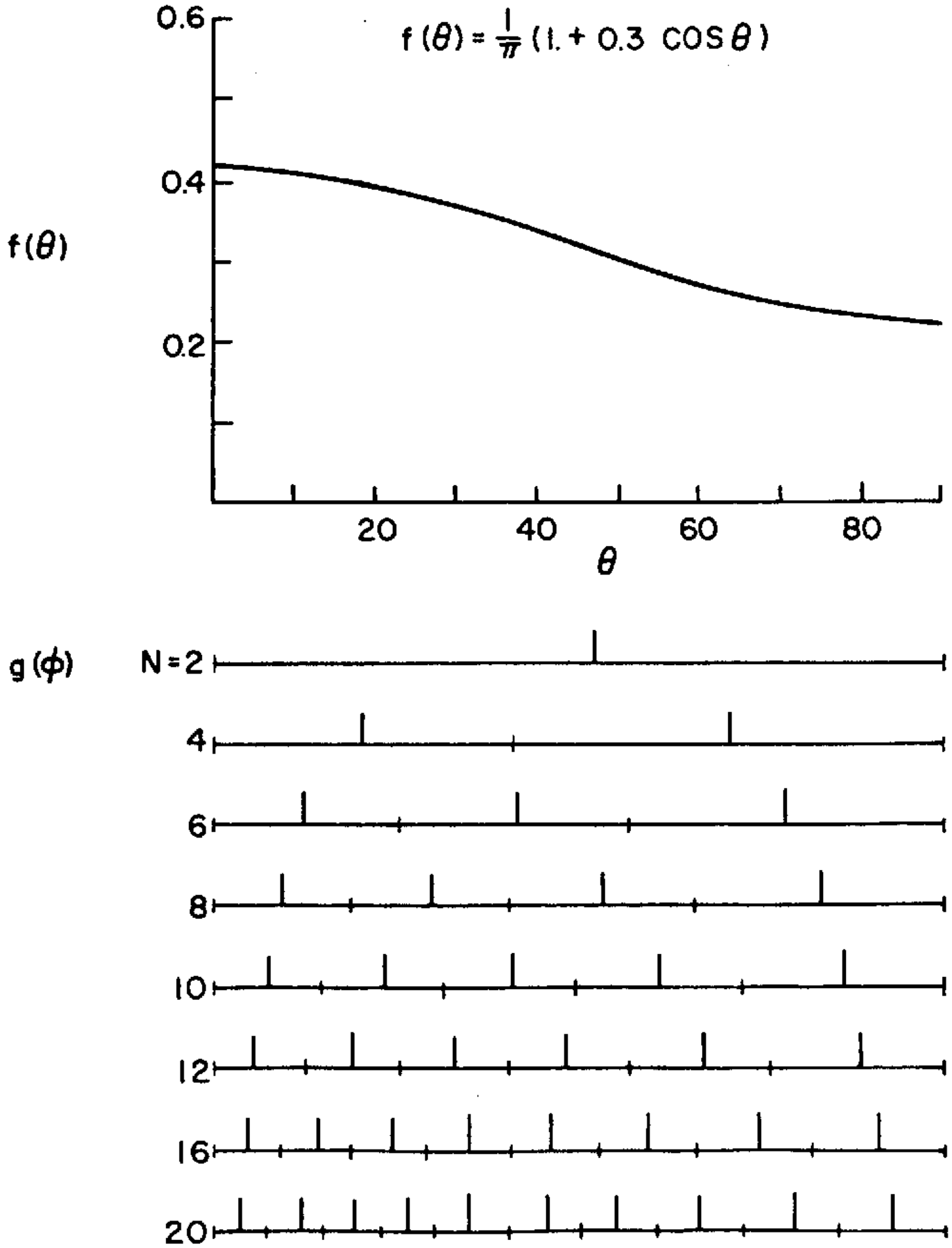
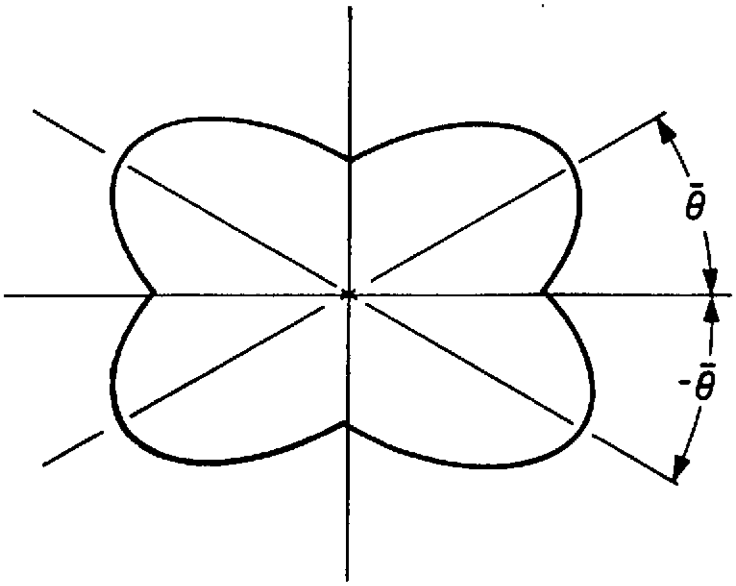


Figure A-2 - Continuous and Discrete Distributions.



$$f(\theta) = \frac{1 + e\ \mathrm{COS}\ 2(\theta = j\ \bar{\theta})}{1 + \frac{2e}{\pi}\ \mathrm{SIN}\ 2\ \bar{\theta}}$$

$$j = +1 \text{ if } 0 \leqslant \theta \leqslant \pi/2$$
$$\pi < \theta \leqslant 3\pi/2$$
$$j = -1 \text{ if } \pi/2 < \theta \leqslant \pi$$
$$3\frac{\pi}{2} < \theta < 2\pi$$

Figure A-3 - Fiber Distribution for RSI Material.

SPACE FRAME ANALYSIS PROGRAM

APPENDIX B

B-1 Program Description

The SPACE Program is a space frame analysis program developed by Materials Sciences Corporation (MSC) for the analysis of three dimensional fibrous materials such as RSI. The various materials being developed for reusable space shuttle insulation have several common factors. The materials are all very low density fibrous systems, which, on a microscale, appear as three-dimensional arrays of trusses with small amounts of matrix material located at the fiber intersections. This observation lead to the development of a micromechanical model of RSI, Ref. 1,2, which can be used to assess the effects of various processing and geometric parameters on the structural properties of RSI.

The SPACE Program treats planar arrays of fiber trusses, wherein the planar arrays are oriented at user specified angles in space. Fiber mechanical and strength properties are supplied by the user for each truss in the model, thereby allowing for inclusion of the effects of variable material properties in the fibers. Additional input data controls the geometric parameters, namely fiber length to diameter ratio between fiber intersections, initial fiber curvatures, fiber orientations within each plane, and orientations of the planes in space. Finally, the applied loading, in three-dimensional stress space, is input to the program.

Given the above data, the program computes the stress/strain response of the defined material under the given loading. Incremental loading is applied since the initial fiber curvature introduces non-linearity in that the effective fiber stiffness is a function of the applied load.

The program prints the strain state for each load increment such that the nonlinear stress/strain behavior can be observed. In addition, each fiber pair (truss) is checked at each load increment to determine if its ultimate stress has been exceeded. If a truss breaks, it is eliminated from the model, and the model stiffness and redistributed fiber stresses are recomputed at the breaking load. If further trusses break, they are eliminated also, until either the complete model collapses, or a stable configuration is obtained. If a stable configuration is obtained, the loading is then increased until an additional truss fails, at which time the same process as above is repeated until complete failure of the model is attained. Details of the analytical treatment in the program have been described in Refs. 1 and 2 and will not be repeated here. A flow diagram describing the major paths of information flow and calculations are given in Figure B-1. The remainder of Appendix B describes the input requirements of the program. Appendix C gives a sample case describing the program output, while Appendix D provides a list of the program applicable to a CDC 6600 computer, utilizing the RUN compiler.

Effective utilization of the SPACE Program requires determining the constituent material geometry and properties of the fibers forming the RSI material. That is, the fiber properties must be known, along with the variability of the fibers in the material. An effective approach to determining the spatial distribution of fibers and representing that distribution with a relatively small number of trusses has been described in detail in Appendix A.

All input to the program is accomplished through a namelist ("DATA") format for ease of keeping track of the values given to each variable for a given deck setup. The input can be broken into three main areas: control parameters determine the number of iterations permitted per stress solution, and define the convergence and divergence criteria for the iterative solution scheme. Geometry definition variables comprise the major input values and provide a complete description of the material model and fiber properties. Finally, the applied loading variables define the initial stress state to be applied to the model, the number of stress increments to be permitted and the size of each stress increment. Many of the variables have default values defined in the program to minimize the input required. A listing of the input variables along with their physical description and default values follows.

It should be pointed out that the program is written such that multiple cases can be executed during one computer run by simply adding additional namelist sets with the data to be changed for each case. That is, the program executes the current case and searches the input data for an additional input namelist, if none exists, the program terminates. The only restriction to the above method of running multiple cases is that the angular orientation of the fibers in each truss must not be changed. That is, BT (I,J) may only be input in the first namelist, all other variables may be changed in successive runs.

B-2 Program Input Variables

Control Parameters

NIT	Number of iterations permitted for determining strains and stresses for a particular value of constant applied stress. (Default value is 5)
SEPS	Convergence parameter for iterations, i.e., if two successive stress states differ by less than this value, solution has converged. (Default value is 0.5)

SUPB	Divergence parameter for iterations, i.e., if two successive stress states differ by this value, solution has diverged and execution on that load case terminates. (Default value is 1.E+5)

Geometry Definition Variables

NOR	Number of vertical planes of trusses. These are perpendicular to one plane of fibers. Maximum value is four.
NTR	Number of fiber orientations per plane. Each plane is assumed to have the same number of fiber pairs. Maximum value is thirty.
AD,BD,DD	Dimensions of the unit cell of material being considered. (Default values AD=BD=DD=1.0)
SGM(I,J)	Allowable fiber strength for each fiber in the J^{th} truss of the I^{th} plane. $J = 1 \rightarrow NTR$ $I = 1 \rightarrow NOR + 1$ The $(NOR+1)^{th}$ plane is the horizontal plane, See Fig. 1. Note that the 1,2 and 3 directions in the SPACE Program are unrelated to the RSI coordinates, allowing the user to let the single plane of fibers, i.e., the 2-3 plane, to represent whatever RSI orientation appears suitable. In the sample case, Appendix C, the major material distribution differences are in the N-S and N-T planes, consequently the model was defined so that the 1-direction was parallel to the N direction of the RSI, with the 2- and 3-directions being parallel to the S- and T-directions respectively.
RAT(I,J)	Fiber length to diameter ratio between joints.
EC(I,J)	Eccentricity of fibers (initial midspan deflection in fiber diameters).
EY(I,J)	Youngs modulus of fibers.
L(I,J)	Length of each truss (cannot exceed unit cell dimensions).
VTI(I,J)	Volume fraction of each truss in the model.
TEMP(J),J=1,3	Linear temperature variation in 1,2, 3 directions across material element.
ALPHA	Fiber coefficient of expansion, constant for all fibers.
NB(I,J)	Number of bays, or intersections, per fiber.
BT(I,J)	Angular orientation of fibers in the J^{th} truss of I^{th} plane, degrees.
AL(I)	Angular orientation of I^{th} plane $I=1\rightarrow NOR$.

Applied Loading Variables

SGO(I,1)	I=1,6 Applied initial stress state on model I=1; σ_{11} I=4; σ_{23} I=2; σ_{22} I=5; σ_{13} I=3; σ_{33} I=6; σ_{12}
NINC	Maximum number of loading increments. (Default value is 100)
MSCAL	Maximum number of re-evaluations of stress distributions per loading. (Used to curtail calculations if model cannot sustain loading at a given load level) (Default value is 5)
SMLT	Stress increment multiple. Stresses increment in steps of (initial stress) * SMLT (Default value is 1.0) Note that SMLT increases the magnitude of the stress tensor and not the direction.

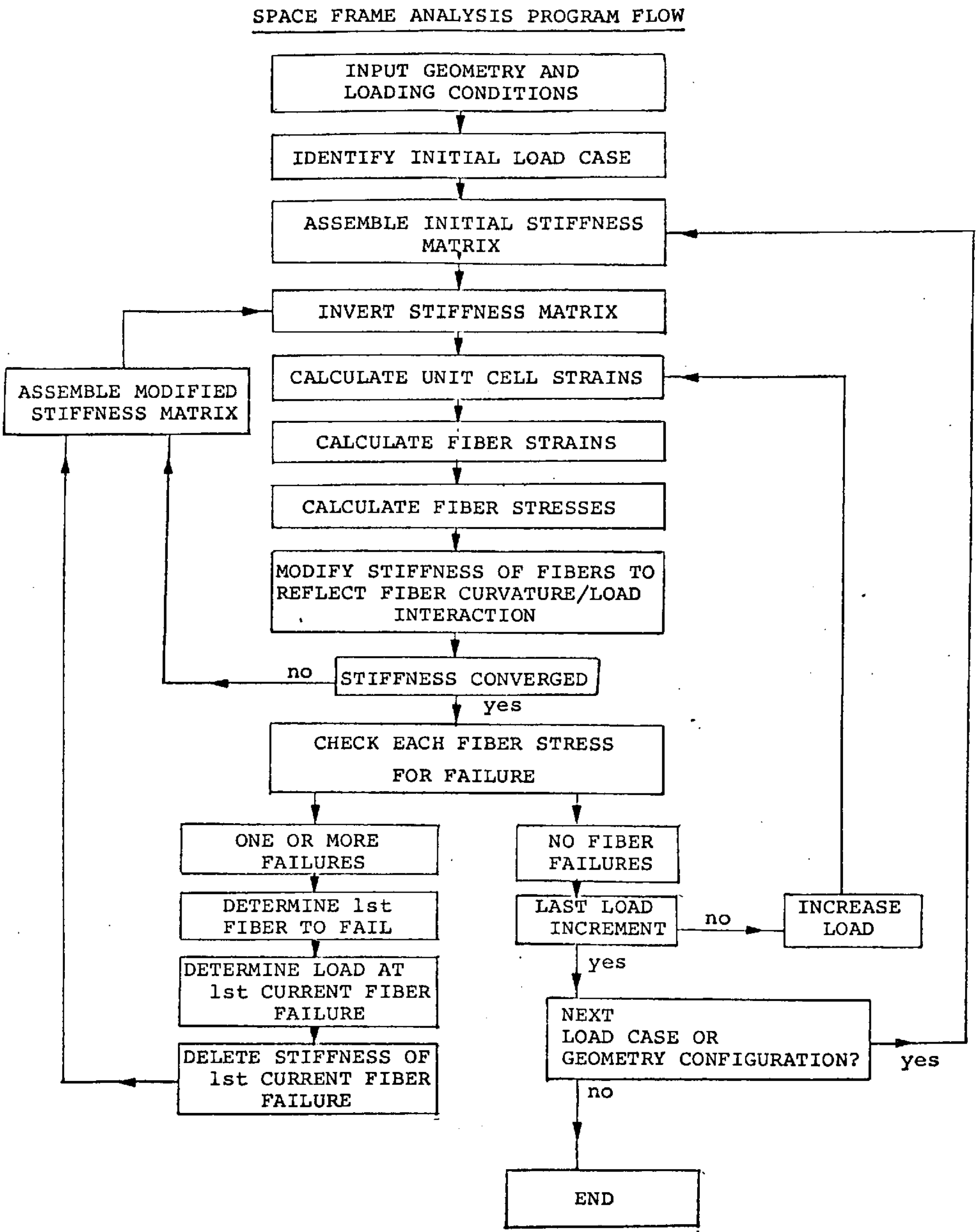


Figure B-1 - Space Flow Diagram.

SPACE SAMPLE CASE

APPENDIX C

The sample problem describing the input data required to model the RSI material described eariler in this report is provided here, along with the output from a typical case.

The following NAMELIST data was used to generate the RSI model and run two load cases:

```
$DATA
     NIT=20, SEPS=1.0E-03,SUPB=2.0E03,NOR=4,NTR=8,
SGM(1,1)=40*0.4E05,
RAT(1.1)=40*10.0E00,
EC(1,1)=40*1.0E00,
EY(1,1)=40*0.2E08,
L(1,1)=40*1.0E00,
VTI(1,1)=40*.02E-02,
TEMP(1)=3*0.0,   ALPHA=0.0,
NB(1,1)=40*4.0E00,
BT(1,1)=5*85.97,
BT(1,2)=5*77.81,
BT(1,3)=5*69.35,
BT(1,4)=5*60.35,
BT(1,5)=5*50.44,
BT(1,6)=5*39.09,
BT(1,7)=5*25.48,
BT(1,8)=5*8.99,
AL(1)=.0E00,  45.0E00,  -45.0E00,  90.0E00,
SGO(1,1)=1.0,0.0,0.0,0.0,0.0,0.0,
NINC=8.,  MXCAL=2,   SMLT=10.,
AD=1.0,   BD=1.0,    DD=1.0$
$DATA
SGO(1,1)=0.0,0.0,1.0,0.0,0.0,0.0$
```

The following pages are an output listing of the above model, giving the major output data.

SPACE FRAME MODEL 1

MODEL GEOMETRY

DIMENSIONS OF MODEL   A = 1.00000E+00   B = 1.00000E+00   C = 1.00000E+00
VOLUME = 1.00000E+00

NUMBER OF TRUSS ORIENTATIONS = 4
NUMBER OF FIBER ORIENTATIONS PER TRUSS = 8

VOLUME FRACTION OF MODEL = 1.24903E+00

ORIENTATIONS TRUSS	FIBERS IN TRUSS	NUMBER OF BAYS	LENGTH OF TRUSS	VOLUME FRACTION
0.	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04
	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04

FIBER PROPERTIES

ORIENTATIONS TRUSS	FIBERS IN TRUSS	YOUNGS MODULUS	ECCENT.	CROSS-SECTIONAL AREA	MAXIMUM STRESS
0.	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
0.	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
0.	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
0.	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
0.	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
0.	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
0.	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
0.	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04
4.50000E+01	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
4.50000E+01	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
4.50000E+01	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
4.50000E+01	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
4.50000E+01	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
4.50000E+01	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
4.50000E+01	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
4.50000E+01	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04
-4.50000E+01	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
-4.50000E+01	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
-4.50000E+01	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
-4.50000E+01	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
-4.50000E+01	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
-4.50000E+01	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
-4.50000E+01	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
-4.50000E+01	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04
9.00000E+01	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
9.00000E+01	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
9.00000E+01	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
9.00000E+01	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
9.00000E+01	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
9.00000E+01	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
9.00000E+01	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
9.00000E+01	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04
	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04

ANALYSIS

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

DIRECTION	APPLIED LOAD	STRAIN
11	1.00000E+00	1.41636E-04
22	0.	-3.81283E-05
33	0.	-1.36260E-05
12	0.	-3.11030E-13
23	0.	3.90976E-19
31	0.	-1.34076E-18

ORIENTATIONS TRUSS	FIBERS IN TRUSS	STRESS	ORIENTATIONS TRUSS	FIBERS IN TRUSS	STRESS

1	1	-3.69851E+02	1	2	-1.92805E+02
1	3	1.63463E+02	1	4	7.00834E+02
1	5	1.41896E+03	1	6	2.29696E+03
1	7	3.24466E+03	1	8	3.96079E+03
2	1	-3.82619E+02	2	2	-3.08066E+02
2	3	-1.58043E+02	2	4	6.82872E+01
2	5	3.70810E+02	2	6	7.40771E+02
2	7	1.14020E+03	2	8	1.44211E+03
3	1	-3.82619E+02	3	2	-3.08066E+02
3	3	-1.58043E+02	3	4	6.82872E+01
3	5	3.70810E+02	3	6	7.40771E+02
3	7	1.14020E+03	3	8	1.44211E+03
4	1	-3.95387E+02	4	2	-4.23327E+02
4	3	-4.79550E+02	4	4	-5.64369E+02
4	5	-6.77752E+02	4	6	-8.16432E+02
4	7	-9.66187E+02	4	8	-1.07940E+03
5	1	-1.07107E+03	5	2	-8.66091E+02
5	3	-4.53608E+02	5	4	1.68686E+02
5	5	1.00033E+03	5	6	2.01707E+03
5	7	3.11444E+03	5	8	3.94362E+03

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

DIRECTION	APPLIED LOAD	STRAIN
11	1.10000E+01	1.55050E-03
22	0.	-4.19227E-04
33	0.	-1.49514E-04
12	0.	-3.39379E-12
23	0.	5.73941E-18
31	0.	-1.06490E-17

TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
1	1	-4.05825E+03	1	2	-2.12009E+03
1	3	1.77995E+03	1	4	7.65134E+03
1	5	1.54736E+04	1	6	2.50004E+04
1	7	3.52384E+04	1	8	4.29440E+04
2	1	-4.19812E+03	2	2	-3.38283E+03
2	3	-1.74207E+03	2	4	7.33397E+02
2	5	4.03895E+03	2	6	8.07473E+03
2	7	1.24238E+04	2	8	1.57054E+04
3	1	-4.19812E+03	3	2	-3.38283E+03
3	3	-1.74207E+03	3	4	7.33397E+02
3	5	4.03895E+03	3	6	8.07473E+03
3	7	1.24238E+04	3	8	1.57054E+04
4	1	-4.33799E+03	4	2	-4.64546E+03
4	3	-5.26415E+03	4	4	-6.19748E+03
4	5	-7.44504E+03	4	6	-8.97081E+03
4	7	-1.06183E+04	4	8	-1.18635E+04
5	1	-1.17732E+04	5	2	-9.52874E+03
5	3	-5.01110E+03	5	4	1.80604E+03
5	5	1.08927E+04	5	6	2.19517E+04
5	7	3.38269E+04	5	8	4.27586E+04

MEMBER FAILURE: TRUSS 1 FIBER 8
MEMBER FAILURE: TRUSS 5 FIBER 8

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

DIRECTION	APPLIED LOAD	STRAIN
11	1.02448E+01	2.38060E-03
22	0.	-6.38067E-04
33	0.	-2.27040E-04
12	0.	-5.20077E-12
23	0.	7.35110E-18
31	0.	-1.96920E-17

TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
1	1	-6.15839E+03	1	2	-3.18578E+03
1	3	2.79563E+03	1	4	1.17903E+04
1	5	2.37521E+04	1	6	3.82882E+04
1	7	5.38704E+04	1	8	0.
2	1	-6.37271E+03	2	2	-5.12078E+03
2	3	-2.60118E+03	2	4	1.20036E+03
2	5	6.27354E+03	2	6	1.24615E+04
2	7	1.91224E+04	2	8	2.41435E+04
3	1	-6.37271E+03	3	2	-5.12078E+03
3	3	-2.60118E+03	3	4	1.20036E+03
3	5	6.27354E+03	3	6	1.24615E+04
3	7	1.91224E+04	3	8	2.41435E+04
4	1	-6.58703E+03	4	2	-7.05551E+03
4	3	-7.99820E+03	4	4	-9.42025E+03
4	5	-1.13210E+04	4	6	-1.36455E+04
4	7	-1.61552E+04	4	8	-1.80521E+04
5	1	-1.79121E+04	5	2	-1.44737E+04
5	3	-7.55214E+03	5	4	2.89387E+03
5	5	1.67954E+04	5	6	3.36705E+04
5	7	5.17385E+04	5	8	0.

MEMBER FAILURE: TRUSS 1 FIBER 7

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

DIRECTION	APPLIED LOAD	STRAIN
11	1.02448E+01	3.04913E-03
22	0.	-8.27776E-04
33	0.	-2.59670E-04
12	0.	-6.61388E-12
23	0.	9.12515E-18
31	0.	-1.96952E-17

TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
1	1	-6.99689E+03	1	2	-3.22510E+03
1	3	4.36246E+03	1	4	1.57600E+04
1	5	3.08969E+04	1	6	4.92602E+04
1	7	0.	1	8	0.
2	1	-7.27213E+03	2	2	-5.71018E+03
2	3	-2.56656E+03	2	4	2.17590E+03
2	5	8.50065E+03	2	6	1.62099E+04
2	7	2.45021E+04	2	8	3.07484E+04
3	1	-7.27213E+03	3	2	-5.71018E+03
3	3	-2.56656E+03	3	4	2.17590E+03
3	5	8.50065E+03	3	6	1.62099E+04
3	7	2.45021E+04	3	8	3.07484E+04

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4	1	-7.54736E+03	4	2	-8.19484E+03
4	3	-9.49767E+03	4	4	-1.14629E+04
4	5	-1.40896E+04	4	6	-1.73017E+04
4	7	-2.07695E+04	4	8	-2.33904E+04
5	1	-2.32389E+04	5	2	-1.88245E+04
5	3	-9.93713E+03	5	4	3.47757E+03
5	5	2.13090E+04	5	6	4.29090E+04
5	7	6.59820E+04	5	8	0.

MEMBER FAILURE: TRUSS 5 FIBER 7

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

DIRECTION	APPLIED LOAD	STRAIN
11	1.02448E+01	4.11875E-03
22	0.	-1.03387E-03
33	0.	-3.62777E-04
12	0.	-8.99540E-12
23	0.	1.27385E-17
31	0.	-2.23711E-17

TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
1	1	-9.79426E+03	1	2	-4.68641E+03
1	3	5.58877E+03	1	4	2.10013E+04
1	5	4.14241E+04	1	6	6.61308E+04
1	7	0.	1	8	0.
2	1	-1.01600E+04	2	2	-7.98879E+03
2	3	-3.61865E+03	2	4	2.97420E+03
2	5	1.17588E+04	2	6	2.24521E+04
2	7	3.39367E+04	2	8	4.25760E+04
3	1	-1.01600E+04	3	2	-7.98879E+03
3	3	-3.61865E+03	3	4	2.97420E+03
3	5	1.17588E+04	3	6	2.24521E+04
3	7	3.39367E+04	3	8	4.25760E+04
4	1	-1.05257E+04	4	2	-1.12904E+04
4	3	-1.28291E+04	4	4	-1.51500E+04
4	5	-1.82519E+04	4	6	-2.20451E+04
4	7	-2.61399E+04	4	8	-2.92347E+04
5	1	-2.89745E+04	5	2	-2.31098E+04
5	3	-1.13004E+04	5	4	6.52201E+03
5	5	3.01517E+04	5	6	5.86875E+04
5	7	0.	5	8	0.

MEMBER FAILURE: TRUSS 1 FIBER 6

SPACE FRAME MODEL 2

MODEL GEOMETRY

DIMENSIONS OF MODEL A = 1.00000E+00 B = 1.00000E+00 C = 1.00000E+00
VOLUME = 1.00000E+00

NUMBER OF TRUSS ORIENTATIONS = 4
NUMBER OF FIBER ORIENTATIONS PER TRUSS = 8

VOLUME FRACTION OF MODEL = 1.24903E+00

ORIENTATIONS TRUSS	FIBERS IN TRUSS	NUMBER OF BAYS	LENGTH OF TRUSS	VOLUME FRACTION
0.	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04
	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04

FIBER PROPERTIES

ORIENTATIONS TRUSS	FIBERS IN TRUSS	YOUNG'S MODULUS	ECCENT.	CROSS-SECTIONAL AREA	MAXIMUM STRESS
0.	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
0.	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
0.	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
0.	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
0.	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
0.	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
0.	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
0.	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04
4.50000E+01	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
4.50000E+01	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
4.50000E+01	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
4.50000E+01	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
4.50000E+01	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
4.50000E+01	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
4.50000E+01	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
4.50000E+01	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04
-4.50000E+01	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
-4.50000E+01	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
-4.50000E+01	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
-4.50000E+01	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
-4.50000E+01	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
-4.50000E+01	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
-4.50000E+01	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
-4.50000E+01	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04
9.00000E+01	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
9.00000E+01	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
9.00000E+01	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
9.00000E+01	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
9.00000E+01	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
9.00000E+01	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
9.00000E+01	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
9.00000E+01	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04
	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04

ANALYSIS

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

DIRECTION	APPLIED LOAD	STRAIN
11	0.	-1.36294E-05
22	0.	-9.37055E-06
33	1.00000E+00	4.78628E-05
12	0.	8.52167E-14
23	0.	-4.04352E-19
31	0.	-1.61782E-18

ORIENTATIONS TRUSS	FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS

1	1	1.36743E+03	1	2	1.29735E+03
1	3	1.15633E+03	1	4	9.43570E+02
1	5	6.59118E+02	1	6	3.11143E+02
1	7	-6.46903E+01	1	8	-3.48819E+02
2	1	1.36773E+03	2	2	1.30008E+03
2	3	1.16395E+03	2	4	9.58552E+02
2	5	6.83953E+02	2	6	3.48033E+02
2	7	-1.47783E+01	2	8	-2.89069E+02
3	1	1.36773E+03	3	2	1.30008E+03
3	3	1.16395E+03	3	4	9.58552E+02
3	5	6.83953E+02	3	6	3.48033E+02
3	7	-1.47782E+01	3	8	-2.89069E+02
4	1	1.36803E+03	4	2	1.30281E+03
4	3	1.17156E+03	4	4	9.73533E+02
4	5	7.08788E+02	4	6	3.84923E+02
4	7	3.51336E+01	4	8	-2.29318E+02
5	1	-2.70118E+02	5	2	-2.74974E+02
5	3	-2.84747E+02	5	4	-2.99490E+02
5	5	-3.19198E+02	5	6	-3.43304E+02
5	7	-3.69335E+02	5	8	-3.89013E+02

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

DIRECTION	APPLIED LOAD	STRAIN
11	0.	-1.49926E-04
22	0.	-1.03068E-04
33	1.10000E+01	5.25434E-04
12	0.	9.36965E-13
23	0.	-4.40999E-18
31	0.	-1.46045E-17

TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
1	1	1.49611E+04	1	2	1.41965E+04
1	3	1.26570E+04	1	4	1.03323E+04
1	5	7.22048E+03	1	6	3.40784E+03
1	7	-7.17243E+02	1	8	-3.83735E+03
2	1	1.49644E+04	2	2	1.42263E+04
2	3	1.27403E+04	2	4	1.04963E+04
2	5	7.49282E+03	2	6	3.81307E+03
2	7	-1.68108E+02	2	8	-3.18010E+03
3	1	1.49644E+04	3	2	1.42263E+04
3	3	1.27403E+04	3	4	1.04963E+04
3	5	7.49282E+03	3	6	3.81307E+03
3	7	-1.68108E+02	3	8	-3.18010E+03
4	1	1.49677E+04	4	2	1.42562E+04
4	3	1.28236E+04	4	4	1.06604E+04
4	5	7.76513E+03	4	6	4.21821E+03
4	7	3.81007E+02	4	8	-2.52281E+03
5	1	-2.97079E+03	5	2	-3.02421E+03
5	3	-3.13171E+03	5	4	-3.29389E+03
5	5	-3.51068E+03	5	6	-3.77584E+03
5	7	-4.06217E+03	5	8	-4.27863E+03

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

DIRECTION	APPLIED LOAD	STRAIN
11	0.	-2.86225E-04
22	0.	-1.96750E-04
33	2.10000E+01	1.00109E-03
12	0.	1.78831E-12
23	0.	-7.83209E-18
31	0.	-2.81076E-17

TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
1	1	2.84103E+04	1	2	2.69622E+04
1	3	2.40452E+04	1	4	1.96365E+04
1	5	1.37281E+04	1	6	6.47792E+03
1	7	-1.38003E+03	1	8	-7.32647E+03
2	1	2.84166E+04	2	2	2.70188E+04
2	3	2.42033E+04	2	4	1.99483E+04
2	5	1.42464E+04	2	6	7.25045E+03
2	7	-3.31490E+02	2	8	-6.07173E+03
3	1	2.84166E+04	3	2	2.70188E+04
3	3	2.42033E+04	3	4	1.99483E+04
3	5	1.42464E+04	3	6	7.25045E+03
3	7	-3.31490E+02	3	8	-6.07173E+03
4	1	2.84228E+04	4	2	2.70755E+04
4	3	2.43614E+04	4	4	2.02601E+04
4	5	1.47646E+04	4	6	8.02268E+03
4	7	7.16983E+02	4	8	-4.81687E+03
5	1	-5.67053E+03	5	2	-5.77252E+03
5	3	-5.97775E+03	5	4	-6.28737E+03
5	5	-6.70125E+03	5	6	-7.20745E+03
5	7	-7.75407E+03	5	8	-8.16728E+03

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

DIRECTION	APPLIED LOAD	STRAIN
11	0.	-4.22527E-04
22	0.	-2.90417E-04
33	3.10000E+01	1.47484E-03
12	0.	2.63917E-12
23	0.	-1.28818E-17
31	0.	-5.00643E-17

TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
1	1	4.17181E+04	1	2	3.95972E+04
1	3	3.53228E+04	1	4	2.88574E+04
1	5	2.01826E+04	1	6	9.52159E+03
1	7	-2.05301E+03	1	8	-1.08162E+04
2	1	4.17273E+04	2	2	3.96803E+04
2	3	3.55550E+04	2	4	2.93158E+04
2	5	2.09454E+04	2	6	1.06604E+04
2	7	-5.04876E+02	2	8	-8.96395E+03
3	1	4.17273E+04	3	2	3.96803E+04
3	3	3.55550E+04	3	4	2.93158E+04
3	5	2.09454E+04	3	6	1.06604E+04
3	7	-5.04876E+02	3	8	-8.96395E+03
4	1	4.17364E+04	4	2	3.97634E+04
4	3	3.57872E+04	4	4	2.97740E+04
4	5	2.17080E+04	4	6	[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4	7	1.04311E+03	4	8	-7.11148E+03
5	1	-8.36933E+03	5	2	-8.51989E+03
5	3	-8.82286E+03	5	4	-9.27992E+03
5	5	-9.89088E+03	5	6	-1.06381E+04
5	7	-1.14450E+04	5	8	-1.20549E+04

MEMBER FAILURE: TRUSS 1 FIBER 1
MEMBER FAILURE: TRUSS 2 FIBER 1
MEMBER FAILURE: TRUSS 3 FIBER 1
MEMBER FAILURE: TRUSS 4 FIBER 1

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

DIRECTION	APPLIED LOAD	STRAIN
11	0.	-5.58636E-04
22	0.	-3.83935E-04
33	2.96957E+01	1.95566E-03
12	0.	3.48834E-12
23	0.	-1.26954E-17
31	0.	-4.24687E-17

TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
1	1	0.	1	2	5.23447E+04
1	3	4.67136E+04	1	4	3.81892E+04
1	5	2.67383E+04	1	6	1.26444E+04
1	7	-2.68378E+03	1	8	-1.42946E+04
2	1	0.	2	2	5.24539E+04
2	3	4.70190E+04	2	4	3.87925E+04
2	5	2.77438E+04	2	6	1.41479E+04
2	7	-6.36594E+02	2	8	-1.18458E+04
3	1	0.	3	2	5.24539E+04
3	3	4.70190E+04	3	4	3.87925E+04
3	5	2.77438E+04	3	6	1.41479E+04
3	7	-6.36594E+02	3	8	-1.18458E+04
4	1	0.	4	2	5.25630E+04
4	3	4.73243E+04	4	4	3.93957E+04
4	5	2.87488E+04	4	6	1.56504E+04
4	7	1.41031E+03	4	8	-9.39659E+03
5	1	-1.10633E+04	5	2	-1.12624E+04
5	3	-1.16630E+04	5	4	-1.22673E+04
5	5	-1.30750E+04	5	6	-1.40629E+04
5	7	-1.51297E+04	5	8	-1.59360E+04

MEMBER FAILURE: TRUSS 1 FIBER 2
MEMBER FAILURE: TRUSS 2 FIBER 2
MEMBER FAILURE: TRUSS 3 FIBER 2
MEMBER FAILURE: TRUSS 4 FIBER 2

SOLUTION FOR STRESS CONVERGES IN 3 ITERATIONS

DIRECTION	APPLIED LOAD	STRAIN
11	0.	-8.22897E-04
22	0.	-5.65390E-04
33	2.96957E+01	2.99701E-03
12	0.	5.13656E-12
23	0.	-1.47[illegible]E-17

31	0.	-8.12669E-17

TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
1	1	0.	1	2	0.
1	3	7.12752E+04	1	4	5.84641E+04
1	5	4.12136E+04	1	6	1.99150E+04
1	7	-3.33460E+03	1	8	-2.09701E+04
2	1	0.	2	2	0.
2	3	7.17200E+04	2	4	5.93446E+04
2	5	4.26851E+04	2	6	2.21229E+04
2	7	-3.17130E+02	2	8	-1.73622E+04
3	1	0.	3	2	0.
3	3	7.17200E+04	3	4	5.93446E+04
3	5	4.26851E+04	3	6	2.21229E+04
3	7	-3.17130E+02	3	8	-1.73622E+04
4	1	0.	4	2	0.
4	3	7.21646E+04	4	4	6.02248E+04
4	5	4.41555E+04	4	6	2.43284E+04
4	7	2.69891E+03	4	8	-1.37533E+04
5	1	-1.62891E+04	5	2	-1.65825E+04
5	3	-1.71727E+04	5	4	-1.80630E+04
5	5	-1.92531E+04	5	6	-2.07086E+04
5	7	-2.22801E+04	5	8	-2.34681E+04

MEMBER FAILURE: TRUSS 4 FIBER 3

SOLUTION FOR STRESS CONVERGES IN 3 ITERATIONS

DIRECTION	APPLIED LOAD	STRAIN
11	0.	-9.46584E-04
22	0.	-5.77144E-04
33	2.96957E+01	3.36218E-03
12	0.	5.02068E-12
23	0.	-1.37373E-17
31	0.	-7.05499E-17

TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
1	1	0.	1	2	0.
1	3	7.97129E+04	1	4	6.53154E+04
1	5	4.59116E+04	1	6	2.19268E+04
1	7	-4.28974E+03	1	8	-2.41791E+04
2	1	0.	2	2	0.
2	3	8.03484E+04	2	4	6.65744E+04
2	5	4.80176E+04	2	6	2.50905E+04
2	7	3.92926E+01	2	8	-1.90039E+04
3	1	0.	3	2	0.
3	3	8.03484E+04	3	4	6.65744E+04
3	5	4.80176E+04	3	6	2.50905E+04
3	7	3.92928E+01	3	8	-1.90039E+04
4	1	0.	4	2	0.
4	3	0.	4	4	6.78326E+04
4	5	5.01214E+04	4	6	2.82493E+04
4	7	4.36423E+03	4	8	-1.38266E+04
5	1	-1.66427E+04	5	2	-1.70635E+04
5	3	-1.79102E+04	5	4	-1.91875E+04
5	5	-2.08947E+04	5	6	-2.29826E+04
5	7	-2.52368E+04	5	8	-2.69407E+04

MEMBER FAILURE: TRUSS 2 FIBER 3

SPACE PROGRAM LISTING

APPENDIX D

The following pages present a listing of the CDC 6600 version of the SPACE program. The program is written for a "RUN" compiler, and requires 70K of core to compile and execute. The compilation of the program and execution of the sample case given in Appendix C required less than 13 system seconds of time.

```
                PROGRAM MAIN (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
          C
          C     ************************************************************************
          C     *                                                                      *
          C     *                                SPACE                                 *
          C     *                                                                      *
          C     *                             VERS  1  MOD  0                          *
          C     *                                                                      *
          C     ************************************************************************
          C
          C
000003          COMMON   /CINPUT/AD,BD,DD,NB,L,EY,EC,A,VMOD,VTI,V,SGM
000003          COMMON/LOC2/STO
000003          DIMENSION TEMP(3)
000003          DIMENSION         EY( 5,30),A( 5,30),EC( 5,30),BT( 5,30),NB( 5,30),
               1                  L( 5,30),AL( 5),SG0( 6,1),TRIG(1,6),TRMO( 6,1),
               2                  EV(6,1),C( 21, 5,30),D(6,6),DIRF(1,1),SGM( 5,30),
               3                  ETA( 5,30),EP( 5,30),RAT( 5,30),SGF( 5,30),
               4                  SGP( 5,30),G(  6, 5,30),E(6,6),Z(6,6),DE( 5,30),
               5                  DM( 5,30),STORS( 5,30),SM( 6),VT( 5,30)
000003          DIMENSION         SLN(6,1),SLP(6,1),SGC( 5,30),VTI( 5,30),
               1                  FRAC( 5,30),TMPFL( 5,30,40)
000003          DIMENSION         II(40),JJ(40)
000003          NAMELIST/DATA/     NIT,SEPS,SUPB,NOR,NTR,AD,BD,DD,SGM,RAT,EC,EY,L,
               1               VTI,TEMP,ALPHA,NB,AL,SG0,NINC,MXCAL,SMLT,BT
000003          DATA              MXCAL,NINC,NIT,SMLT,SEPS,SUPB
               1                   /5,100,5,1.,.5,1.0E+05/
000003          REAL              NB,L
000003          INTEGER STO(5,30)
000003          EQUIVALENCE       (DE,EP)
000003          DATA              PI/3.1415926E0/,EXPARG/173.0E0/
000003          LOGICAL           PSBT,MSINGD,IFAIL( 5,30)
          C
          C
000003          DSEC(X) =  1.0E0/ COS(X)
000012          RAD(X) =  X/57.29578
000016          DCOTH(X) = 1.0E 00/ TANH(X)
000024          U(X) =  SQRT(X)*PI/2.
000033          CDEL(C,A) =  C*A*(1.-(PI/2.)*(1.- COS(    U(A)))/(    U(A)*
               1                SIN(    U(A))))/(1.-A)
000060          TDEL(C,A) =  C*A*(1.-(PI/2.)/(    U(A)*DCOTH(    U(A)/2.)))/
               1               (1.+A)
000101          EVAL(Y,A,C,D) = A*Y/(A+4.*(2.*C*D+D**2))
000114          F(X) = 1.00E 00 -  EXP(-X)
          C
          C     INPUT
          C
000123          AD=1.0
000125          BD=1.0
000126          DD=1.0
000127          ICS=0
000130        1 ICS=ICS+1
000132          READ(5,DATA)
000134          IF(EOF,5) 33,32
```

```
              C     INPUT  PER  CASE
              C
              C     CONTROL  PARAMETERS
000137          32 NORP=  NOR + 1
              C
              C      RESET MATRIX STO TO ZERO
              C
000141              DO 19 KDF=1,5
000143              DO 19 KDZ=1,30
000144         19   STO(KDF,KDZ)=0
              C     MODEL  GEOMETRY
              C     STRESS  LIMIT
              C     FIBER  AND  TRUSS  PROPERTIES
              C     ANGULAR  ORIENTATIONS
              C     INTIAL  LOADING
              C
              C
              C     INITIAL  COMPUTATIONS  AND ASSIGNMENTS
000152              DO 440 I=1,NORP
000154              DO 440 J=1,NTR
000155              IFAIL(I,J) = .FALSE.
000160         440 CONTINUE
000164              MSINGD = .FALSE.
000165              INC =  0
000166              IT =  0
000167              ITOT =  0
000170              MEMB = 1
000171              VMOD =  0.0E 00
000172              KNT = NORP*NTR
000174              V =  AD*BD*DD
000177              DO 480 I=1,6
000200              SM(I) =  SMLT*SGO(I,1)
000202              SLN(I,1) = 0.0E 00
000203         480 CONTINUE
              C
              C
000205              DO 910 I=1,NORP
000206              DO 910 J=1,NTR
000207              IF (INP.EQ.2) GO TO 890
000211              DM(I,J) =  L(I,J)*DSEC(RAD(BT(I,J)))/(2.0*NB(I,J)*KAT(I,J))
000227              ETA(I,J) =  4.*NB(I,J)**2*DD/(L(I,J)* TAN(RAD(BT(I,J))))
000242         890 CONTINUE
000242              A(I,J) =  PI*DM(I,J)**2/4.0E0
000251              VT(I,J) =  2.*NB(I,J)*A(I,J)/( SIN(RAD(BT(I,J)))*AD*BD)
000266              FRAC(I,J) =  VTI(I,J)/VT(I,J)
000272              VMOD =  VMOD + VT(I,J)
000274         910 CONTINUE
              C
              C     PRINT  OUT  INPUT  INFORMATION
000300              CALL INPUT(NOR,NTR,ICS, AL, BT)
              C
              C
              C     DEGREE  TO  RADIAN  CONVERSION
000304              DO 912 I=1,NOR
000306              AL(I) =  RAD(AL(I))
```

```
000312      912 CONTINUE
000315          DO 913 I=1,NORP
000316          DO 913 J=1,NTR
000317          BT(I,J) =  RAD(BT(I,J))
000324      913 CONTINUE
          C
          C     RETURN  TO  915  TO  INCREMENT  LOADING
000331      915 CONTINUE
          C     E*  AT  ALPHA = 0
000331          DO 917 I=1,NORP
000333          DO 917 J=1,NTR
000334          IF(IFAIL(I,J))    GO TO 917
000337          DE(I,J) =  EY(I,J)/(8.0E0* EC(I,J)**2+1.0E0)
000347      917 CONTINUE
          C     RETURN  TO  920  FOR  NEXT  ITERATIVE  STEP
          C     INITIALIZE  MATRICES  D + E  TO  ZERO
000354      920 CONTINUE
000354          DO 950 M=1,6
000356          DO 950 N=1,6
000357          D(M,N) =  0.0E 00
000362          E(M,N) =  0.0E0
000365      950 CONTINUE
          C
          C
000371          DO 1005 I=1,6
000372          TRMO(I,1) =  V*SGO(I,1)
000375     1005 CONTINUE
          C     EVALUATE  MATRICES  D + E+  FIRST  FOR +BETA + SECONDLY  FOR -BETA
000376          PSBT = .TRUE.
000377          GO TO 1020
000400     1010 CONTINUE
000400          DO 1015 I=1,NORP
000402          DO 1015 J=1,NTR
000403          BT(I,J) = -BT(I,J)
000406     1015 CONTINUE
000413          PSBT = .FALSE.
000414     1020 CONTINUE
          C
000414          DO 1750 I=1,NOR
000416          DO 1750 J=1,NTR
000417          IF(IFAIL(I,J)) GO TO 1750
          C     SET  PRELIMINARY  VALUE  OF  MATRIX  ELEMENTS
000422          PP      =  ETA(I,J)*DM(I,J)*RAT(I,J)*A(I,J)/2.*FRAC(I,J)
000433          SNA    =   SIN(AL(I))
000436          SN2A   =   SIN(2.*AL(I))
000443          SNA2   =  SNA**2
000444          SNA3   =  SNA2*SNA
000445          SN2A2  =  SN2A**2
000447          SNA4   =  SNA2**2
000450          SNB2   =   SIN(BT(I,J))**2
000454          SNB4   =  SNB2**2
000455          SN2B   =   SIN(2.*BT(I,J))
000463          SN2B2  =  SN2B**2
000464          CSA    =   COS(AL(I))
000467          CSA2   =  CSA**2
```

```
000470            CSA3  =  CSA2*CSA
000471            CSA4  =  CSA2**2
000472            CSB2  =   COS(BT(I,J))**2
000476            CSB4  =  CSB2**2
            C
            C     ELEMENTS  OF  D MATRIX
000477            C(  1,I,J) =  PP*CSA4*CSB4
000506            C(  2,I,J) =  PP*CSA2*SNA2*CSB4
000515            C(  3,I,J) =  PP*CSA2*CSB2*SNB2
000525            C(  4,I,J) = -PP*CSA2*SN2A*CSB4
000535            C(  5,I,J) = -PP*CSA2*SNA*CSB2*SN2B
000547            C(  6,I,J) = -PP*CSA3*CSB2*SN2B
000557            C(  7,I,J) =  PP*CSB4*SNA4
000567            C(  8,I,J) =  PP*CSB2*SNB2*SNA2
000575            C(  9,I,J) = -PP*CSB4*SNA2*SN2A
000605            C( 10,I,J) = -PP*SNA3*CSB2*SN2B
000615            C( 11,I,J) = -PP*CSA*SNA2*CSB2*SN2B
000627            C( 12,I,J) =  PP*SNB4
000635            C( 13,I,J) = -PP*SN2A*CSB2*SNB2
000644            C( 14,I,J) = -PP*SNA*SNB2*SN2B
000654            C( 15,I,J) = -PP*CSA*SNB2*SN2B
000665            C( 16,I,J) =  PP*SN2A2*CSB4
000674            C( 17,I,J) =  PP*SNA*SN2A*CSB2*SN2B
000704            C( 18,I,J) =  PP*CSA*SN2A*CSB2*SN2B
000715            C( 19,I,J) =  PP*SNA2*SN2B2
000724            C( 20,I,J) =  PP*SNA*CSA*SN2B2
000733            C( 21,I,J) =  PP*CSA2*SN2B2
000742       1750 CONTINUE
            C
            C     FORM  UPPER  TRIANGLE  OF  D MATRIX
000747            MC = 0
000750            DO 1800 M=1,6
000751            DO 1800 N=M,6
000752            MC = MC + 1
000754            DO 1800 I=1,NOR
000755            DO 1800 J=1,NTR
000756            IF(IFAIL(I,J)) GO TO 1800
000761            D(M,N) =  D(M,N) + C( MC,I,J)*DE(I,J)
000774       1800 CONTINUE
            C
            C     FORM  SYMMETRIC  ELEMENTS  OF  D
001005            DO 1850 M=2,6
001007            LD =  M-1
001011            DO 1850 N=1,LD
001012            D(M,N) =  D(N,M)
001017       1850 CONTINUE
            C
001023            I =  NORP
001025            DO 1900 J=1,NTR
001026            IF(IFAIL(I,J)) GO TO 1900
001031            PP      =  ETA(I,J)*DM(I,J)*RAT(I,J)*A(I,J)/2.*FRAC(I,J)
001042            SNB2  =   SIN(BT(I,J))**2
001046            SNB4  =  SNB2**2
001047            SN2B  =   SIN(2.*BT(I,J))
001055            SN2B2 =  SN2B**2
```

```
001056          CSB2  =   COS(BT(I,J))**2
001062          CSB4  =  CSB2**2
         C
         C      ELEMENTS  OF  E MATRIX
001063          G(  1,I,J) =  PP*CSB4
001071          G(  2,I,J) =  PP*CSB2*SNB2
001076          G(  3,I,J) = -PP*CSB2*SN2B
001102          G(  4,I,J) =  PP*SNB4
001106          G(  5,I,J) = -PP*SNB2*SN2B
001113          G(  6,I,J) =  PP*SN2B2
001117     1900 CONTINUE
         C
         C      FORM  UPPER  TRIANGLE  OF  E MATRIX
001122          DO 1910 J=1,NTR
001123          IF(IFAIL(I,J)) GO TO 1910
001126          E(1,1) =  E(1,1) + G(  1,I,J)*DE(I,J)
001134          E(1,2) =  E(1,2) + G(  2,I,J)*DE(I,J)
001143          E(1,4) =  E(1,4) + G(  3,I,J)*DE(I,J)
001151          E(2,2) =  E(2,2) + G(  4,I,J)*DE(I,J)
001160          E(2,4) =  E(2,4) + G(  5,I,J)*DE(I,J)
001166          E(4,4) =  E(4,4) + G(  6,I,J)*DE(I,J)
001175     1910 CONTINUE
         C
         C      FORM  SYMMETRIC  ELEMENTS  OF  E
001200          E(2,1) =  E(1,2)
001201          E(4,1) =  E(1,4)
001203          E(4,2) =  E(2,4)
         C
         C      CHECK  FOR +BETA  OR -BETA
001204          IF(PSBT) GO TO 1010
001206          DO 1915 I=1,NORP
001207          DO 1915 J=1,NTR
001210          BT(I,J) = -BT(I,J)
001213     1915 CONTINUE
         C
         C      FORM  SUM  OF  MATRICES  D + E
001220     1917 CONTINUE
001220          DO 1920 M=1,6
001222          DO 1920 N=1,6
001223          Z(M,N) =  D(M,N) + E(M,N)
001232     1920 CONTINUE
001236          IF(MSINGD) GO TO 1967
         C
         C
         C      INVERT  RESULTANT  MATRIX
001237          CALL  INVRTD(Z,6,6,DET,1,E-15,IRANK,1.00E-50)
         C
         C      CHECK  FOR  SINGULAR  MATRIX
001246          IF(IRANK.EQ.6) GO TO 1968
001250          MSINGD = .TRUE.
001251          WRITE(6,9710) IRANK,DET
001260          GO TO 1917
001261     1967 CONTINUE
001261          WRITE(6,9715) ((Z(K1,L1),L1=1,6),K1=1,6)
001277          MSINGD = .FALSE.
```

```
001300          GO TO 7000
001301     1968 CONTINUE
          C
          C      STRESS  CALCULATIONS
001301     2000 CONTINUE
001301          DO 4000 I=1,NORP
001303          DO 4000 J=1,NTR
001304          IF(IFAIL(I,J))   GO TO 4000
001307          IF(I.EQ.NORP) GO TO 2050
001311          SNA   =   SIN(AL(I))
001313          SNA2  =  SNA**2
001314          SN2A  =   SIN(2.*AL(I))
001321          CSA   =   COS(AL(I))
001324          CSA2  =  CSA**2
001325     2050 CONTINUE
001325          SN2B  =   SIN(2.*BT(I,J))
001334          SNB2  =   SIN(BT(I,J))**2
001340          CSB2  =   COS(BT(I,J))**2
001345          IF(I.EQ.NORP) GO TO 2080
          C
          C      STRESS-STRAIN  FACTORS
001347          TRIG(1,1) =  CSA2*CSB2
001351          TRIG(1,2) =  CSB2*SNA2
001353          TRIG(1,3) =  SNB2
001354          TRIG(1,4) = -SN2A*CSB2
001356          TRIG(1,5) = -SNA*SN2B
001360          TRIG(1,6) = -CSA*SN2B
001361     2080 CONTINUE
          C
          C
          C      STORE  STRESS  VALUE  FROM  PREVIOUS  ITERATION
001361          IF(IT.EQ.0) GO TO 3110
001362          SGP(I,J) =  SGF(I,J)
001367     3110 CONTINUE
          C      CALCULATE  STRAIN  VALUES
001367          CALL  MXMULD(Z,TRMO,EV,6,6,1,6,6,1)
001400          DO 3115 ITMP=1,3
001402          EV(ITMP,1) = EV(ITMP,1) + .5*ALPHA*TEMP(ITMP)
001407     3115 CONTINUE
001410          CALL MXMULD(TRIG,EV,DIRF,1,6,1,1,6,1)
001421          COMD = DIRF(1,1)
001423          TRIG(1,5) = -TRIG(1,5)
001424          TRIG(1,6) = -TRIG(1,6)
001425          CALL MXMULD(TRIG,EV,DIRF,1,6,1,1,6,1)
001435          IF( ABS(COMD).LE. ABS(DIRF(1,1)))  GO TO 3201
001442          DIRF(1,1) = COMD
001442     3201 IF(I.LT.NORP)  GO TO 3525
          C      CALCULATE  STRESS  VALUES
001445          SGF(I,J) =  EP(I,J)*(EV(1,1)*CSB2+EV(2,1)*SNB2-EV(4,1)*SN2B)
001460          COMD = EP(I,J)*(EV(1,1)*CSB2 +EV(2,1)*SNB2 +EV(4,1)*SN2B)
001470          IF( ABS(COMD).LE. ABS(SGF(I,J)))  GO TO 3202
001476          SGF(I,J) = COMD
001500     3202 GO TO 3550
001501     3525 CONTINUE
001501          SGF(I,J) =  EP(I,J)*DIRF(1,1)
```

```
001507     3550 CONTINUE
001507          ALP =  16.*SGF(I,J)/(PI**2*EY(I,J))*(RAT(I,J))**2
001522          ABSA =   ABS(ALP)
001523          IF(SGF(I,J).LE.0.0E 00)  EP(I,J) =  EVAL(EY(I,J),ABSA,EC(I,J),
               1                                    CUEL(EC(I,J),ABSA))
001543          IF(SGF(I,J).GT.0.0E 00)  EP(I,J) =  EVAL(EY(I,J),ABSA,EC(I,J),
               1                                    TUEL(EC(I,J),ABSA))
001563     4000 CONTINUE
          C
          C     STRESS  CONVERGENCE  TEST
001570          IF(IT.NE.0) GO TO 4010
001571          IT = 1
001572          GO TO 920
001573     4010 CONTINUE
001573          DO 5000 I=1,NORP
001575          DO 5000 J=1,NTR
001576          IF(IFAIL(I,J))    GO TO 5000
001601          DSG =   ABS(SGF(I,J)-SGP(I,J))
          C     CHECK  FOR  ZERO  STRESS  OR  RELATIVE  STRESS .LT. 1.D-06
001606          IF((SGP(I,J).EQ.0.).OR.(DSG.LT.1.E-06))  GO TO 4800
001617          DSG =   ABS(DSG/SGP(I,J))
001621     4800 CONTINUE
001621          IF(DSG.LT.SEPS) GO TO 5000
001624          IF(DSG.GT.SUPB) GO TO 4900
          C     STRESS  ITERATION
001627          IT =  IT + 1
001630          IF(IT.LT.NIT) GO TO 920
          C     NO  CONVERGENCEE  WITHIN  ITERATION  LIMIT
001632          ICON = 1
001633          GO TO 5100
          C     DIVERGENCE
001634     4900 ICON =  2
001635          GO TO 5100
001636     5000 CONTINUE
          C     NORMAL  CONVERGENCE
001643          ICON =  3
001644     5100 GO TO(5200,5250,5300),ICON
          C
          C     NON-CONVERGENCE  DUMP
001653     5200 CONTINUE
001653          CALL CDUMP(NORP,NTR,ICON,IT,SGF,SGP)
001657          GO TO 7000
          C
          C     DIVERGENCE  DUMP
001660     5250 CONTINUE
001660          CALL CDUMP(NORP,NTR,ICON,IT,SGF,SGP)
001664          GO TO 7000
          C
          C     CONVERGED  SOLUTION  ANALYSIS
          C
001665     5300 CONTINUE
001665          WRITE(6,9720)  IT
          C     CHECK:  INCRIMENTATION  LIMIT
001673          IF(INC.GE.NINC) GO TO 7000
001676          INC =  INC + 1
```

```
001677          IT =  0
          C
          C     STORE  LOADINGS  FOR  PRESENT  AND  PREVIOUS  INCRIMENTATIONS
001700          IF(MEMB.NE.1)  GO TO 5955
001702          DO  5950  I=1,6
001703          SLP(I,1) = SLN(I,1)
001705          SLN(I,1) = SGO(I,1)
001706     5950 CONTINUE
          C
          C
          C     COMPUTE  MAXIMUM  STRESS  COMPARISON  TERM  FOR  EACH  MEMBER
001710     5955 CONTINUE
001710          DO 5960 I=1,NORP
001712          DO 5960 J=1,NTR
001713          IF(IFAIL(I,J)) GO TO 5960
001716          ALP =  16.*SGF(I,J)/(PI**2*EY(I,J))*(RAT(I,J))**2
001730          ALB =  ABS(ALP)
001731          TRM2 =  PI*EY(I,J)*EC(I,J)*U(ALB)/RAT(I,J)**2
001742          IF(SGF(I,J).LE.0.0E 00)  SGC(I,J) = SGF(I,J) + 8.*SGF(I,J)*
               1                         (CDEL(EC(I,J),ALB)+EC(I,J)) + ALB*TRM2/
               2                         ((1.-ALB)* TAN(U(ALB)))
001774          IF(SGF(I,J).GT.0.0E 00)  SGC(I,J) = SGF(I,J) + 8.*SGF(I,J)*
               1                         (-TDEL(EC(I,J),ALB)+EC(I,J)) - ALB*TRM2/
               2                         ((1.+ALB)* TANH(U(ALB)))
002026     5960 CONTINUE
          C
002033     5975 CONTINUE
002033     5977 CONTINUE
          C
          C     STRESS-STRAIN  OUTPUT  FOR  THIS  LOADING
002033          CALL OUTPSS(NORP,NTR,SGO,SGC,EV)
002037          IF(INC.EQ.1)  GO TO 6060
          C     RETAIN  NUMBER  OF  FAILED  MEMBERS
002041          IRT =  ITOT
          C
          C     CHECK  COMPUTED  STRESS  AGAINST  MAXIMUM  ALLOWABLE  STRESS
002043     6000 CONTINUE
002043          K = 0
002044          DO 6050 I=1,NORP
002046          DO 6050 J=1,NTR
002047          IF(IFAIL(I,J)) GO TO 6050
002052          IF( ABS(SGC(I,J)).LT.SGM(I,J)) GO TO 6050
          C     STORE TEMPORARILY MEMBERS FAILING UNDER APPPLIED LOAD INCREMENT
002061          K = K + 1
002062          TMPFL(I,J,K) =  ABS(SGC(I,J))
002071          II(K) = I
002072          JJ(K) = J
002074     6050 CONTINUE
002101          IF (K.EQ.0)  GO TO 6051
          C     FIND FIRST FAILED MEMBER (OR MEMBERS)
002102          CALL RESET(TMPFL,K,IFAIL,SGM,II,JJ,KMAX,ITOT,MEMB,1.00E-02,
               1          MXCAL,ISENT)
002116          IF (ISENT.EQ.1)  GO TO 7000
          C     RETAIN SLOPE TERMS (IN TERMS OF FIRST FAILED MEMBER)
          C     FOR INTERPOLATION ROUTINE
```

```
002120          IM=II(KMAX)
002122          JM=JJ(KMAX)
002124          SGDEL=ABS(SGC(IM,JM)-STORS(IM,JM))
002132          SMDEL=SGM(IM,JM)-ABS(STORS(IM,JM))
        C
        C       CHECK  SENTINELS  GOVERNING  FAILURE  ANALYSIS
002136   6051   CONTINUE
002136          IF((ITOT.EQ.IRT).AND.(MEMB.EQ.2))  GO TO 6052
        C       .T.  ---=  NO FURTHER FAILURES AFTER FIRST REEVALUATION
002146          IF(.NOT.((ITOT.EQ.IRT).AND.(MEMB.EQ.3)))  GO TO 6060
        C       .F.  ---=  NO FURTHER FAILURES AFTER MORE THAN ONE REEVALUATION
002155   6052   CONTINUE
002155          MEMB = 1
002156          DO 6055 I=1,6
002160          SLN(I,1) = SGO(I,1)
002162   6055   CONTINUE
002164   6060   CONTINUE
        C       STORE  STRESS  VALUES  FOR  PRESENT  LOADING
002164          DO 6150 I=1,NORP
002166          DO 6150 J=1,NTR
002167          IF(IFAIL(I,J)) GO TO 6150
002172          STORS(I,J) =  SGC(I,J)
002176   6150   CONTINUE
        C
002203          IF(INC.EQ.1)  GO TO 6500
        C       CHECK  IF  ALL  MEMBERS  HAVE  FAILED
002205          IF(ITOT.GE.KNT) GO TO 7000
        C       CHECK  FOR  FAILED  MEMBERS
        C        MEMB = 1  ---=  NO FAILURE OR ADDITIONAL FAILURE, INCREMENT IN
        C                        STANDARD FASHION
        C        MEMB = 2  ---=  FIRST FAILURE, CALCULATE SG* + REEVALUATE
        C        MEMB = 3  ---=  FURTHER FAILURES UNDER GIVEN SG*, CONTINUE REEVALUATION
002210          GO TO (6500,6200,915), MEMB
        C
        C       CALCULATE  SG*,  INTERPOLATED  LOAD
002217   6200   CONTINUE
002217          IF(INC.EQ.1)  GO TO 6500
002221          DO 6250 I=1,6
002223          SLDEL =  SLN(I,1)-SLP(I,1)
002225          SGO(I,1) =  (SMDEL/SGDEL)*SLDEL + SLP(I,1)
002231   6250   CONTINUE
002233          GO TO 915
        C
        C       INCREMENT  APPLIED  LOAD
002233   6500   CONTINUE
002233          DO 6550 I=1,6
002235          SGO(I,1) =  SGO(I,1) + SM(I)
002240   6550   CONTINUE
002241          GO TO 915
002242   7000   CONTINUE
        C  CONVERT RADIANS TO DEGREES.
002242          DO 219 I=1,NOR
002244          AL(I)=AL(I)*57.29578
002246   219    CONTINUE
002250          DO 319 I=1,NORP
```

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002252             DO 319 J=1,NTR
002253             BT(I,J)=BT(I,J)*57.29578
002257        319  CONTINUE
002263             GO TO 1
             C
             C
             C
002264        9710 FORMAT (//* MATRIX  IS  SINGULAR  OF  RANK  =  *,I2,
                  1          *+   DETERMINANT  =  *,E15.5/)
002264        9715 FORMAT (6E12.5)
002264        9720 FORMAT (//*  SOLUTION FOR STRESS CONVERGES IN *,I2,
                  1          * ITERATIONS*//)
             C
             C
             C
             C
002264          33 STOP
002266             END
```

```
              SUBROUTINE INPUT(NOR,NTR,ICS,IAL,IBT)
        C
000010        COMMON   /CINPUT/AD,BD,DD,NB,L,EY,EC,A,VMOD,VTI,V,SGM
000010        REAL              NB( 5,30),L( 5,30),IBT( 5,30),IAL( 5)
000010        DIMENSION         EY( 5,30),A( 5,30),EC( 5,30),
             1                  VTI( 5,30),SGM( 5,30)
        C
        C
000010        WRITE(6,9610) ICS
000015        WRITE(6,9615)
000021        WRITE(6,9620)
000025        WRITE(6,9615)
000031        WRITE(6,9625) AD,BD,DD
000043        WRITE(6,9627) V
000051        WRITE(6,9630) NOR,NTR
000064        WRITE(6,9631) VMOD
000072        WRITE(6,9635)
000076        NORP = NOR + 1
000103        DO 100 I =1,NORP
000104        DO 100 J =1,NTR
000105        IF(I.NE.NORP) WRITE(6,9650) IAL(I),IBT(I,J),NB(I,J),L(I,J),
             1                            VTI(I,J)
000157        IF(I.EQ.NORP) WRITE(6,9651)        IBT(I,J),NB(I,J),L(I,J),
             1                            VTI(I,J)
000224    100 CONTINUE
000231        WRITE(6,9640)
000235        WRITE(6,9615)
000241        WRITE(6,9645)
000245        DO 150 I =1,NORP
000252        DO 150 J =1,NTR
000253        IF(I.NE.NORP) WRITE(6,9650) IAL(I),IBT(I,J),EY(I,J),EC(I,J),
             1                            A(I,J),SGM(I,J)
000334        IF(I.EQ.NORP) WRITE(6,9651)        IBT(I,J),EY(I,J),EC(I,J),
             1                            A(I,J),SGM(I,J)
000410    150 CONTINUE
000415        WRITE(6,9680)
000421        WRITE(6,9615)
        C
000425   9610 FORMAT (1H1,50X,*SPACE FRAME MODEL*,I2)
000425   9615 FORMAT (     51X,*---------------------*)
000425   9620 FORMAT (//51X,*MODEL GEOMETRY*)
000425   9625 FORMAT (/20X,*DIMENSIONS OF MODEL*,10X,*A =*,E12.5,5X,*B =*,E12.5,
             1          5X,*C =*,E12.5)
000425   9627 FORMAT (50X,*VOLUME =*,E12.5)
000425   9630 FORMAT (/20X,*NUMBER OF TRUSS ORIENTATIONS =*,I2,
             1         /20X,*NUMBER OF FIBER ORIENTATIONS PER TRUSS =*,I2)
000425   9631 FORMAT (/20X,*VOLUME FRACTION OF MODEL =*,E12.5)
000425   9645 FORMAT (/29X,*ORIENTATIONS*         ,20X,*YOUNG(S*,10X,*ECCENT.*,
             1          10X,*CROSS-*,10X,*MAXIMUM*/26X,*TRUSS*,10X,*FIBERS IN*,
             2          10X,*MODULUS*,25X,*SECTIONAL*,12X,*STRESS*/43X,*TRUSS*,
             3          47X,*AREA*)
000425   9640 FORMAT (//50X,*FIBER PROPERTIES*)
000425   9635 FORMAT (/29X,*ORIENTATIONS*,18X,*NUMBER OF*,7X,*LENGTH OF*,
             1         8X,*VOLUME*,
```

```
                2       /26X,*TRUSS*,10X,*FIBERS IN*,13X,*BAYS*,13X,*TRUSS*,
                3       10X,*FRACTION*,
                4       /45X,*TRUSS*/)
000425     9650 FORMAT ( 24X,2(E12.5,2X),4( 5X,E12.5))
000425     9651 FORMAT ( 38X,E12.5,2X,    4( 5X,E12.5))
000425     9680 FORMAT(//50X,*ANALYSIS*)
000425          RETURN
000426          END
```

```
                SUBROUTINE RESET(TMPFL,K,IFAIL,SGM,II,JJ,KMAX,IT,MEMB,EPS,MXCAL,
               *                     ISENT)
000017          COMMON/LOC2/ STO
          C
000017          LOGICAL          IFAIL( 5,30)
000017          REAL             RAT(100),TMPFL( 5,30,40),SGM( 5,30),LARGE,EPS
000017          INTEGER II(40),JJ(40),STO(5,30)
000017          ISENT = 0
          C     FORM RATIO OF STRESS AT FAILURE TO MAXIMUM STRESS
000020          DO 50 I=1,K
000022          IM=II(I)
000024          JM=JJ(I)
000026          RAT(I)=TMPFL(IM,JM,I)/SGM(IM,JM)
000037       50 CONTINUE
          C     FIND LARGEST RATIO
000041          CALL MAXVAL(K,RAT,KMAX,LARGE)
          C     DETERMINE FAILED MEMBERS FOR THIS LOAD
          C                              (I.E. THOSE WITHIN EPS OF MAXIMUM RATIO)
000044          DO 100 I=1,K
000051          IF((LARGE-RAT(I)).GT.EPS)  GO TO 100
000057          ITEMP = II(I)
000061          JTEMP = JJ(I)
000063          IFAIL(ITEMP,JTEMP) = .TRUE.
000066          STO(ITEMP,JTEMP)=1
000071          IT = IT + 1
000072          WRITE(6,9720)  II(I),JJ(I)
000112      100 CONTINUE
          C
          C     SET REEVALUATION COUNTER = 0 BEFORE INITIAL REEVALUATION
000120          IF(MEMB.EQ.2)  KRCAL=0
          C     RESET SENTINEL ONLY AFTER FIRST REEVALUATION
000123          IF(MEMB.EQ.2)  MEMB=3
          C     SET SENTINEL INDICATING FIRST MEMBER FAILURE UNDER PRESENT LOAD
000125          IF(MEMB.EQ.1)  MEMB=2
000130          IF(MEMB.NE.3)  RETURN
          C     LIMIT NUMBER OF REEVALUATIONS PER LOADING BY *MXCAL*
000132          IF (KRCAL.GE.MXCAL)  ISENT=1
000137          IF (KRCAL.GE.MXCAL)  RETURN
000142          KRCAL = KRCAL + 1
000144          RETURN
000144     9720 FORMAT (10X,*MEMBER FAILURE:*,3X,*TRUSS*,I2,3X,*FIBER*,I2)
000144          END
```

```
               SUBROUTINE OUTPSS(NORP,NTR,SGO,SGF,EV)
          C
000010         COMMON/LOC2/ STO
000010         REAL            SGO(6,1),EV(6,1),SGF( 5,30)
000010         DIMENSION         DR(6)
000010         INTEGER STO(5,30)
          C
000010         DATA DR/4H  11,4H  22,4H  33,4H  12,4H  23,4H  31/
000010         WRITE(6,9750)
          C    AFTER A FIBER FAILS SET THE STRESS TO ZERO.
000013         DO 2 KJ3=1,5
000020         DO 2 KJ4=1,30
000021         IF( STO (KJ3,KJ4). EQ. 0) GO TO 2
000024         SGF(KJ3,KJ4)=0.0
000026       2 CONTINUE
          C    SET ALL ELEMENTS OF MATRIX STO TO ZERO.
000032         DO 1 KJ1=1,5
000034         DO 1 KJ2=1,30
000035       1 STO(KJ1,KJ2)=0
000043         DO 100 I=1,6
000045         WRITE(6,9762) DR(I),SGO(I,1),EV(I,1)
000071     100 CONTINUE
000076         IF(NTR.EQ.1) WRITE(6,9769)
000106         IF(NTR.GT.1) WRITE(6,9770)
000117         DO 150 I=1,NORP
000121         DO 150 J=1,NTR,2
000122         JP =  J+1
000124         NMJ =  NTR-J
000125         IF(NMJ.EQ.0) WRITE(6,9775) I,J,SGF(I,J)
000147         IF(NMJ.GT.0) WRITE(6,9775) I,J,SGF(I,J),I,JP,SGF(I,JP)
000205     150 CONTINUE
          C
000212    9750 FORMAT (//20X,*DIRECTION*,20X,*APPLIED LOAD*,20X,*STRAIN*/ )
000212    9762 FORMAT (24X,A4,2(20X,E15.5))
000212    9769 FORMAT (20X,*ORIENTATIONS*,15X,*STRESS*/10X,*TRUSS*,10X,
              1         *FIBERS IN*/27X,*TRUSS*/)
000212    9770 FORMAT (2(20X,*ORIENTATIONS*,15X,*STRESS*,5X)/10X,*TRUSS*,10X,
              1         *FIBERS IN*,30X,*TRUSS*,10X,*FIBERS IN*/2/X,*TRUSS*,
              2         50X,*TRUSS*/)
000212    9775 FORMAT (2(12X,I2,12X,I2,15X,E15.5))
000212         RETURN
000212         END
```

```
              SUBROUTINE COUMP(NORP,NTR,ICON,IT,SGF,SGP)
        C
000011        REAL             SGF( 5,30),SGP( 5,30)
000011        DIMENSION        CONMSG(2,2)
000011        DATA CONMSG/10H DOES NOT ,10HCONVERGE  ,10H DIVERGES ,
             *            10H          /
000011        ITM =  IT-1
000013        WRITE(6,9710)  (CONMSG(J,ICON),J=1,4)
000030        WRITE(6,9720)
000034        WRITE(6,9725)
000040        WRITE(6,9726)  IT,ITM
000053        DO 100 I=1,NORP
000060        DO 100 J=1,NTR
000061        WRITE(6,9730)  I,J,SGF(I,J),SGP(I,J)
000110    100 CONTINUE
000120   9710 FORMAT (//10X,*SOLUTION  FOR  STRESS  *,4A4//)
000120   9720 FORMAT (10X,*TERMINAL  STRESS  VALUES*)
000120   9725 FORMAT (10X,*TRUSS*,10X,*   FIBERS  *,10X,2(10X,*STRESS*))
000120   9726 FORMAT (56X,2(*(ITER.*,I2,*)*,10X))
000120   9730 FORMAT (12X,I2,15X,I2,15X,2(5X,E12.5))
000120        RETURN
000120        END
```

```
                  SUBROUTINE MAXVAL(K,Y,KMAX,UPPER)
            C
            C     DETERMINE MAXIMUM OF ARRAY OF VALUES
            C               AND SUBSCRIPT ASSOCIATED WITH MAXIMUM
            C
            C                                            PARAMETERS USED
            C
            C     Y       :  ARRAY NAME
            C     K       :  NUMBER OF ELEMENTS IN ARRAY
            C     UPPER   :  MAXIMUM VALUE OF Y
            C     KMAX    :  SUBSCRIPT ASSOCIATED WITH UPPER
            C
 000007           REAL             Y(K),UPPER
 000007           UPPER = Y(1)
 000007           KMAX = 1
 000010           IF(K.EQ.1)  GO TO 150
 000012           DO 100 I=2,K
 000013           IF(Y(I).LT.UPPER)  GO TO 100
 000016           UPPER = Y(I)
 000017           KMAX = I
 000020       100 CONTINUE
 000023       150 CONTINUE
 000023           RETURN
 000024           END
```

```
                SUBROUTINE MXMULD(A,B,C,NROWA,NCOLA,NCOLB,MA,NA,NB)
          C
000014          DIMENSION A(NROWA,NCOLA),B(NCOLA,NCOLB),C(NROWA,NCOLB)            R06D0002
000014          REAL            A,B,C,X                                           R06D0003
000014          DO 20 I=1,MA                                                      R06D0004
000015          DO 20 J=1,NB                                                      R06D0005
000016          X=0.                                                              R06D0006
000017          DO 10 K=1,NA                                                      R06D0007
000021       10 X=X+A(I,K)*B(K,J)                                                 R06D0008
000035       20 C(I,J)=X                                                          R06D0009
000047          RETURN
000047          END
```

```
                 SUBROUTINE INVRTD(A,NDIM,N,DETA,EPS,IRANK,UNDER)
          C
          C      ROUTINE INVRTD INVERTS AN N X N MATRIX USING GAUSS-JORDAN
          C      ELIMINATION METHOD
          C
          C                                   * VARIABLE DICTIONARY *
          C
          C      A(N,N)                  : MATRIX TO BE INVERTED PASSED,INVERSE RETURNED
          C      NDIM                    : UPPER LIMIT TO MATRIX DIMENSION
          C      N                       : DIMENSION OF MATRIX
          C      IRANK                   : RANK OF MATRIX
          C      DETA                    : DETERINANT OF MATRIX
          C      EPS                     : ADJUSTABLE TOLERANCE FACTOR COMPARED TO
          C                                VALUE OF PIVOTAL ELEMENT DURING INVERSION
          C      UNDER                   : UNDERFLOW LIMIT (CHECK ON COMPUTED VAR.)
          C
          C      ***********************************************************************
          C
000012           DIMENSION A(NDIM,NDIM)
000012           INTEGER IR(60),IC(60),R,S
          C      CHECK MATRIX ELEMENTS FOR UNDERFLOW POSSIBILITIES
000012           DO 5 I=1,N
000013           DO 5 J=1,N
000014           IF( ABS(A(I,J)).LT.UNDER)  A(I,J) = 0.0E 00
000027         5 CONTINUE
000034           DETA=1.                                                R12D0006
000035           SUM=0.                                                 R12D0007
000036           DO 10 I = 1,N                                          R12D0008
000037           DO 10 J = 1,N                                          R12D0009
000040        10 SUM=SUM+A(I,J)**2                                      R12D0010
000052           SUM= SQRT(SUM)                                         R12D0011
000054           DMA = N**2                                             R12D0012
000061           RMS=SUM/DMA                                            R12D0013
000063           TOL=EPS*RMS                                            R12D0014
000064           DO 20 I = 1,N                                          R12D0015
000066           IR(I)=0                                                R12D0016
000067        20 IC(I)=0                                                R12D0017
000072           S=0                                                    R12D0018
000073           R = N                                                  R12D0019
000074        30 I=0                                                    R12D0020
000075           J=0                                                    R12D0021
000076           TEST=0.0                                               R12D0022
000077           DO 50 K = 1,N                                          R12D0023
000100           IF(IR(K).NE.0)GO TO50                                  R12D0024
000102           DO 40 L = 1,N                                          R12D0025
000103           IF(IC(L).NE.0)GO TO40                                  R12D0026
000105           X= ABS(A(K,L))                                         R12D0027
000112           IF(X.LT.TEST)GO TO40                                   R12D0028
000114           I=K                                                    R12D0029
000116           J=L                                                    R12D0030
000117           TEST=X                                                 R12D0031
000120        40 CONTINUE                                               R12D0032
000123        50 CONTINUE                                               R12D0033
000126           PIV=A(I,J)                                             R12D0034
```

```
000133         IF( ABS(DETA).LT.UNDER)  DETA = 0.00E 00
000137         DETA=PIV*DETA
000141         IF ( ABS(PIV) .LE. TOL) GO TO 150
000143         IR(I)=J
000145         IC(J)=I
000146         PIV = 1.0E0/PIV
000150         A(I,J)=PIV
000153         DO 60 K = 1,N
000155      60 IF(K.NE.J)A(I,K)=A(I,K)*PIV
000166         DO 90 K = 1,N
000167         IF (K.EQ.I) GO TO 90
000171         PIV1 = A(K,J)
000175      70 DO 80 L = 1,N
000177         IF( ABS(PIV1).LT.UNDER)  PIV1=0.0E 00
000203         IF( ABS(A(I,L)).LT.UNDER)  A(I,L) = 0.00E 00
000217      80 IF(L.NE.J)A(K,L)=A(K,L)-PIV1*A(I,L)
000235      90 CONTINUE
000240         DO 100 K = 1,N
000241     100 IF(K.NE.I)A(K,J)=-PIV*A(K,J)
000253         S=S+1
000254         IF(S.LT.R)GO TO 30
000256     110 DO 140 I = 1,N
000260         K=IC(I)
000262         M=IR(I)
000263         IF(K.EQ.I)GO TO 140
000265         DETA=-DETA
000266         DO 120 L = 1,N
000267         TEMP=A(K,L)
000273         A(K,L)=A(I,L)
000302     120 A(I,L)=TEMP
000306         DO 130 L = 1,N
000307         TEMP=A(L,M)
000314         A(L,M)=A(L,I)
000322     130 A(L,I)=TEMP
000330         IC(M)=K
000332         IR(K)=M
000333     140 CONTINUE
000336     150 IRANK=S
000337         RETURN
000340         END
```