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COMPUTERIZED MULTILEVEL ANALYSIS FOR MULTILAYERED FIBER COMPOSITES

by Christos C. Chamis
Lewis Research Center
Cleveland, Ohio

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ABSTRACT

A FORTRAN IV computer code for the micromechanics, macromechanics, and laminate analysis of multilayered fiber composite structural components is described. The code can be used either individually or as a subroutine within a complex structural analysis/synthesis program. The inputs to the code are constituent materials properties, composite geometry, and loading conditions. The outputs are various properties for ply and composite; composite structural response, including bending-stretching coupling; and composite stress analysis, including comparisons with failure criteria for combined stress. The code was used successfully in the analysis and structural synthesis of flat panels, in the buckling analysis of flat panels, in multilayered composite material failure studies, and lamination residual stresses analysis.

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INTRODUCTION

Multilayered filamentary composites are structural materials which have evolved in recent years. These composites are constructed by laminating several plies (layers). The plies, in turn, consist of high strength filaments which are embedded in a low strength, low density (for nonmetallic matrices) matrix material while the matrix is in its molten state. Subsequently, the system is processed at specified pressures and temperatures. The result is a very light (for nonmetallic matrix composites), high strength material. Its strength depends on the orientation of the filaments with respect to the direction of the maximum anticipated stress. Coincidence of the filaments with the direction of maximum stress utilizes this material most efficiently and gives it its most attractive features, stiffness and strength to weight ratio.

Multilayered filamentary composites as structural materials have exhibited great potential in space vehicles, deep submergence vessels, radomes, and other structures where the stiffness and strength to weight ratio, nonmagnetic, structural damping, elevated temperature, and environmental resistant properties are important. The underlying structural strength principle for these materials is that the filaments are the primary load carrying members while the matrix provides the structural integrity by serving as a load transferring medium, providing rigidity (keeping the filaments fixed in their position), and protecting the filaments from exposure to unfavorable environment.

Though multilayered filamentary composites have many desirable design features, as a structural material they are at the dawn of their great potential. One of the factors that keeps these composite materials at the dawn of their great potential is the designer's lack of proven and readily available mathematical formalisms which could be used to select constituent materials when the structural application of the composite is specified. These types of mathematical formalisms constitute a multilevel analysis encompassing the following levels: micromechanics, macromechanics, combined-stress strength functions, laminate analysis, and delamination criteria. This type of multilevel analysis is quite extensive and cumbersome. It needs to be transformed into an efficient computer code to be effective and practical.

A FORTRAN IV computerized multilevel analysis for multilayered fiber composites which has grown to maturity over the past several years is the subject of this paper. This multilevel analysis includes all the levels mentioned previously. It has been extensively used for analyzing several fiber composite systems. The computer code is described herein from the engineer's/analyst's usage viewpoint. Therefore, the description is limited to input/output, results produced and application versatility. The complete documentation of the code is given in [1]. Several of the mathematical functions programed are described briefly as part of the code output.

OBTAINING AND USING THE CODE

The mechanics required to use this code for the analysis of multilayered fiber composites are described in some detail. Here, it is assumed that the user is interested in using the code as a tool only and that he has available to him a FORTRÁN IV manual.

The physical representation of the code is illustrated in Fig. 1. The geometry of the constituents, the ply, and the composite are defined in this figure. The required input properties, correlation coefficients, and computed properties are summarized in Fig. 1 in symbolic form.

The physical arrangement of the code is illustrated in Fig. 2. The numbers given in each block of cards are for subsequent discussion and do not appear on the code. Four steps are required to use the code in the user's computer facility:

(1) Obtain the code.

(2) Make it operational in the user's computer facility.

(3) Supply the input data.

(4) Interpret the code output results.

Obtain the Code

The code can be obtained in cards or tape from [2]. If this is not convenient or possible, then the cards can be punched from the compiled listing appended in [1].

Make It Operational

Making the program operational requires the availability of a FORTRAN compiler in the user's computer facility, certain control cards at the beginning of the code, and the card that preceeds each subroutine. Consult your computer group about these items. The control cards present in the code are only for the Lewis IBM 7044/7094 direct couple system. Once the deck of cards has been assembled as is shown in Fig. 2 (except Input Data) with the proper control cards, the user is ready to compile the code in his facility. The compilation will indicate whether any additional modifications are needed. Most modifications will be minor and will usually deal with certain logical and subroutine call statements peculiar to each compiler. Consult your computer group for these modifications.

Supply the Input Data

The physical arrangement of the input data cards is illustrated in Fig. 3. The numbers in the group of cards are for identification purposes in this description and do not appear on the cards. A sample input data sheet is illustrated in Table 1 for the Thornel-50/epoxy composite system.

Listings of input data for several composite systems are appended in [1]. These systems are shown graphically in Fig. 4. The input data for these systems can be punched from the listings, and the cards that need alterations for the specific problem can be modified accordingly.

Input data for additional composite systems may be easily prepared. This is done by selecting a related system from those available and modifying those entries that need modification.

After the input data have been properly assembled (as is shown in Fig. 3), it is placed in its physical position (Fig. 2), and the code is ready to be run for results.

Input Ply Properties

There could be cases when the user would prefer to supply some of his own ply properties instead of using the code to compute them. The user has to provide his own formats for these cases. The physical location for these statements is described in the section MAIN PROGRAM. A flow chart of the MAIN PROGRAM is shown in Fig. 5. The functions of the subroutines are listed in Table 2.

OUTPUT AND MATHEMATICAL RELATIONS

The program output consists of printing out (1) the input data, (2) the composite three-dimension strain-stress and stress-strain relations about the structural axes (see Fig. 6), (3) the composite properties generated in array PC, (4) the composite constitutive equations about the structural axes, (5) the reduced bending and axial stiffness, (6) displacement-force relations, (7) the current load or displacement condition, and (8) the ply properties, stresses, and margin of safety generated in array PL.

The printout of the input data is preceded by its code name. For example, the first and second lines of printout are

THORNEL-50/EPOXY

NL,NPL,NPC,NFPE,NLC

8 71 54 1420 1

The output of code generated data is preceded by title headings. The output of the composite three-dimensional strain-stress temperature relations and composite stress-strain relations about the structural axes are printed under the headings

3-D COMPOSITE STRAIN STRESS RELATIONS - STRUCTURAL AXES

The matrices $[E_c]_s^{-1}$ and $\{\alpha_c\}_s$ in the equation

$$\{e_c\}_s = [E_c]_s^{-1}\{\sigma_c\} - \Delta T\{\alpha_c\}_s$$

are printed out.

3-D STRESS STRAIN RELATIONS - STRUCTURAL AXES

The matrix $[E_c]_s$ in

$$\{\sigma_c\}_s = [E_c]_s\{\varepsilon_c\}_s$$

is printed out. The subscript s in the preceding equations indicates that the relations are written about the structural axes. It is noted that these properties are only local to subroutine GACD3. They can be made global if needed.

The output of the composite properties, generated in array PC are printed under the heading

COMPOSITE PROPERTIES - VALID ONLY FOR CONSTANT TEMPERATURE THROUGH THICKNESS

LINES 1 TO 31 3-D COMPOSITE PROPERTIES ABOUT MATERIAL AXES

LINES 33 TO 54 2-D COMPOSITE PROPERTIES ABOUT STRUCTURAL AXES

Fifty-four entries are printed under this heading as follows:

PC(1)	ρ_c	weight density
PC(2)	t_c	thickness
PC(3) to PC(11)	$[E_c]$	three-dimensional stress-strain relations about material axes
PC(12) to PC(14)	$\{\alpha_c\}$	three-dimensional coefficients of expansion about material axes
PC(15) to PC(18)	$\{K_c\},H_c$	three-dimensional heat conductivities and heat capacity along material axes
PC(19) to PC(30)	$E_{c11},G_{c12},\nu_{c12}$	three-dimensional constants about material axes
PC(31)	$\bar{z}$	distance to reference plane from bottom of composite
PC(32)	--------------	blank
PC(33) to PC(38)	$[E_c]$	two-dimensional stress-strain relations about structural axes

PC(39) to PC(47)	$E_{c11}, G_{c12}, \nu_{c12}$	two-dimensional elastic constants along structural axes
PC(48) to PC(54)	$\{\alpha_c\}, K_c, H_c$	two-dimensional coefficients of thermal expansion, heat conductivities, and heat capacity along structural axes

The output for the composite constitutive equations are printed under the heading

FORCES FORCE DISPLACEMENT RELATIONS DISPL THERMAL FORCES

$$\begin{Bmatrix} \{N_{cx}\} \\ \\ \{M_{cx}\} \end{Bmatrix} = \begin{bmatrix} [A_{cx}][C_{cx}] \\ \\ [C_{cx}][D_{cx}] \end{bmatrix} \begin{Bmatrix} \{\varepsilon_{csx}\} \\ \\ \{w_{cb}\} \end{Bmatrix} - \begin{Bmatrix} \{N_{c\Delta Tx}\} \\ \\ \{M_{c\Delta Tx}\} \end{Bmatrix}$$

The elements of matrices A_{cx}, C_{cx}, $N_{c\Delta Tx}$, and $M_{c\Delta Tx}$ are printed out.

The output for the reduced bending rigidities is printed under the heading

REDUCED BENDING RIGIDITIES

The elements of D^R_{cx} are printed out in one line.

The output for the reduced axial stiffness A^R_{cx} is printed out under the heading

REDUCED STIFFNESS MATRIX

The inverse of the constitutive equations is printed out under the heading

DISP DISPLACEMENT FORCE RELATIONS FORCES

$$\begin{Bmatrix} \{\varepsilon_{cax}\} \\ \\ \{w_{cb}\} \end{Bmatrix} = \begin{bmatrix} [A_{cx}] & [C_{cx}] \\ \\ [C_{cx}] & [D_{cx}] \end{bmatrix}^{-1} \begin{Bmatrix} \{N_{cx}\} \\ \\ \{M_{cx}\} \end{Bmatrix}$$

The elements of this inverse are printed out.

The output for the current load condition is printed next to the headings

FOR THIS CASE NBS(X,Y,XY-M) IS

and

FOR THIS CASE MBS(X,Y,XY-M) IS

The current values of $\bar{N}_{cx}$, $\bar{N}_{cy}$, $\bar{N}_{cxy}$, $\bar{M}_{cx}$, $\bar{M}_{cy}$, and $\bar{M}_{cxy}$ are printed out under these headings.

The output for the current displacement conditions is printed under the heading

FOR THIS CASE THE DISPLACEMENTS DISV(ECSXX,ECSYY,ECSXY,WCBXX,WCBYY,WCBXY) ARE

The output of the ply properties generated in array PL are printed out under the heading

LAYER PROPERTIES, ROWS-PROPERTY, COLUMNS-LAYER

Seventy-one entries are printed out under this heading as follows:

PL(1,I)	k_v	ply void content
PL(2,I)	k_f	ply apparent fiber content
PL(3,I)	$\bar{k}_f$	ply actual fiber content
PL(4,I)	k_m	ply apparent matrix content
PL(5,I)	$\bar{k}_m$	ply actual matrix content
PL(6,I)	ρ_ℓ	ply weight density
PL(7,I)	t_ℓ	ply layer thickness
PL(8,I)	δ_ℓ	ply and interply layer thickness
PL(9,I)	H_j	interply layer distortion energy coefficient
PL(10,I)	$\bar{z}$	distance from bottom of composite to ply centroid
PL(11,I)	z_{cg}	distance from reference plane to ply centroid

PL(12,I)	θ_{cs}	angle from structural axes to composite material axes (same for all plies), Fig. 6
PL(13,I)	θ_{ℓ}	angle from ply material axes to composite material axes, Fig. 6
PL(14,I)	$\theta_{\ell s}$	angle from ply material axes to composite structural axes, Fig. 6
PL(15,I) to PL(23,I)	$[E_{\ell}]$	ply stress-strain relations
PL(24,I) to PL(26,I)	$\{\alpha_{\ell}\}$	ply thermal coefficients of expansion
PL(27,I) to PL(29,I)	$\{K_{\ell}\}$	ply heat conductivities
PL(30,I)	$H_{c\ell}$	ply heat capacity
PL(31,I) to PL(32,I)	$E_{\ell 11}, \nu_{\ell 12}, G_{\ell 12}$	ply elastic constants
PL(43,I) to PL(48,I)	$\rho_{\mu 22}, \rho_{\mu 12}, \rho_{\mu 13}$	ply strain magnification factors
PL(49,I)	$\rho_{\mu de\ell}$	interply delamination factor
PL(50,I)	ΔT	ply temperature
PL(51,I) to PL(60,I)	$S_{\ell 11T}$, etc.	ply limiting stresses
PL(61,I)	$K_{\ell 12\alpha\beta}$	coefficient in combined-stress - strength criterion
PL(62,I)	------------	ply margin of safety — from distortion energy
PL(63,I)	------------	interply delamination margin of safety
PL(64,I) to PL(69,I)	$\{\varepsilon_{\ell}\},\{\sigma_{\ell}\}$	ply applied strains and stresses
PL(70,I)	$\Delta\rho_{j}$	adjacent ply relative rotation
PL(71,I)	------------	margin of safety from Hoffman's failure criterion

The failure criterion may be determined by either of the following methods.

(1) Modified distortion energy

$$F = 1 - \left[\left(\frac{\sigma_{\ell 11\alpha}}{S_{\ell 11\alpha}}\right)^2 + \left(\frac{\sigma_{\ell 22\beta}}{S_{\ell 22\beta}}\right)^2 - K'_{\ell 12\alpha\beta}K_{\ell 12\alpha\beta}\,\frac{\sigma_{\ell 11\alpha}}{S_{\ell 11\alpha}}\,\frac{\sigma_{\ell 22}}{S_{\ell 22}} + \left(\frac{\sigma_{\ell 12S}}{S_{\ell 12S}}\right)^2\right]_i \rightarrow PL(62,I)$$

(2) Hoffman's criterion

$$F = 1 - \left[\frac{\sigma^2_{\ell 11} - \sigma_{\ell 11}\sigma_{\ell 22}}{S_{\ell 11C}S_{\ell 11T}} + \frac{\sigma^2_{\ell 22}}{S_{\ell 22C}S_{\ell 22T}} + \frac{S_{\ell 11C} - S_{\ell 11T}}{S_{\ell 11C}S_{\ell 11T}}\,\sigma_{\ell 11} + \frac{S_{\ell 22C} - S_{\ell 22T}}{S_{\ell 22C}S_{\ell 22T}}\,\sigma_{\ell 22} + \frac{\sigma^2_{\ell 12}}{S^2_{\ell 12S}}\right]_i \rightarrow PL(71,I)$$

$F > 0$ no failure

$F = 0$ incipient failure

$F < 0$ failure

where σ denotes stress and S the limit stress always taken positive. The subscripts denote direction and sense.

The interply delamination criterion for the j^{th} interply layer at the m^{th} load condition is governed by

$$\left[1 - \left(\frac{|\Delta\phi|}{\Delta\phi_{del}}\right)_j\right] \rightarrow PL(63,I) \qquad \text{when} \quad i > 1$$

$$\Delta\phi_j = \frac{1}{2}\left(\varepsilon_{cyy} - \varepsilon_{cxx}\right)\left(\sin 2\theta_i - \sin 2\theta_{i-1}\right) + \frac{1}{2}\,\varepsilon_{cxy}\left(\cos 2\theta_i - \cos 2\theta_{i-1}\right)$$

$$\{\varepsilon_{cx}\} = [A_{cx}]^{-1}\left\langle\{\bar{N}_{cx}\} + \{N_{c\Delta Tx}\} + [C_{cx}]\{w_{cbx}\}\right\rangle$$

or as given by the displacement force equation described previously.

The inputs to the subroutines to generate the PL array are the ply angle measured from the structural axes (θ_i from PL(14,I)), the distance from the reference plane to centroid of the ply ($z_{\ell i}$ from PL(11,I)), the ply temperature ($\Delta T_{\ell i}$ from PL(50,I)), the interply delamination limit ($\Delta\phi_{delj}$ from PL(60,I)), and the ply thermoelastic properties stored in PL(24 to 26,-I) and PL(31 to 42,I). The ply extensional and coupling rigidities A_{cx} = ACX and C_{cx} = CPC; the local curvatures w_{cbx} = WXX; the adjustment constants $K'_{\ell 12TT}$ = BET(1,7), $K'_{\ell 12CT}$ = BET(2,7), $K'_{\ell 12TC}$ = BET(1,8), and $K'_{\ell 12CC}$ = BET(2,8); and the load conditions $\overline{N}_{cx}$ = NBS(m). All other adjustment constants are input data.

A sample output for a Thornel-50/epoxy angle ply composite is given in Table 3.

CODE APPLICATIONS

This computerized multilevel analysis has been applied extensively to various aspects of fiber composite analysis, design, and optimization. Typical cases include: nonmetallic [3,4,5] and metallic [6] fiber composite characterization, random composite characterization [7], lamination residual stresses [8,9,10], buckling of fiber composite anisotropic plates [11,12], exploratory designs of fiber composite turbine blades (unpublished notes), feasibility studies of high-tip-speed compressor blades made from advanced fiber composites [10], failure analysis of flat and tubular members [3,4], gross and local impact studies [13,14], structural synthesis, and sensitivity studies of flat plates [3], and other important factors in designing with fiber composites [15].

IMMEDIATE EXTENSIONS

The code can be readily modified and supplemented to handle nonlinear material response, temperature dependent properties, inter, and intraply hybrid fiber composites. The details of these modifications become apparent once the user has some experience in using the code.

REFERENCES

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TABLE I. - INPUT DATA FOR THORNEL-50/EPOXY COMPOSITE

```
THORNEL-50/EPOXY
  8    71    54 1420     1
   .50000E.08     .10000E.07     .10000E.07     .20000E.00     .25000E.00
   .20000E.00     .13000E.07     .70000E.06     .13000E.07     .57000E.06
   .57000E.06     .57000E.06     .36000E.00     .36000E.00     .36000E.00
   .00000E.00     .00000E.00     .00000E.00
   .40000E.01     .20000E.01     .40000E.01     .20000E.01     .00000E.00
   .00000E.00     .00000E.00     .23560E.01     .00000E.00     .00000E.00
   .00000E.00     .00000E.00     .00000E.00     .00000E.00     .10000E.01
   .10000E.01     .10000E.01     .00000E.00     .00000E.00     .00000E.00
  -.55000E-06     .56000E-05     .56000E-05
   .42800E-04     .42800E-04     .42800E-04
   .58000E.03     .58000E.02     .58000E.02     .17000E.00     .12500E.01
   .12500E.01     .12500E.01     .25000E.00     .00000E.00     .00000E.00
   .00000E.00     .22500E.00
   .10000E.01     .10000E.01     .10500E.01     .10500E.01
   .31416E.01
F
F
F
F
   .00000E.00     .05900E.00     .04430E.00     .00026E.00
   .00000E.00     .00000E.00     .00000E.00     .00000E.00     .00000E.00
  0.00000E.00    0.00000E.00    0.00000E.00
  0.50000E.00    0.50000E.00    0.50000E.00    0.50000E.00    0.50000E.00
  0.50000E.00    0.50000E.00    0.50000E.00
   .00000E.00     .45000E.02    -.45000E.02     .90000E.02     .90000E.02
  -.45000E.02     .45000E.02     .00000E.00
   .00805E.00     .00805E.00     .00800E.00     .00800E.00     .00800E.00
   .00805E.00     .00805E.00     .00800E.00
 -0.30000E.03   -0.30000E.03   -0.30000E.03   -0.30000E.03   -0.30000E.03
 -0.30000E.03   -0.30000E.03   -0.30000E.03
   .83000E.00     .10000E.01     .26000E.00     .27000E.00     .17000E.00
   .16500E.02     .10000E.01     .10000E.01     .04650E.00     .10000E.01
   .50000E.00     .13300E.02     .31900E.05     .10000E.01     .10000E.01
   .10000E.01
   .23000E.06     .21000E.05     .02000E.00     .05000E.00     .04500E.00
   .04500E.00
   .50000E.04     .00000E.00     .00000E.00
   .10000E.03     .00000E.00     .00000E.00
  0.00000E.00    0.00000E.00    0.00000E.00    0.00000E.00    0.00000E.00
  0.00000E.00
```

TABLE 2. - SUBROUTINE DESCRIPTION

Subroutine	Function
INVA	Matrix inverse
GLLSC	Simple limit stresses (strengths) ply (unidirectional composite)
GACD3	Three-dimensional laminate thermoelastic properties
GPCFD2	Two-dimensional laminate thermoelastic properties
GPH	Ply heat conductivities
GECL	Ply thermoelastic properties
GSMF	Strain magnification factors
COMPSA	Laminate analysis, ply stress-strain, ply margin of safety

TABLE 3. - SAMPLE CASE OUTPUT

Angle Ply Composite

```
THORNEL-5C/EPOXY


NL,NPL,NPC,NFPE,NLC
   8   71   54 1420    1

EF11,EF22,EF23,NUF12,NUF23,NUF13,EF12,EF23,EF13,EM11,EM22,EM33,NUM12,NUM23 NUM13,EM12,EM23,EM13
 0.50000E 08  0.11000E 07  0.10000E 07  0.20000E 00  0.25000E 00  0.20000E 00  0.13000E 07  0.70000E 06  0.13000E 07  0.57000E 06
 0.57000E 06  0.57000E 06  0.36000E 00  0.36000E 00  0.36000E 00  0.           0.           0.
VCF
 0.40000E 01  0.20000E 01  0.40000E 01  0.20000E 01  0.           0.           0.           0.23560E 01  0.           0.
 0.           0.           0.           0.           0.10000E 01  0.10000E 01  0.10000E 01  0.           0.           0.
VAF
-0.55000E-06  0.56000E-05  0.56000E-05
VAM
 0.42800E-04  0.42800E-04  0.42800E-04
CHM
 0.58000E 03  0.58000E 02  0.53000E 02  0.17000E 00  0.12500E 01  0.12500E 01  0.12500E 01  0.25000E 00  0.           0.
 0.           0.22500E 00
BTA
 0.10000E 01  0.10000E 01  0.10500E 01  0.10500E 01
PIE
 0.31416E 01

TLINP
     F

CSANB
     F

BICE
     F

RINDV
     F

THCS,RHOF,RHCM,DIAF
 0.           0.59000E-01  0.44300E-01  0.26000E-03
KVL
 0.           0.           0.           0.           0.           0.           0.           0.
KFL
 0.50000E 00  0.50000E 00  0.50000E 00  0.50000E 00  0.50000E 00  0.50000E 00  0.50000E 00  0.50000E 00
THLC
 0.30000E 02 -0.30000E 02  0.30000E 02 -0.30000E 02 -0.30000E 02  0.30000E 02 -0.30000E 02  0.30000E 02
TL
 0.80500E-02  0.80500E-02  0.80000E-02  0.80000E-02  0.80000E-02  0.80500E-02  0.80500E-02  0.80000E-02
PTEMP
-0.30000E 03 -0.30000E 03 -0.30000E 03 -0.30000E 03 -0.30000E 03 -0.30000E 03 -0.30000E 03 -0.30000E 03

BET
 0.82000E 00  0.10000E 01  0.26000E 00  0.27000E 00  0.17000E 00  0.16500E 02  0.10000E 01  0.10000E 01  0.46500E-01  0.10000E 01
 0.50000E 00  0.13300E 02  0.31900E 05  0.10000E 01  0.10000E 01  0.10000E 01

LSC
 0.23000E 06  0.21000E 05  0.20000E-01  0.50000E-01  0.45000E-01  0.45000E-01

NBS
 0.50000E 04  0.           0.

MBS
 0.50000E 02  0.           0.

DISV1
 0.           0.           0.           0.           0.           0.
```

TABLE 3. - SAMPLE CASE OUTPUT (CONT'D)

3-D COMPOSITE STRAIN STRESS TEMPERATURE RELATIONS - STRUCTURAL AXES

0.1430E-06	-0.2449E-06	0.4471E-07	0.	0.	0.	-0.3131E-05
-0.2449E-06	0.7909E-06	-0.2246E-06	-0.	-0.	-0.	0.1199E-04
0.4471E-07	-0.2246E-06	0.9353E-06	0.	0.	0.	0.2933E-04
0.	0.	0.	0.2937E-05	0.	0.	-0.
0.	0.	0.	0.	0.2937E-05	0.	-0.
0.	0.	0.	0.	0.	0.2000E-06	-0.

3-D COMPOSITE STRESS STRAIN RELATIONS - STRUCTURAL AXES

0.1504E 08	0.4779E 07	0.4285E 06	-0.	-0.	0.
0.4779E 07	0.2875E 07	0.4620E 06	-0.	-0.	0.
0.4285E 06	0.4620E 06	0.1160E 07	-0.	-0.	-0.
-0.	-0.	-0.	0.3405E 06	-0.	-0.
-0.	-0.	-0.	-0.	0.3405E 06	-0.
0.	0.	-0.	-0.	-0.	0.5001E 07

COMPOSITE PROPERTIES - VALID ONLY FOR CONSTANT TEMPERATURE THROUGH THICKNESS
LINES 1 TO 31 3-D COMPOSITE PROPERTIES ABOUT MATERIAL AXES
LINES 33 TO 54 2-D COMPOSITE PROPERTIES ABOUT STRUCTURAL AXES

1	RHOL	0.5165E-01
2	TC	0.6400E-01
3	CC11	0.1504E 08
4	CC12	0.4779E 07
5	CC13	0.4285E 06
6	CC22	0.2875E 07
7	CC23	0.4620E 06
8	CC33	0.1160E 07
9	CC44	0.3405E 06
10	CC55	0.3405E 06
11	CC66	0.5001E 07
12	CTE11	-0.3131E-05
13	CTE22	0.1199E-04
14	CTE33	0.2933E-04
15	HK11	0.2189E 03
16	HK22	0.7544E 02
17	HK33	0.3715E 01
18	HHC	0.2043E 00
19	EC11	0.6992E 07
20	EC22	0.1264E 07
21	EC33	0.1069E 07
22	EC23	0.3405E 06
23	EC31	0.3405E 06
24	EC12	0.5001E 07
25	NUC12	0.1712E 01
26	NUC21	0.3096E 00
27	NUC13	-0.3126E 00
28	NUC31	-0.4780E-01
29	NUC23	0.2839E 00
30	NUC32	0.2401E 00
31	ZCGC	0.3200E-01
32	B2DEC	0.
33	CC11	0.1488E 08
34	CC12	0.4608E 07
35	CC13	0.
36	CC22	0.2691E 07
37	CC23	0.
38	CC33	0.5001E 07
39	EC11	0.6992E 07
40	EC22	0.1264E 07
41	EC12	0.5001E 07
42	NUC12	0.1712E 01
43	NUC21	0.3096E 00
44	CSN13	-0.
45	CSN31	-0.
46	CSN23	-0.
47	CSN32	0.
48	CTE11	-0.3131E-05
49	CTE22	0.1199E-04
50	CTE12	-0.
51	HK11	0.2189E 03
52	HK22	0.7544E 02
53	HK12	-0.
54	HHC	0.2043E 00

TABLE 3. - SAMPLE CASE OUTPUT (CONT'D)

FORCES	FORCE DISPLACEMENT RELATIONS						DISPL	THERMAL FORCES
NX	0.9525E 06	0.2949E 06	0.	0.1221E-03	0.4578E-04	0.1068E-03	UX	-0.1656E 03
NY	0.2949E 06	0.1722E 06	0.	0.4578E-04	0.2289E-04	0.3815E-04	VX	-0.3427E 03
NXY	0.	0.	0.3200E 06	0.1068E-03	0.3815E-04	0.3052E-04	VXPUY	0.
MX	0.1221E-03	0.4578E-04	0.1068E-03	0.3251E 03	0.1007E 03	0.6390E 02	WXX	-0.2235E-07
MY	0.4578E-04	0.2289E-04	0.3815E-04	0.1007E 03	0.5879E 02	0.2260E 02	WYY	-0.2980E-07
MXY	0.1068E-03	0.3815E-04	0.3052E-04	0.6390E 02	0.2260E 02	0.1092E 03	WXY	0.2980E-07

REDUCED BENDING REGIDITIES

0.32513E 03 0.10067E 03 0.63900E 02 0.10067E 03 0.58793E 02 0.22595E 02 0.63900E 02 0.22595E 02 0.10924E 03

REDUCED STIFFNESS MATRIX

0.95252E 06 0.29494E 06 -0.49233E-10 0.29494E 06 0.17225E 06 -0.19281E-10 -0.49233E-10 -0.19281E-10 0.32003E 06

DISP.	DISPLACEMENT FORCE RELATIONS						FORCES
UX	0.2235E-05	-0.3827E-05	0.1132E-21	-0.3456E-12	0.6409E-12	-0.7792E-12	NX
VX	-0.3827E-05	0.1236E-04	0.1559E-21	0.6225E-12	-0.2756E-11	-0.3680E-12	NY
VXPBY	0.1132E-21	0.1559E-21	0.3125E-05	-0.8006E-12	-0.5443E-12	-0.2920E-12	NXY
WXX	-0.3456E-12	0.6225E-12	-0.8006E-12	0.6830E-02	-0.1104E-01	-0.1712E-02	MX
WYY	0.6409E-12	-0.2756E-11	-0.5443E-12	-0.1104E-01	0.3631E-01	-0.1055E-02	MY
WXY	-0.7792E-12	-0.3680E-12	-0.2920E-12	-0.1712E-02	-0.1055E-02	0.1037E-01	MXY

DISP.	DISPLACEMENT FORCE RELATIONS						FORCES
0.1211E-01	0.2235E-05	-0.3827E-05	0.1132E-21	-0.3456E-12	0.6409E-12	-0.7792E-12	0.4833E 04
-0.2273E-01	-0.3827E-05	0.1236E-04	0.1559E-21	0.6225E-12	-0.2756E-11	-0.3680E-12	-0.3427E 03
-0.4003E-10	0.1132E-21	0.1559E-21	0.3125E-05	-0.8006E-12	-0.5443E-12	-0.2920E-12	0.
0.3415E 00	-0.3456E-12	0.6225E-12	-0.8006E-12	0.6830E-02	-0.1104E-01	-0.1712E-02	0.5000E 02
-0.5518E 00	0.6409E-12	-0.2756E-11	-0.5443E-12	-0.1104E-01	0.3631E-01	-0.1055E-02	-0.2980E-07
-0.8561E-01	-0.7792E-12	-0.3680E-12	-0.2920E-12	-0.1712E-02	-0.1055E-02	0.1037E-01	0.2980E-07

FOR THIS CASE NBS(X,Y,XY-M) IS 5000. 0. 0.

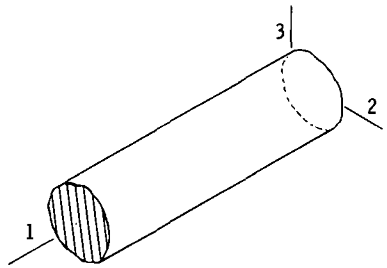
FOR THIS CASE MBS(X,Y,XY-M) IS 50. 0. 0.

LAYER PROPERTIES, ROWS-PROPERTY, COLUMNS-LAYER

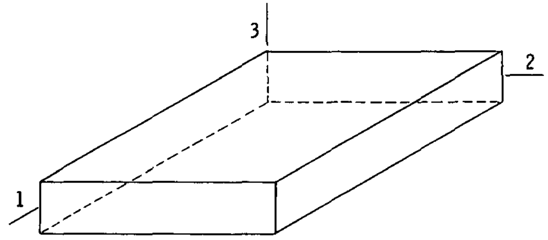
1	KV	0.	0.	0.	0.	0.	0.	0.	0.
2	KF	0.5000E 00	0.5000E 00	0.5000E 00	0.5000E 00	0.5000E 00	0.5000E 00	0.5000E 00	0.5000E 00
3	KFB	0.5000F 00	0.5000E 00	0.5000E 00	0.5000E 00	0.5000E 00	0.9000E 00	0.5000E 00	0.5000E 00
4	KM	0.5000E 00	0.5000E 00	0.5000E 00	0.5000E 00	0.5000E 00	0.5000E 00	0.5000E 00	0.5000E 00
5	KMB	0.5000E 00	0.5000E 00	0.5000E 00	0.5000E 00	0.5000E 00	0.5000E 00	0.5000E 00	0.5000E 00
6	RHOL	0.5165E-01	0.5165E-01	0.5165E-01	0.5165E-01	0.5165E-01	0.5165E-01	0.5165E-01	0.5165E-01
7	TL	0.8000E-02	0.8000E-02	0.8000E-02	0.8000E-02	0.8000E-02	0.8000E-02	0.8000E-02	0.8000E-02
8	DELTA	0.6586E-04	0.6586E-04	0.6586E-04	0.6586E-04	0.6586E-04	0.6586E-04	0.6586E-04	0.5586E-04
9	ILOC	-0.0000E-19	0.	0.	0.	0.	0.	0.	0.
10	ZB	0.4000E-02	0.1200E-01	0.2000E-01	0.2800E-01	0.3600E-01	0.4400E-01	0.5200E-01	0.6000E-01
11	ZGC	-0.2800E-01	-0.2000E-01	-0.1200E-01	-0.4000E-02	0.4000E-02	0.1200E-01	0.2000E-01	0.2800E-01
12	THCS	0.	0.	0.	0.	0.	0.	0.	0.
13	THLC	0.5236E 00	-0.5236E 00	0.5236E 00	-0.5236E 00	-0.5236E 00	0.5236E 00	-0.5236E 00	0.5236E 00
14	THLS	0.5236E 00	-0.5236E 00	0.5236E 00	-0.5236E 00	-0.5236E 00	0.5236E 00	-0.5236E 00	0.5235E 00
15	SC11	0.2549E 08	0.2549E 08	0.2549E 09	0.2549E 08	0.2549E 08	0.2549E 08	0.2549E 09	0.2549E 08
16	SC12	0.4118E 06	0.4118E 06	0.4118E 06	0.4118E 06	0.4118E 06	0.4118E 06	0.4118E 06	0.4118E 06
17	SC13	0.4118E 06	0.4118E 06	0.4118E 06	0.4118E 06	0.4118E 06	0.4118E 06	0.4118E 05	0.4118E 06
18	SC22	0.1160E 07	0.1160E 07	0.1160E 07	0.1160E 07	0.1160E 07	0.1160E 07	0.1160E 07	0.1160F 07
19	SC23	0.4787E 06	0.4787E 06	0.4787E 06	0.4787E 06	0.4787E 06	0.4787E 06	0.4787E 05	0.4787E 06

TABLE 3. - SAMPLE CASE OUTPUT (CONC'D)

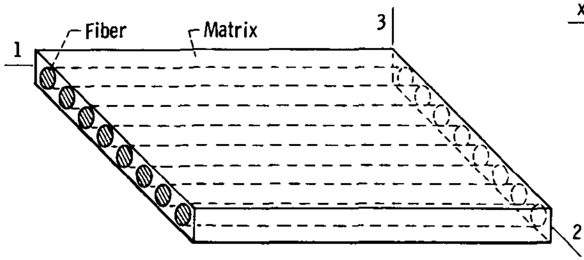
20	SC33	0.1160E 07	0.1160E 07	0.1160E 07	0.1160E 07	0.1160E 07	0.1160E 07	0.1160E 07	0.1160E 07
21	SC44	0.3405E 06	0.3405E 06	0.3405E 06	0.3405E 06	0.3405E 06	0.3405E 06	0.3405E 06	0.3405E 06
22	SC55	0.3405E 06	0.3405E 06	0.3405E 06	0.3405E 06	0.3405E 06	0.3405E 06	0.3405E 06	0.3405E 06
23	SC66	0.6339E 06	0.6339E 06	0.6339E 06	0.6339E 06	0.6339E 06	0.6339E 06	0.6339E 06	0.6339E 06
24	CTE11	-0.6138E-07	-0.6138E-07	-0.6138E-07	-0.6138E-07	-0.6138E-07	-0.6138E-07	-0.6138E-07	-0.6138E-07
25	CTE22	0.2334E-04	0.2334E-04	0.2334E-04	0.2334E-04	0.2334E-04	0.2334E-04	0.2334E-04	0.2334E-04
26	CTE33	0.2334E-04	0.2334E-04	0.2334E-04	0.2334E-04	0.2334E-04	0.2334E-04	0.2334E-04	0.2334E-04
27	HK11	0.2906E 03	0.2906E 03	0.2906E 03	0.2906E 03	0.2906E 03	0.2906E 03	0.2906E 03	0.2906E 03
28	HK22	0.3715E 01	0.3715E 01	0.3715E 01	0.3715E 01	0.3715E 01	0.3715E 01	0.3715E 01	0.3715E 01
29	HK33	0.3715E 01	0.3715E 01	0.3715E 01	0.3715E 01	0.3715E 01	0.3715E 01	0.3715E 01	0.3715E 01
30	HCL	0.2043E 00	0.2043E 00	0.2043E 00	0.2043E 00	0.2043E 00	0.2043E 00	0.2043E 00	0.2043E 00
31	EL11	0.2528E 08	0.2528E 08	0.2528E 08	0.2528E 08	0.2528E 08	0.2528E 08	0.2528E 08	0.2528E 08
32	EL22	0.9597E 06	0.9597E 06	0.9597E 06	0.9597E 06	0.9597E 06	0.9597E 06	0.9597E 06	0.9597E 06
33	EL33	0.9597E 06	0.9597E 06	0.9597E 06	0.9597E 06	0.9597E 06	0.9597E 06	0.9597E 06	0.9597E 06
34	GL23	0.3405E 06	0.3405E 06	0.3405E 06	0.3405E 06	0.3405E 06	0.3405E 06	0.3405E 06	0.3405E 06
35	GL13	0.6339E 06	0.6339E 06	0.6339E 06	0.6339E 06	0.6339E 06	0.6339E 06	0.6339E 06	0.6339E 06
36	GL12	0.6339E 06	0.6339E 06	0.6339E 06	0.6339E 06	0.6339E 06	0.6339E 06	0.6339E 06	0.6339E 06
37	NUL12	0.2514E 00	0.2514E 00	0.2514E 00	0.2514E 00	0.2514E 00	0.2514E 00	0.2514E 00	0.2514E 00
38	NUL21	0.9541E-02	0.9541E-02	0.9541E-02	0.9541E-02	0.9541E-02	0.9541E-02	0.9541E-02	0.9541E-02
39	NUL13	0.2514E 00	0.2514E 00	0.2514E 00	0.2514E 00	0.2514E 00	0.2514E 00	0.2514E 00	0.2514E 00
40	NUL31	0.9541E-02	0.9541E-02	0.9541E-02	0.9541E-02	0.9541E-02	0.9541E-02	0.9541E-02	0.9541E-02
41	NUL23	0.4094E 00	0.4094E 00	0.4094E 00	0.4094E 00	0.4094E 00	0.4094E 00	0.4094E 00	0.4094E 00
42	NUL32	0.4094E 00	0.4094E 00	0.4094E 00	0.4094E 00	0.4094E 00	0.4094E 00	0.4094E 00	0.4094E 00
43	SMFK22	0.1522E 01	0.1522E 01	0.1522E 01	0.1522E 01	0.1522E 01	0.1522E 01	0.1522E 01	0.1522E 01
44	SMFD22	0.1918E 01	0.1918E 01	0.1918E 01	0.1918E 01	0.1918E 01	0.1918E 01	0.1918E 01	0.1918E 01
45	SMFS22	0.1344E 01	0.1342E 01	0.1408E 01	0.1400E 01	0.1399E 01	0.1397E 01	0.1399E 01	0.1395E 01
46	SMFC22	-0.0000E-19	-0.0000E-19	-0.0000E-19	-0.0000E-19	-0.0000E-19	-0.0000E-19	-0.0000E-19	-0.0000E-19
47	SMFS12	0.3024E 01	0.3024E 01	0.3024E 01	0.3024E 01	0.3024E 01	0.3024E 01	0.3024E 01	0.3024E 01
48	SMFS23	0.1396E 01	0.1396E 01	0.1395E 01	0.1396E 01	0.1396E 01	0.1396E 01	0.1396E 01	0.1396E 01
49	ILMFC	-0.0000E-19	0.7060E 02	0.7060E 02	0.7060E 02	0.7060E 02	0.7060E 02	0.7060E 02	0.7060E 02
50	TEMPD	-0.3000E 03	-0.3000E 03	-0.3000E 03	-0.3000E 03	-0.3000E 03	-0.3000E 03	-0.3000E 03	-0.3000E 03
51	LSC11T	0.9676E 05	0.9676E 05	0.9676E 05	0.9676E 05	0.9676E 05	0.9676E 05	0.9676E 05	0.9676E 05
52	LSC11C	0.5333E 05	0.5333E 05	0.5333E 05	0.5333E 05	0.5333E 05	0.5333E 05	0.5333E 05	0.5333E 05
53	LSC11D	0.6578E 05	0.6578E 05	0.6578E 05	0.6578E 05	0.6578E 05	0.6578E 05	0.6578E 05	0.6578E 05
54	LSC22T	0.3714E 04	0.3718E 04	0.3544E 04	0.3564E 04	0.3566E 04	0.3572E 04	0.3568E 04	0.3576E 04
55	LSC22C	0.1786E 05	0.1788E 05	0.1704E 05	0.1713E 05	0.1714E 05	0.1717E 05	0.1715E 05	0.1719E 05
56	LSC12	0.2547E 04	0.2547E 04	0.2547E 04	0.2547E 04	0.2547E 04	0.2547E 04	0.2547E 04	0.2547E 04
57	LSC23	0.1866E 04	0.1866E 04	0.1865E 04	0.1866E 04	0.1866E 04	0.1866E 04	0.1866E 04	0.1866E 04
58	LSCC23	-0.0000E-19	-0.0000E-19	-0.0000E-19	-0.0000E-19	-0.0000E-19	-0.0000E-19	-0.0000E-19	-0.0000E-19
59	LSCC13	-0.0000E-19	-0.0000E-19	-0.0000E-19	-0.0000E-19	-0.0000E-19	-0.0000E-19	-0.0000E-19	-0.0000E-19
60	LSCDF	-0.0000E-19	0.1052E-01	0.1052E-01	0.1052E-01	0.1052E-01	0.1052E-01	0.1052E-01	0.1052E-01
61	KL12AB	0.1371E 01	0.1371E 01	0.1371E 01	0.1371E 01	0.1371E 01	0.1371E 01	0.1371E 01	0.1371E 01
62	MUE1E	-0.2387E 01	-0.1400E 02	-0.2529E 02	-0.4584E 02	-0.6868E 02	-0.1003E 03	-0.1282E 03	-0.1774E 03
63	KELROT	-0.0000E-19	0.9605E 00	0.2757E 00	-0.2131E 00	-0.9518E 00	-0.3178E 01	-0.9446E 01	-0.8205E 01
64	EPS11	0.1132E-02	0.2974E-03	0.2429E-02	0.2781E-02	0.4023E-02	0.4375E-02	0.6506E-02	0.5672E-02
65	EPS22	-0.5860E-02	-0.6708E-02	-0.1052E-01	-0.1256E-01	-0.1548E-01	-0.1752E-01	-0.2133E-01	-0.2218E-01
66	EPS12	-0.7315E-02	0.1556E-01	-0.2038E-01	0.2725E-01	0.3310E-01	-0.3997E-01	0.4479E-01	-0.5303E-01
67	SIG11	0.2787E 05	0.7346E 04	0.6117E 05	0.6917E 05	0.1001E 06	0.1084E 06	0.1619E 05	0.1398E 06
68	SIG22	0.1368E 04	0.3495E 03	-0.2804E 04	-0.4677E 04	-0.7190E 04	-0.9062E 04	-0.1222E 05	-0.1323E 05
69	SIG12	-0.4637E 04	0.9862E 04	-0.1292E 05	0.1727E 05	0.2098E 05	-0.2534E 05	0.2839E 05	-0.3362E 05
70	DELFI	-0.0000E-19	-0.4159E-03	-0.7617E-02	0.1276E-01	0.2053E-01	-0.4394E-01	0.1099E 00	-0.9682E-01
71	FFC	-0.2542E 01	-0.1402E 02	-0.2445E 02	-0.4472E 02	-0.6733E 02	-0.9883E 02	-0.1271E 03	-0.1761E 03



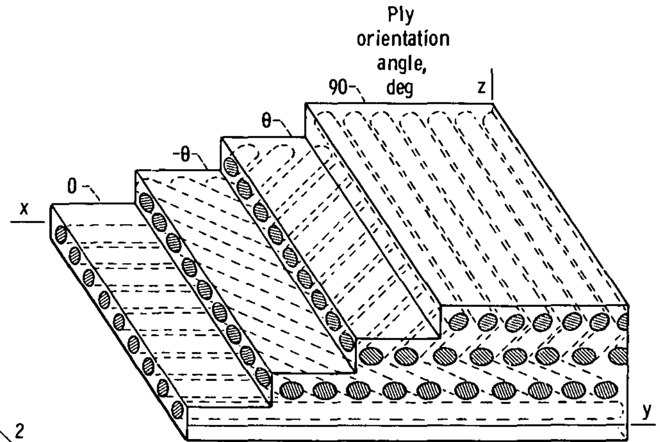
(a) Fiber. Properties needed: $E_{f11,\,22,\,33}$; $\nu_{f12,\,23,\,13}$; $G_{f12,\,23,\,13}$; $\alpha_{f11,\,22,\,33}$; $K_{f11,\,22,\,33}$; H_{cf}, ρ_f, N_f; d_f; S_{ft}.



(b) Matrix. Properties needed: $E_{m11,\,22,\,33}$; $\nu_{m12,\,23,\,13}$; $G_{f12,\,23,\,13}$; $\alpha_{m11,\,22,\,33}$; $K_{m11,\,22,\,33}$; H_{cm}, ρ_m, S_{mc}, e_{mpt}, e_{mpc}, e_{mps}, e_{mpTOR}.



(c) Ply. Input: Fiber and matrix properties: β_e, β_h, β_s, ΔT. Properties computed: $E_{\ell 11,\,22,\,33}$; $\nu_{\ell 12,\,23,\,13}$; $G_{\ell 12,\,23,\,13}$; $\alpha_{\ell 11,\,22,\,33}$; $K_{\ell 11,\,22,\,33}$; $H_{c\ell}$, ρ_ℓ, t_ℓ, δ_ℓ, $S_{\ell 11T,\,11C,\,22T,\,22C,\,12S,\,23S}$; $K_{\ell 12}$. Stress analysis: $\epsilon_{\ell 11,\,22,\,12}$; $\sigma_{\ell 11,\,22,\,12}$; $1.0 - F(\sigma, S, K_{\ell 12})$.



(d) Composite. Input: Ply properties; $\theta_{\ell i}$; H_j, $K'_{\ell 12\alpha\beta}$; $\bar{N}_{cx}$, $\bar{M}_{cx}$ or U_{cx}, W_{cx}. Output: $\{\epsilon_{cx}\} = [E_c]\{\sigma_c\} + \Delta T\{\alpha_c\}$; $[E_c]^{-1}$; $K_{cxx,\,yy,\,xy}$, H_c, $\begin{Bmatrix}\bar{N}_{cx}\\ \bar{M}_{cx}\end{Bmatrix} = \begin{bmatrix}A_{cx} C_{cx}\\ C_{cx} D_{cx}\end{bmatrix}\begin{Bmatrix}U_{cx}\\ W_{cx}\end{Bmatrix} + \begin{Bmatrix}N_{cx\Delta T}\\ M_{cx\Delta T}\end{Bmatrix}$ and the inverse, $\Delta\varphi_{de\ell j}$.

Figure 1. - Typical multilayered fiber composite and some basic definitions.

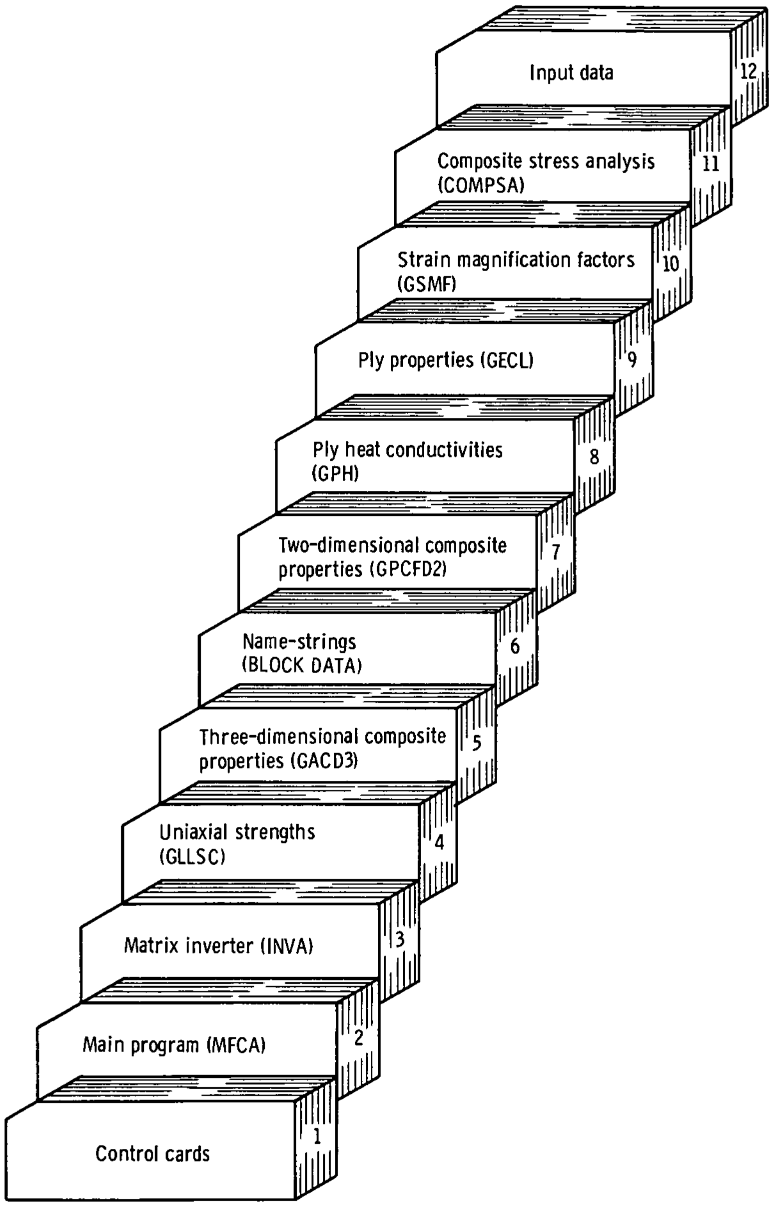


Figure 2. - Code physical arrangement.

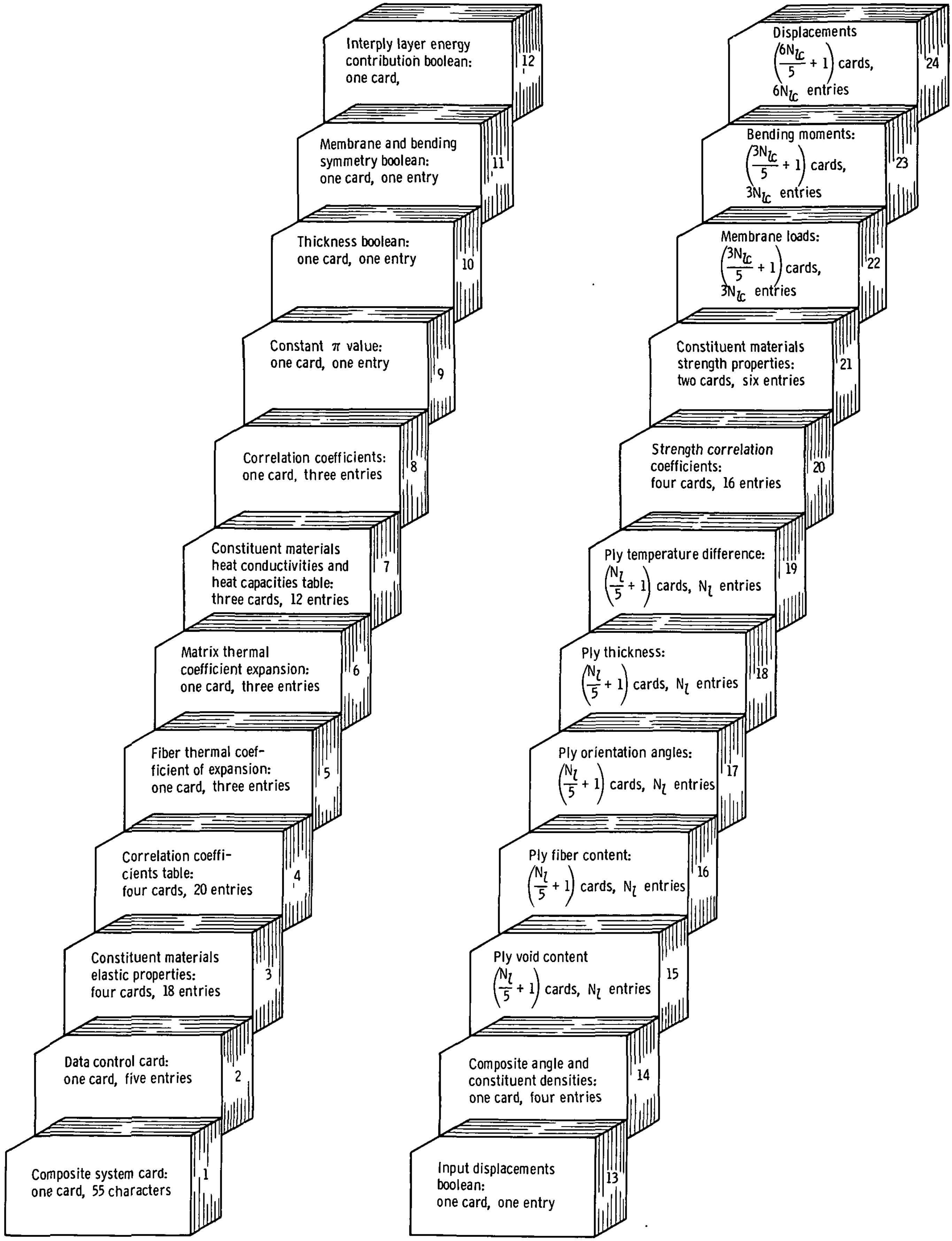


Figure 3. - Physical arrangement of input data cards.

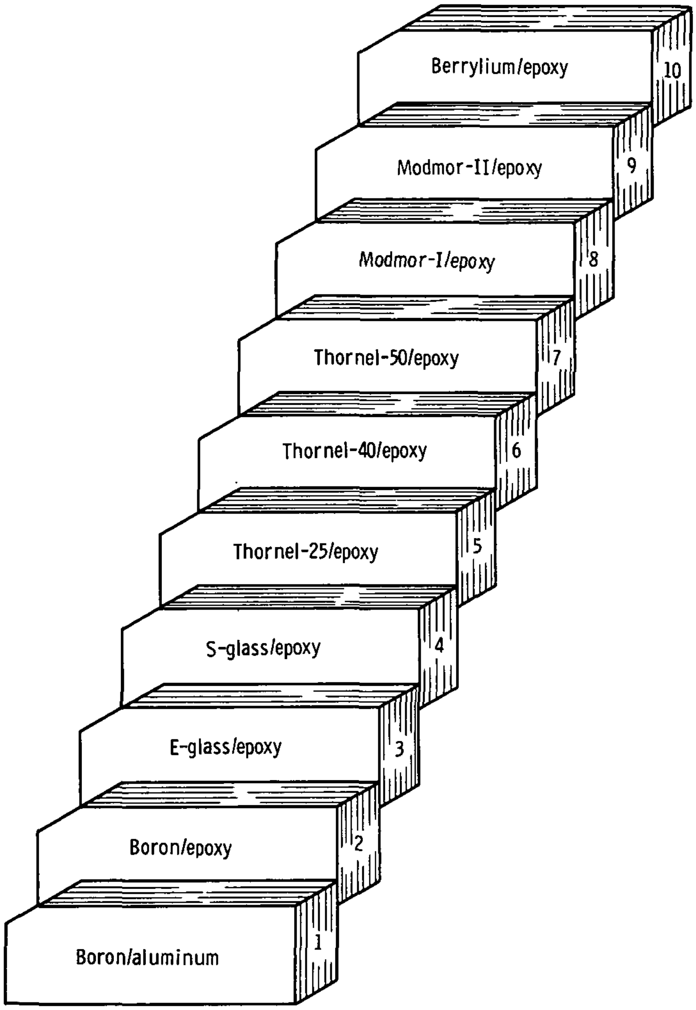


Figure 4. - Composite systems for which input data are supplied.

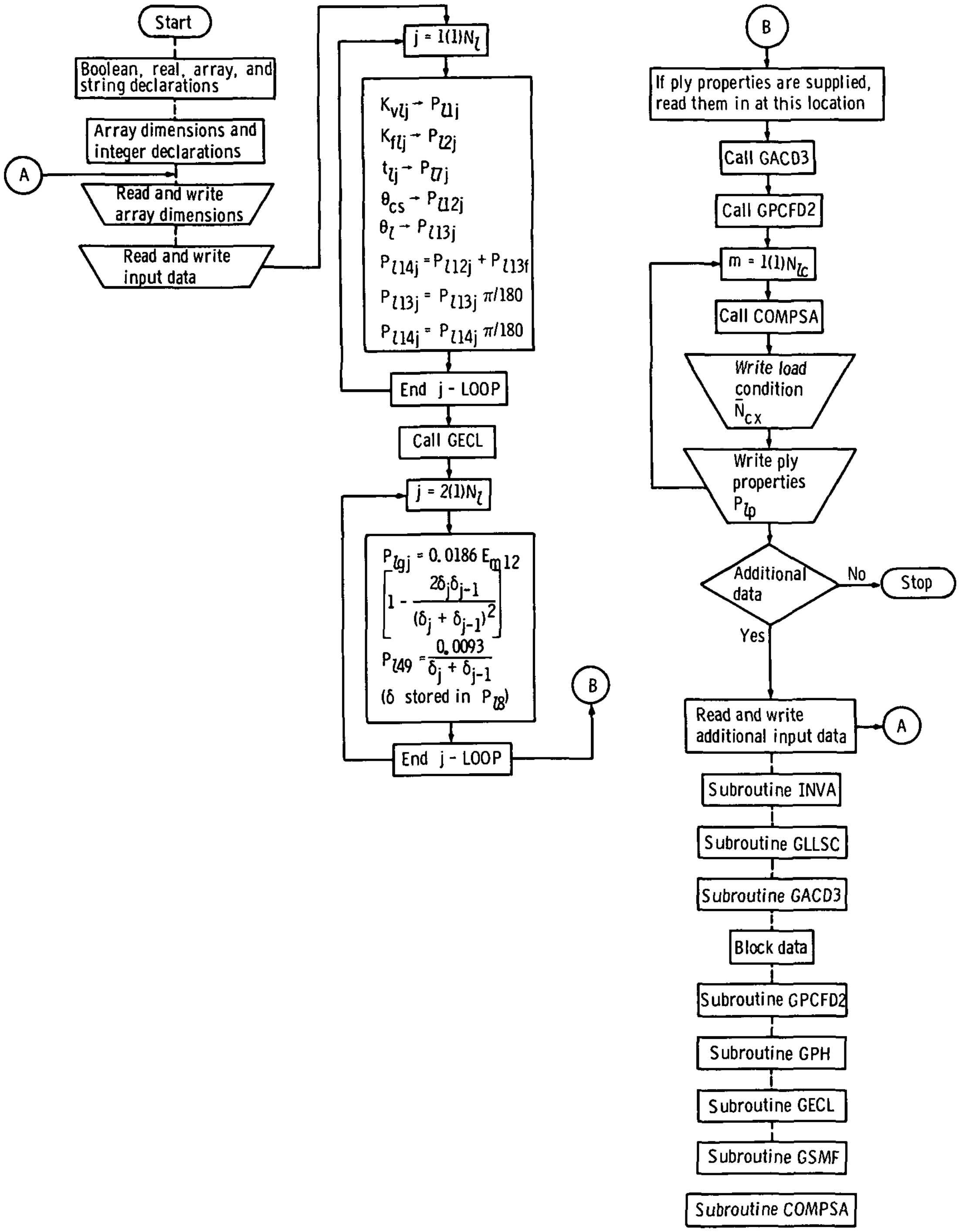


Figure 5. - Code MAIN PROGRAM flow chart.

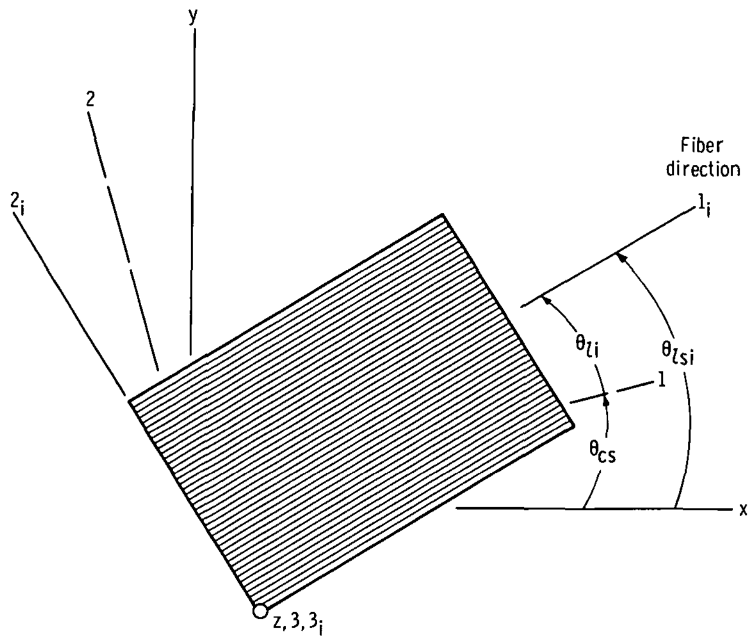


Figure 6. - Ply orientation geometry. Composite structural axes, x, y, z; composite material axes, 1, 2, 3; ply material axes (coincides with fiber direction, $1_i, 2_i, 3_i$).