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Center for Composite Materials

COMPUTATIONAL ALGORITHMS FOR PREDICTING THE MECHANICAL PROPERTIES OF SHEET MOLDING MATERIALS

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COMPUTATIONAL ALGORITHMS FOR PREDICTING THE MECHANICAL PROPERTIES OF SHEET MOLDING MATERIALS

by

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S. McGee
P. Mroz

Advisor: R. L. McCullough

June 1979

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INTRODUCTION

The recent demands on the automotive industry for weight-saving have focused attention on the use of polymeric materials reinforced by short lengths of reinforcing fibers. These short fiber composite systems can be molded to give rigid, lightweight structural components. The utilization of these materials in load-bearing applications necessarily directs attention to their mechanical properties and, in particular, to the role that processing plays in establishing the mechanical performance of these multicomponent materials.

Unlike the traditional materials of construction, these heterogeneous materials exhibit a wide range of properties which are dependent on the initial fiber/resin/filler composition as well as the particular internal microstructure developed during fabrication. This sensitivity to processing is manifest in both the magnitude and directional dependence of the mechanical, thermal, electrical, and transport properties.

The wide range of possible compositions, fiber length distributions, and fiber orientation distributions that may be utilized in and generated during the manufacture of components from these materials precludes a total reliance on direct laboratory characterization of the anisotropic mechanical properties. Consequently, constitutive relationships which connect the composition and processing dependent microstructure to mechanical performance are an important component of the technology for short fiber composite materials.

Constitutive relationships for unidirectional continuous fiber laminates are reasonably well developed. For this special material system, the continuity of the fiber assures that the strain field parallel to the aligned fibers is essentially uniform. However, the stress and strain field transverse to the fiber directions will vary within the body. Consequently, the major difficulty in predicting the behavior of continuous fiber systems is associated with predicting the Transverse Young's Moduli and Shear Moduli. The situation for short fiber composites is considerably more complex. Even if all the fibers were perfectly aligned, the discontinuities would cause fluctuations in the stress and strain fields parallel to the fiber axes.

Recently, Wu and McCullough (Development in Composite Materials, Applied Science Publishers, London, 1977) developed improved variational treatments which provide general bounding relationships for the effective elastic properties of a wide variety of heterogeneous materials, viz, polycrystalline metals, crystalline polymers, continuous fiber reinforced composites, short fiber composites, and particulate reinforced polymers. Upon the specification of certain parameters, the bounding relationships yield families of specific constitutive relationships which contain all reported models as special cases. As would be expected, such general constitutive relationships are somewhat complex. Accordingly, it is useful to introduce simplifications that can yield reasonable engineering estimates while reducing the computational effort required to obtain estimates for the anisotropic Young's moduli and Shear moduli.

Considerable simplification has been achieved through the use of an "Aggregate Model." The important features of the Aggregate Model are described in a subsequent section. In essence, the Aggregate Model treats a short fiber composite as a "grainy metal" in which the properties of the individual grains are averaged over an orientation distribution to yield the effective properties of the bulk material. Even with this simplification, the computational effort remains tedious. Consequently, computer algorithms have been developed to facilitate the prediction of properties from a knowledge of the composition, state of orientation, and the aspect ratio of the fibers of a sheet molding material. Two computational tools have been developed: (1) an interactive FORTRAN routine for general use, and (2) a restricted routine for use on hand-held calculators such as the Texas Instrument TI-59.

(27)

In the following sections [The elements of material modeling are reviewed and ~~the~~ an Aggregate Model was developed as an introduction to the notation used in the subsequent documentation of the computational routine. Examples are provided to illustrate the use of the computational tools.]

author, modified

BACKGROUND

Before proceeding with the development of models for predicting the behavior of sheet molding materials in terms of composition, fiber geometry and fiber orientation, it will be useful to briefly review the basic principles and notations used for the description of the mechanical behavior of materials. For this purpose, attention will be first directed to the general characterization of the load-deformation response of homogeneous (single component) materials. These results will be used in subsequent sections to develop the effective load-deformation characteristics of heterogeneous (multicomponent) materials.

Generalized Materials Descriptors

The load-deformation response characteristics of an isotropic material (e.g., an amorphous polymer) are traditionally described by the Engineering constants: The Young's modulus, E; the Shear modulus, G; and Poisson's ratio, ν. The Young's modulus is used to indicate the ability of a material to transfer a pure extension strain (ε) into a pure tensile stress (σ); the Poisson's ratio is used to describe the extent to which the lateral dimensions of a body decrease in response to a pure extensional strain. The Shear modulus is used to describe the ability of a material to transfer a pure shear strain (γ) into a pure shear stress (τ). For isotropic materials, these descriptors are not independent. It can be shown that if the material properties are the same in all directions, then the Engineering constants are related through $G = E/[2(1+\nu)]$.

Many material systems (e.g., drawn polymers, continuous fiber reinforced composites) exhibit properties that vary with the direction in which the load (or deformation) is applied. For the current considerations, materials with orthotropic symmetry are the class of materials with the lowest symmetry that need be considered. Orthotropic symmetry is characteristic of materials whose properties are equivalent across three mutually perpendicular planes. For materials of this symmetry class, it is necessary to characterize the load-deformation response characteristics along three directions of the material (e.g., the longitudinal, transverse, and perpendicular axis). The notation and load-deformation descriptions for the three distinct Young's moduli and the three distinct Shear moduli are schematically defined in Figure 1.

In the Theory of Elasticity (which provides the theoretical basis for the analysis of the mechanical behavior of materials), alternate sets of material descriptors are used: the compliance array, $\underset{\approx}{S}$, and the elastic constant array, $\underset{\approx}{C}$. The compliance array is used to describe the various deformations that result from the application of combined (or individual) loads. The elastic constant array is used to describe the various stresses that result from a general deformation. In the generalized notation, the tensile strain in the "1" direction that results from tensile stresses in the "1", "2", and/or "3" direction are given by

$$\varepsilon_1 = S_{11}\,\sigma_1 + S_{12}\,\sigma_2 + S_{13}\,\sigma_3$$

Similarly,

$$\varepsilon_2 = S_{21}\,\sigma_1 + S_{22}\,\sigma_2 + S_{23}\,\sigma_3$$

$$\varepsilon_3 = S_{31}\,\sigma_1 + S_{32}\,\sigma_2 + S_{33}\,\sigma_3$$

with $S_{ij} = S_{ji}$.

The shear deformations (γ) are related to the shear stresses (τ) by the relationships

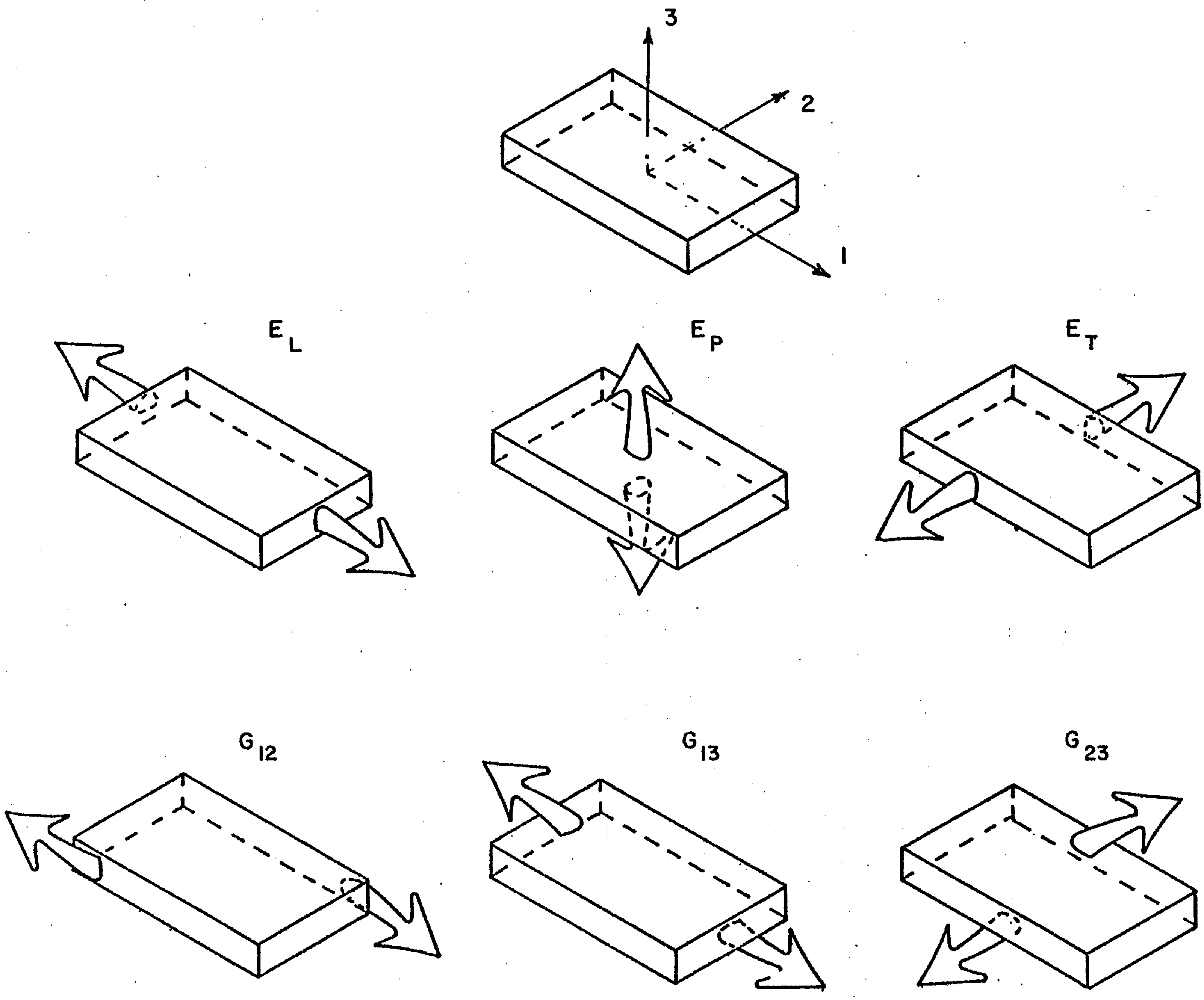
$$\gamma_{23} = S_{44}\,\tau_{23}$$

$$\gamma_{13} = S_{55}\,\tau_{13}$$

$$\gamma_{12} = S_{66}\,\tau_{12}$$

FIGURE 1

Schematic Definition of the Distinct Young's Moduli and Shear Moduli for Materials of Orthotropic Symmetry


3
2
1
E_L
E_P
E_T
G_{12}
G_{13}
G_{23}

These six relationships can be written in compact matrix form as

$$\left|\begin{array}{c}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\\ \varepsilon_{23}\\ \varepsilon_{13}\\ \varepsilon_{12}\end{array}\right| = \left|\begin{array}{cccccc} S_{11} & S_{12} & S_{13} & 0 & 0 & 0\\ S_{21} & S_{22} & S_{23} & 0 & 0 & 0\\ S_{31} & S_{32} & S_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & S_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & S_{55} & 0\\ 0 & 0 & 0 & 0 & 0 & S_{66}\end{array}\right| \times \left|\begin{array}{c}\sigma_1\\ \sigma_2\\ \sigma_3\\ \tau_{23}\\ \tau_{13}\\ \tau_{12}\end{array}\right|$$

or, in symbolic matrix notation

$$\underset{\sim}{\varepsilon} = \underset{\approx}{S}\underset{\sim}{\sigma}$$

where $\underset{\sim}{\varepsilon}$ stands for the 1x6 column vector of ε's and γ's; $\underset{\approx}{S}$ stands for the 6x6 array of the S_{ij}'s; and $\underset{\sim}{\sigma}$ stands for the 1x6 column vector of σ's and τ's.

The elements of the $\underset{\approx}{S}$ array are simply related to the Engineering constants by the relationships summarized at the top of Table I.

In the matrix format, the stress, $\underset{\sim}{\sigma}$, that would result from a general deformation, $\underset{\sim}{\varepsilon}$, is given by

$$\underset{\sim}{\sigma} = \underset{\approx}{C}\underset{\sim}{\varepsilon}$$

Consequently, the elastic constant array is the "inverse" (in a matrix sense) of $\underset{\approx}{S}$, viz,

$$\underset{\approx}{C} = \underset{\approx}{S}^{-1}$$

The relationship of the elements C_{ij} of the $\underset{\approx}{C}$ array to the Engineering constants are summarized in Table I.

Most theoretical treatments are formulated in terms of the elastic constants, $\underset{\approx}{C}$.

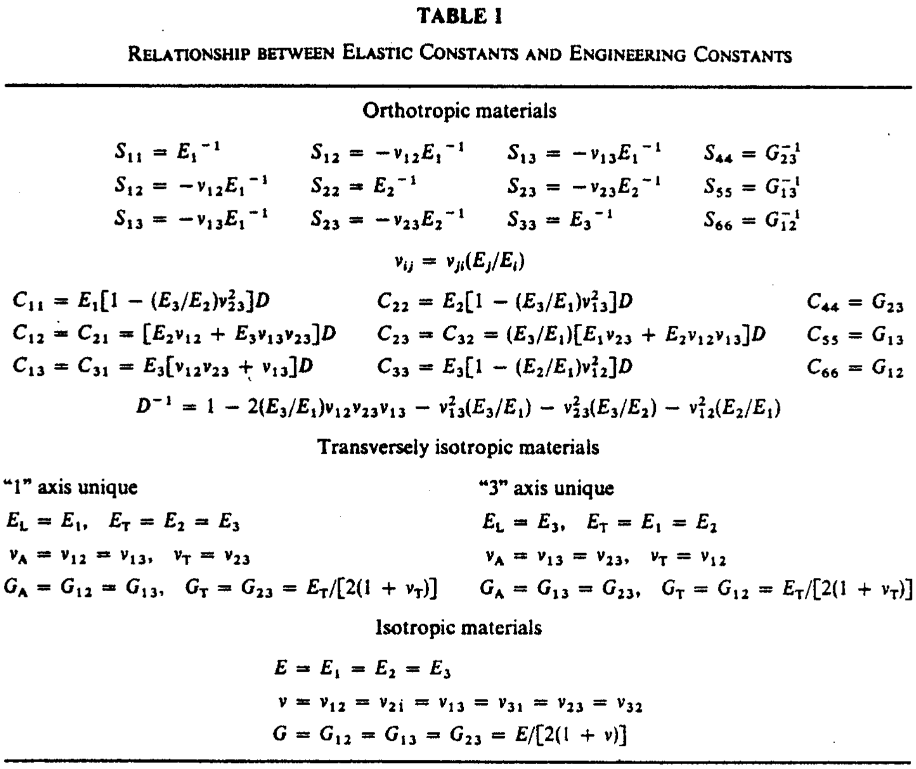


TABLE I

RELATIONSHIP BETWEEN ELASTIC CONSTANTS AND ENGINEERING CONSTANTS

Orthotropic materials

$$\begin{array}{llll} S_{11} = E_1{}^{-1} & S_{12} = -\nu_{12}E_1{}^{-1} & S_{13} = -\nu_{13}E_1{}^{-1} & S_{44} = G_{23}^{-1} \\ S_{12} = -\nu_{12}E_1{}^{-1} & S_{22} = E_2{}^{-1} & S_{23} = -\nu_{23}E_2{}^{-1} & S_{55} = G_{13}^{-1} \\ S_{13} = -\nu_{13}E_1{}^{-1} & S_{23} = -\nu_{23}E_2{}^{-1} & S_{33} = E_3{}^{-1} & S_{66} = G_{12}^{-1} \end{array}$$

$$\nu_{ij} = \nu_{ji}(E_j/E_i)$$

$$\begin{array}{lll} C_{11} = E_1[1 - (E_3/E_2)\nu_{23}^2]D & C_{22} = E_2[1 - (E_3/E_1)\nu_{13}^2]D & C_{44} = G_{23} \\ C_{12} = C_{21} = [E_2\nu_{12} + E_3\nu_{13}\nu_{23}]D & C_{23} = C_{32} = (E_3/E_1)[E_1\nu_{23} + E_2\nu_{12}\nu_{13}]D & C_{55} = G_{13} \\ C_{13} = C_{31} = E_3[\nu_{12}\nu_{23} + \nu_{13}]D & C_{33} = E_3[1 - (E_2/E_1)\nu_{12}^2]D & C_{66} = G_{12} \end{array}$$

$$D^{-1} = 1 - 2(E_3/E_1)\nu_{12}\nu_{23}\nu_{13} - \nu_{13}^2(E_3/E_1) - \nu_{23}^2(E_3/E_2) - \nu_{12}^2(E_2/E_1)$$

Transversely isotropic materials

$$\begin{array}{ll} \text{"1" axis unique} & \text{"3" axis unique} \\ E_L = E_1, \quad E_T = E_2 = E_3 & E_L = E_3, \quad E_T = E_1 = E_2 \\ \nu_A = \nu_{12} = \nu_{13}, \quad \nu_T = \nu_{23} & \nu_A = \nu_{13} = \nu_{23}, \quad \nu_T = \nu_{12} \\ G_A = G_{12} = G_{13}, \quad G_T = G_{23} = E_T/[2(1 + \nu_T)] & G_A = G_{13} = G_{23}, \quad G_T = G_{12} = E_T/[2(1 + \nu_T)] \end{array}$$

Isotropic materials

$$E = E_1 = E_2 = E_3$$

$$\nu = \nu_{12} = \nu_{2i} = \nu_{13} = \nu_{31} = \nu_{23} = \nu_{32}$$

$$G = G_{12} = G_{13} = G_{23} = E/[2(1 + \nu)]$$

(From: Anisotropic Elastic Behavior of Crystalline Polymers, R. L. McCullough, Treatise on Materials Science and Technology, 10B, p. 453-540, Academic Press, New York, 1977)

Additional symmetry of the material results in certain special conditions on the elastic constants, $\underset{\approx}{C}$ (as well as the compliance constants, $\underset{\approx}{S}$, and the engineering constants). Transversely, isotropic symmetry is of particular importance, fibers (e.g., graphite, Kevlar) frequently exhibit transversely isotropic response. Under conditions of transverse isotropy, the structure of the orthotropic array is preserved; however, certain special relationships between the material descriptors are imposed.

These relationships are summarized in Figure 2 and in Table I. Isotropic symmetry is exhibited by many (undrawn) polymer systems. Again, the structure of the orthotropic array is preserved with the special conditions $C_{11} = C_{22} = C_{33}$, and $C_{44} = C_{55} = C_{66} = \frac{1}{2}(C_{11}-C_{12})$. Consequently, no unique material axes exist for isotropic materials (i.e., the properties are the same in all directions). The results of the symmetry conditions for isotropic materials are summarized in Figure 2 and Table I.

These descriptions may be applied to describe the mechanical properties of the individual components of a sheet molding compound as well as the overall properties of the sheet molding material.

Orientation Dependence

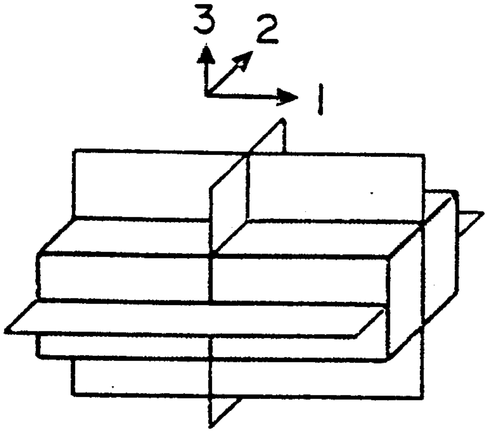
In the preceding discussion of the characterization of material descriptors, the simplifications resulting from material symmetry were emphasized by requiring that the unique axis associated with the symmetry class of the material were coincident with the loading (or deformation) directions imposed on the body of the material. This situation is rarely encountered. For example, fiber-reinforced laminates (e.g., tire plies) are frequently oriented at an angle of 45° with respect to the fiber direction. Fortunately, once the material system has been characterized along the unique axes, the material response in any arbitrary direction can be accurately predicted through the relationships summarized in Figure 3.

These relationships can be used to characterize the load-deformation response characteristics of a material $\bar{\underset{\approx}{A}}(\phi)$ at any arbitrary direction, ϕ, in terms of the associated descriptors associated with the symmetry axes of the material, $\underset{\approx}{A}$.

FIGURE 2

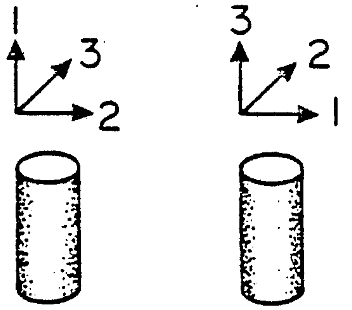
Components of the Elastic Constant Array
for Materials with Orthotropic, Transversely
Isotropic, and Isotropic Materials Symmetry

ORTHOTROPIC MATERIALS



$$\begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{13} \\ \tau_{12} \end{pmatrix} = \begin{pmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{22} & c_{23} & 0 & 0 & 0 \\ c_{13} & c_{23} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{pmatrix} \begin{pmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{pmatrix}$$

TRANSVERSLY ISOTROPIC MATERIALS



SPECIAL CONDITIONS

$c_{22} = c_{33}$

$c_{12} = c_{13}$

$c_{44} = \frac{1}{2}(c_{22} - c_{23})$

$c_{55} = c_{66}$

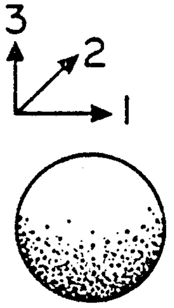
$c_{11} = c_{22}$

$c_{23} = c_{13}$

$c_{44} = c_{55}$

$c_{66} = \frac{1}{2}(c_{11} - c_{12})$

ISOTROPIC MATERIALS

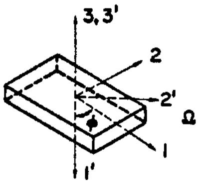


SPECIAL CONDITIONS

$c_{11} = c_{22} = c_{33}$

$c_{12} = c_{13} = c_{23}$

$c_{44} = c_{55} = c_{66} = \frac{1}{2}(c_{11} - c_{12})$



$$\Omega = \begin{pmatrix} \omega_{11} = \cos\phi & \omega_{12} = \sin\phi & \omega_{13} = 0 \\ \omega_{21} = -\sin\phi & \omega_{22} = \cos\phi & \omega_{23} = 0 \\ \omega_{31} = 0 & \omega_{32} = 0 & \omega_{33} = 1 \end{pmatrix}$$

$$\begin{array}{ll}
\bar{A}_{11} = B_1 + B_7 \cos 2\phi + B_8 \cos 4\phi & B_1 = \frac{1}{8}(3A_{11} + 3A_{22} + 2A_{12} + 4A_{66}) \\
\bar{A}_{12} = \bar{A}_{21} = B_2 - B_8 \cos 4\phi & B_7 = \frac{1}{2}(A_{11} - A_{22}) \\
\bar{A}_{16} = \bar{A}_{61} = \frac{1}{2}(B_7 \sin 2\phi) + B_8 \sin 4\phi & B_8 = \frac{1}{8}(A_{11} + A_{22} - 2A_{12} - 4A_{66}) \\
\bar{A}_{22} = B_1 - B_7 \cos 2\phi + B_8 \cos 4\phi & B_2 = \frac{1}{8}(A_{11} + A_{22} + 6A_{12} - 4A_{66}) \\
\bar{A}_{26} = \bar{A}_{62} = \frac{1}{2}(B_7 \sin 2\phi) - B_8 \sin 4\phi & B_6 = \frac{1}{8}(A_{11} + A_{22} - 2A_{12} + 4A_{66}) \\
\bar{A}_{66} = B_6 - B_8 \cos 4\phi &
\end{array}$$

Reduction in the transformation relationships for an orthotropic material in a state of plane stress or strain. The rotation transformation between the material axes ($\hat{e}_1, \hat{e}_2, \hat{e}_3$) and arbitrary load (or deformation) axes ($\hat{e}_1', \hat{e}_2', \hat{e}_3$) reduce to a simple rotation around the common $\hat{e}_3$ axis. Replacement of the A_{ij} by elastic constants C_{ij} yields expressions for the transformed elastic constants ($\bar{A}_{ij} = \bar{C}_{ij}$); replacement of the A_{ij} by the compliance constants S_{ij}, yields expressions for the transformed compliance constants ($\bar{A}_{ij} = \bar{S}_{ij}/m_i m_j$); $m_k = 1$ for $k = 1, 2$, or 3; $m_k = 2$ for $k = 4, 5$, or 6.

FIGURE 3

(From: Anisotropic Elastic Behavior of Crystalline Polymers, R. L. McCullough, ob. cit.)

MATERIALS MODELING

In this section, procedures will be developed for predicting the behavior of sheet molding materials comprised of short reinforcing fibers, particulate fillers, and a polymer phase. The approach proceeds by developing an aggregate model to account for orientation effects. The basic element of the aggregate model is taken to be an arbitrary "micro-region." The properties of the micro-region are subsequently predicted by associating the micro-region with a micro-laminate of aligned fibers. The combination of these results into a computational format for predicting the properties of sheet molding materials is summarized in the final section.

Aggregate Model

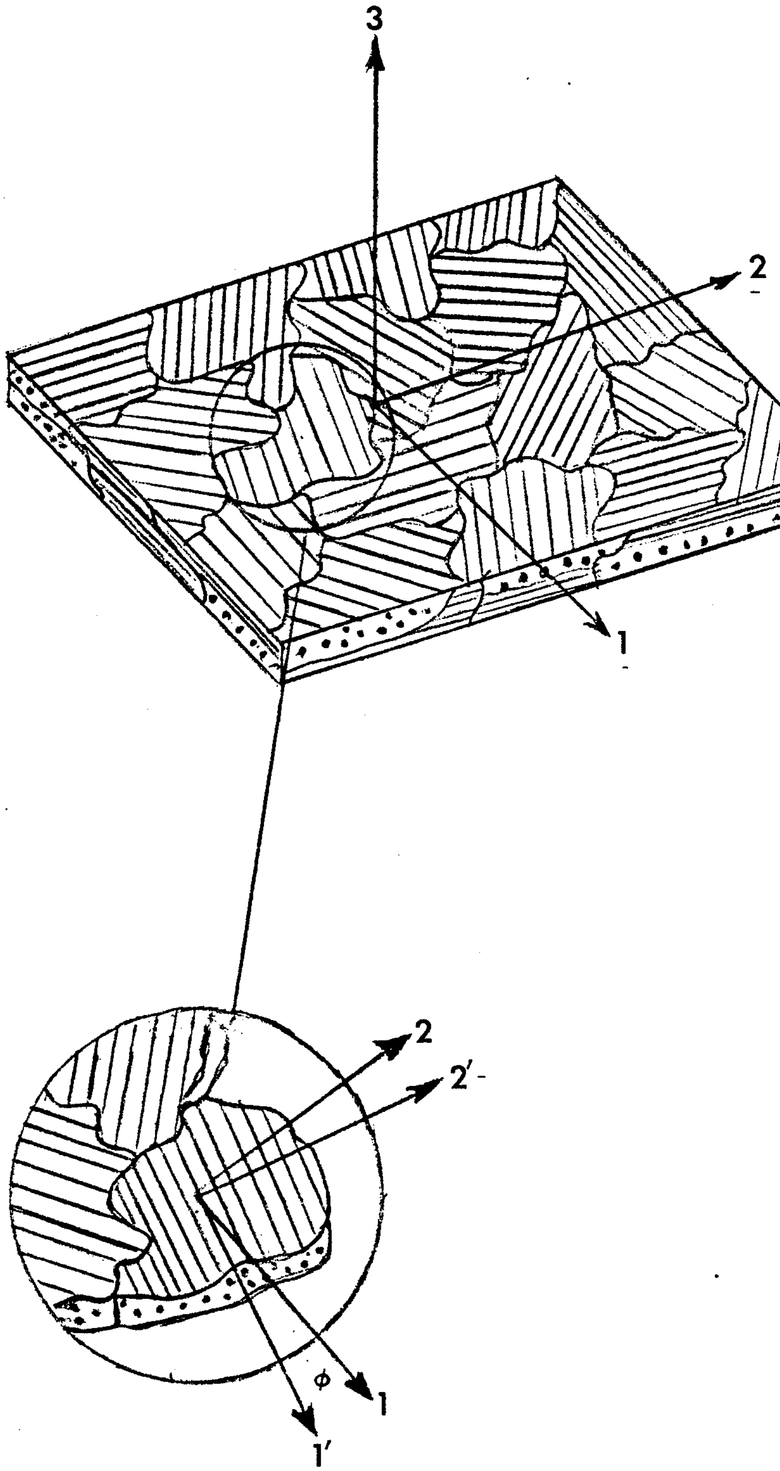
Under the Aggregate Model, a sheet molding material is viewed as partitioned into micro-regions as illustrated in Figure 4. As in the case of "grainy metals," each micro-region is treated as an apparent homogeneous (but anisotropic) material which may be described as an array of elastic constants, $\underset{\approx}{C}$. These micro-regions may assume a variety of orientations with respect to the external axes of the macroscopic body of material. Accordingly, the load-deformation characteristics along the "1", "2", and "3" axes of the bulk material are dependent upon the relative orientation of the unique "1'", "2'", "3'" material axes of the micro-region. Consequently, the transformations given in Figure 3 must be applied to each micro-region to obtain the appropriate contribution of the individual regions to the overall load-deformation response of the bulk material.

The fraction of micro-regions whose unique material axis "1'" makes an angle ϕ with respect to the external body axis "1" may be specified in terms of an orientation distribution function $n(\phi)$. This function gives the relative number of micro-regions whose unique axes are parallel and make an angle

FIGURE 4

Schematic Definition of
the Aggregate Model

AGGREGATE MODEL



ϕ with respect to the external axis. Thus, if all the micro-regions were aligned along the body axis, $n(\phi=0) = 1$ and $n(\phi \neq 0) = 0$. Alternately, if the micro-regions were uniformly distributed in all directions, $n(\phi)$ = a constant for all values of ϕ.

It should be emphasized that the orientation function, $n(\phi)$, does not provide for an "out-of-plane tilting" of the micro-region. This type of orientation function is called a "Planar" distribution. Planar distributions are appropriate to sheet molding materials that are fabricated under conditions which maintain such planarity. Materials formed by injection molding may exhibit "out-of-plane tilting" and therefore will require a different form of an orientation distribution function.

The planar distribution function has the following important features:

$$n(\phi) = n(-\phi)$$

$$n(\phi) = n(+\phi)$$

$$\int_0^{\pi/2} n(\phi)\,d\phi = 1$$

The net contribution of the various micro-regions to the overall load-deformation response is given by averaging the relationships given in Figure 3 over the distribution; viz

$$\langle \underset{\approx}{A} \rangle = \int \underset{\approx}{\bar{A}}(\phi)\,n(\phi)\,d\phi \qquad \text{.... 1}$$

It is useful to introduce certain orientation parameters, "f" and "g" defined as

$$f = 2\,\langle \cos^2\phi \rangle - 1 \qquad \text{.... 2}$$

$$g = (1/5)(8\,\langle \cos^4\phi \rangle - 3) \qquad \text{.... 2b}$$

with

$$\langle \cos^m\phi \rangle = \int_0^{\pi/2} \cos^m\phi\, n(\phi)\,d\phi$$

These orientation parameters are constructed to provide a convenient scale for characterizing the state of orientation of a system. Thus, for $f = g = 0$, the micro-regions are randomly distributed within the "1-2" plane of the bulk material. For $f = g = 1$, the micro-regions are perfectly aligned along the "1" axis of the bulk material. Values of f and g between 0 and 1 represent intermediate states of orientation. These features of the planar orientation are summarized in Figure 5.

The results obtained by averaging under a planar orientation distributions are summarized in Table II in terms of the orientation parameters f and g. As before, the elastic constant array, $\underset{\approx}{C}$, and the compliance array, $\underset{\approx}{S}$, undergo the same transformations so that the results for orientation averaging can be generalized for an arbitrary material descriptor, $\langle\underset{\approx}{A}\rangle$ and base descriptor, $\underset{\approx}{A}$. Thus for $\underset{\approx}{A} \rightarrow \underset{\approx}{C}$, the relationships of Table II yield the orientation average of the elastic constant array; for $\underset{\approx}{A} \rightarrow \underset{\approx}{S}$, the orientation average of the compliance array is obtained. The factor B is introduced to account for the contraction of the compliance and elastic constants to second order tensors. For $\underset{\approx}{A} \rightarrow \underset{\approx}{C}$, $B = 1$; for $\underset{\approx}{A} \rightarrow \underset{\approx}{S}$, $B = 4$.

It can be shown that for reasonable forms for the planar orientation distribution (e.g., $n(\phi) = k\cos^b\phi$) that the orientation parameters f and g are related:

$$g = 2f(7-2f)/[5(4-2f)] \qquad \ldots.\ 3$$

so that only one parameter is required to describe the state of orientation. The orientation parameter, "f", is related to the "root-mean-square" orientation angle

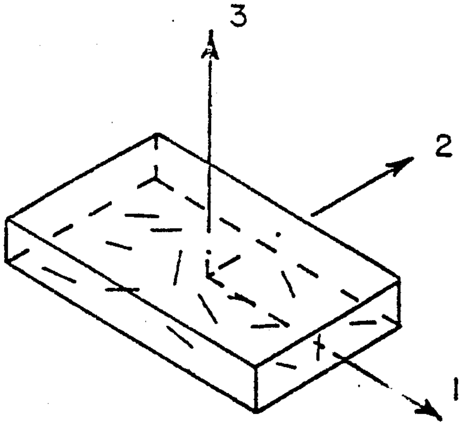
$$\phi_{rms} = \cos^{-1}\sqrt{(1+f)/2}\ .$$

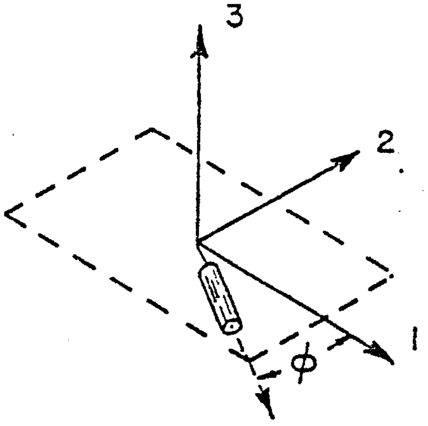
Hence for random distributions, $f = 0$ and $\phi_{rms} = 45°$. For perfect alignment, $f = 1$, and $\phi_{rms} = 0°$. For "slight" orientation, $f = 0.25$, $\phi_{rms} = 40°$; for "moderate" orientation,

FIGURE 5

Summary of the Features of a
Planar Orientation Distribution

Planar Orientation





$$n(\phi) = n(-\phi)$$

$$n(\phi) = n(\pi + \phi)$$

$$\int_0^{\pi/2} n(\phi)\, d\phi = 1$$

$$f_p = 2 \langle \cos^2 \phi \rangle - 1$$

$$g_p = \frac{1}{5} \left[8 \langle \cos^4 \phi \rangle - 3 \right]$$

$$\langle \cos^m \phi \rangle = \int_0^{\pi/2} n(\phi) \cos^m \phi \, d\phi$$

<u>Aligned</u>

$f_p = 1$

$g_p = 1$

<u>Random</u>

$f_p = 0$

$g_p = 0$

TABLE II

Averaged Properties of a Planar Orientation Distribution

PLANAR ORIENTATION

$$\langle A_{11} \rangle = A_{11}^{o} - \left[a_{11} + \frac{5}{B} a_{66}\right] f \quad + \frac{5}{B} a_{66} g$$

$$\langle A_{12} \rangle = A_{12}^{o} + 4\, a_{12} f \ - 5 a_{12} g$$

$$\langle A_{13} \rangle = A_{13}^{o} - \ a_{13} f$$

$$\langle A_{22} \rangle = A_{22}^{o} - \left[a_{22} + \frac{5}{B} a_{66}\right] f \quad + \frac{5}{B} a_{66} g$$

$$\langle A_{23} \rangle = A_{23}^{o} - \ a_{23} f$$

$$\langle A_{33} \rangle = A_{33}^{o}$$

$$\langle A_{44} \rangle = A_{44}^{o} - \ a_{44} f$$

$$\langle A_{55} \rangle = A_{55}^{o} - \ a_{55} f$$

$$\langle A_{66} \rangle = A_{66}^{o} + 4\, a_{66} f \ - 5 a_{66} g$$

$$a_{ij} = A_{ij}^{o} - A_{ij}$$

$A_{11}^{o} = A_{22}^{o} = k^{A} + \mu^{A}$

$A_{13}^{o} = A_{23}^{o} = \ell^{A}$

$A_{44}^{o} = A_{55}^{o} = B\gamma^{A}$

$A_{12}^{o} = k^{A} - \mu^{A}$

$A_{33}^{o} = n^{A}$

$A_{66} = B\mu^{A}$

$k^{A} = \frac{1}{4}\left[A_{11} + A_{22} + 2A_{12}\right]$

$\mu^{A} = \frac{1}{8}\left[A_{11} + A_{22} - 2A_{12} + \frac{4}{8} A_{66}\right]$

$\ell^{A} = \frac{1}{2}\left[A_{13} + A_{23}\right]$

$\gamma^{A} = \frac{1}{2B}\left[A_{44} + A_{55}\right]$

$n^{A} = A_{33}$

$f = 0.5$, $\phi_{rms} = 30°$ while for "significant" orientation, $f = 0.75$, $\phi_{rms} = 20°$.

The aggregate model serves as a reasonable means of introducing relationships to account for the particular internal state of orientation of the representative micro-regions. The next task is to identify the nature of the arbitrary micro-regions and relate the properties of the micro-region, $\underset{\approx}{C}^*$, to the composition and fiber geometry of the sheet molding material.

Micro-Laminate Model

The preceding treatment of the aggregate model was based upon an arbitrary specification of a "micro-region." Indeed, the elements of the elastic constant array, $\underset{\approx}{C}$, that is used to describe the mechanical behavior of the micro-region could be treated as adjustable parameters for curve fitting. Since as many as nine independent parameters could be required, this empirical approach does not appear to be fruitful. In this section, the characteristic micro-region of the aggregate model is treated as a micro-laminate of perfectly aligned fibers. Accordingly, the domain of a micro-region is specified as that portion of the material that can be partitioned into volume elements in which the fibers within the region are all aligned parallel to an axis that makes an angle ϕ with the external body axis. The identification of such a region specifies the effective aspect ratio of the fiber. Thus for a sheet molding material (e.g., SMC-25) comprised of relatively long and straight collections of fibers, the aspect ratio would be large (e.g., $a > 250$). Alternately, for a sheet molding material in which the fiber bundles are "swirled" (e.g., SMC-65) such that arc length is relatively short, the effective aspect ratio could be as low as $a = 1 \rightarrow 10$.

Under this view of the micro-regions, the properties can be obtained from appropriate models for laminates. The general Wu-McCullough relationship can be specialized to this purpose.

The general relationship is of the form

$$\underset{\approx}{C}^* = \underset{\approx}{C}_o + (\underset{\approx}{M}^{-1} + \underset{\approx}{E}_o)^{-1} \qquad \text{.... 4}$$

where $\underset{\approx}{C}^*$ is the 6x6 array of elastic constants for the microlaminate. The term $\underset{\approx}{C}_o$ is a 6x6 array of elastic constant for a "reference" material. The term $\underset{\approx}{E}_o$ is a 6x6 array which takes into account correlation effects. The elements of $\underset{\approx}{E}_o$ are dependent upon the aspect ratio, a, and certain elements of $\underset{\approx}{C}_o$. The elements of $\underset{\approx}{E}_o$ are summarized in Table III.

The quantity $\underset{\approx}{M}$ is a 6x6 array that is dependent upon the composition and the properties of the components compensated for correlation effects, viz,

$$\underset{\approx}{M} = \Sigma v_i \underset{\approx}{m}_i \qquad \text{.... 5}$$

where v_i is the volume fraction of the i'th component; the term $\underset{\approx}{m}_i$ is a 6x6 array of the properties of component "i" compensated for correlations through the following relationships

$$\underset{\approx}{m}_i = (\underset{\approx}{R}_i^{-1} - \underset{\approx}{E}_o)^{-1} \qquad \text{.... 6a}$$

$$\underset{\approx}{R}_i = \underset{\approx}{C}_i - \underset{\approx}{C}_o \qquad \text{.... 6b}$$

The term $\underset{\approx}{C}_i$ is the 6x6 array of elastic constants for the i'th component

The versatility of the Wu-McCullough relationship is manifest through the term $\underset{\approx}{C}_o$. Assigning a reference material "zero" rigidity ($\underset{\approx}{C}_o = \underset{\approx}{0}$) yields the classic Reuss model; assigning the reference material an infinite rigidity ($\underset{\approx}{C}_o = \underset{\sim}{\infty}$) yields the Voigt model. If the reference material is taken as the resin phase ($\underset{\approx}{C}_o = \underset{\approx}{C}_{resin}$), the "best lower bounds" are obtained. If the fiber phase is selected as the reference phase ($\underset{\approx}{C}_o = \underset{\approx}{C}_{fiber}$), the "best upper bounds" are obtained. Usually, these bounds are too far apart to provide useful predictions. For the case, $\underset{\approx}{C}^* = \underset{\approx}{C}_o$, the "self-consistent" field models are obtained.

TABLE III
Elements of $\underset{\approx}{E}_o$

$$\underset{\approx}{E}_o = \begin{vmatrix} n & \ell & \ell & 0 & 0 & 0 \\ \ell & k+u & k-u & 0 & 0 & 0 \\ \ell & k-u & k+u & 0 & 0 & 0 \\ 0 & 0 & 0 & 4u & 0 & 0 \\ 0 & 0 & 0 & 0 & 4m & 0 \\ 0 & 0 & 0 & 0 & 0 & 4m \end{vmatrix}$$

$n = 4\alpha h_5(a) - 4\beta h_2(a)$

$\ell = 2\alpha h_4(a)$

$k = \alpha h_3(a) - \beta h_1(a)$

$u = \frac{1}{2}\alpha h_3(a) - \beta h_1(a)$

$m = 2\alpha h_4(a) - \beta[\frac{1}{2}h_1(a) + h_2(a)]$

$\alpha = (C^o_{22} - C^o_{44})/(4C^o_{22}C^o_{44})$

$\beta = 1/(4C^o_{44})$

$h_2(a) = 1 - h_1(a)$

$h_4(a) = \frac{1}{2}[1 - h_3(a) - h_5(a)]$

TABLE III (con't)

For $0 \le a < 1$

$$y^2 = a^2/(1-a^2)$$

$$h_1(a) = y^2\{[(1/y) + y]\tan^{-1}(1/y) - 1\}$$

$$h_3(a) = y^4\{[(1+y^2)/2y^2] + 1\ [\tfrac{1}{2}(1/y)^3 - (1-y) - (3/2)y]\tan^{-1}(1/y)]\}$$

$$h_5(a) = (1+y^2)[(3-y^2)/(1+y^2) - (3/2)y\tan^{-1}(1/y))]$$

For $a = 1$

$$h_1(a) = 2/3$$

$$h_3(a) = 8/15$$

$$h_5(a) = 1/5$$

For $1 < a < \infty$

$$x^2 = (a^2-1)/a^2$$

$$Z = \{\ell n[(1+x)/(1-x)]\}/x$$

$$h_1(a) = [1 - \tfrac{1}{2}(1-x)Z]/x$$

$$h_3(a) = [(3/2) - \tfrac{1}{2} + \tfrac{1}{4}(x^2+2x-3)Z]/x^2$$

$$h_5(a) = [(1-x^2)/x^2]^2\{[(3-2x)/2(1-x)] - (3/4)Z)\}$$

It has been shown that the properties for a wide-range of fiber reinforced resin systems can be accurately predicted by assigning values to the $\underset{\approx}{C}_o$ array that correspond to a material (of equivalent composition and concentration) reinforced by spheres (aspect ratio = 1) rather than fibers. It was proposed that standard samples of glass bead reinforced resins be prepared and characterized over a range of volume fractions to provide the data necessary for constructing the $\underset{\approx}{C}_o$ array. These experimentally determined values for $\underset{\approx}{C}_o$ could be used in conjunction with Eq. 4 to predict the properties of fiber reinforced systems.

Recently, it was shown that the experimental determination of $\underset{\approx}{C}_o$ is not required. A model for particulate systems has been developed which accurately predicts the behavior of a wide variety of particulate filled systems over the sensible range ($v_p \leq 0.8$) of concentration of filler, v_p.

The "S-Mixing Rule" model for particulate systems is of the form

$$\underset{\approx}{S}_p = v_r \underset{\approx}{S}_{Lo} + v_p \underset{\approx}{S}_{Hi} + \tfrac{1}{2} v_r v_p (\underset{\approx}{S}_{Lo} - \underset{\approx}{S}_{Hi})$$

where v_r and v_p are the respective volume fractions of resin and filler particles. The quantity $\underset{\approx}{S}_{Lo} = \underset{\approx}{C}_{Lo}^{-1}$ where $\underset{\approx}{C}_{Lo}$ is obtained from Eq. 4 with $\underset{\approx}{C}_o = \underset{\approx}{C}_{resin}$ and the aspect ratio of the E_o term taken as a = 1. Similarly, the quantity $\underset{\approx}{S}_{Hi} = \underset{\approx}{C}_{Hi}^{-1}$ is obtained from Eq. 4 with $\underset{\approx}{C}_o = \underset{\approx}{C}_{filler}$ and a = 1. The relationships given in Table I are used to obtain the Young's modulus, Shear modulus, and Poisson's ratio from the computed values of $\underset{\approx}{S}_p$ for the particulate system.

The demonstrated success of the "S-Mixing Rule" provides a convenient means for generating the appropriate values for the parameters of the reference phase, $\underset{\approx}{C}_o$, as required by Eq. 4.

For a two-component fiber/resin system, the effective mechanical properties of the material may be predicted by the following procedures:

(i) For the current volume fraction of fiber and resin the appropriate values of $\underset{\approx}{C}_o$ are obtained by the application of the "S-mixing rule" (Eq. 5) for a system comprised of the equivalent volume fraction of resin and particles (a = 1) with the particles assigned the properties of the fiber.

(ii) The values obtained for $\underset{\approx}{C}_o$ are used in Eq. 4 along with the effective aspect ratio of the fiber to predict the properties of the micro-laminate, $\underset{\approx}{C}^*$.

(iii) The properties of the micro-laminate are subjected to the orientation averaging prescribed in Table II for a specified state of orientation, f.

(iv) The averaged values of $\underset{\approx}{C}$ for the sheet molding material are converted to the compliance array, $\underset{\approx}{S}$, and subsequently to the Engineering constants via the relationships given in Table I.

These procedures can be extended to resin/fiber/filler systems by introducing the notion of a "surrogate" matrix. In this approach, the resin and particulate filler system are viewed as a matrix phase. The properties of the matrix phase may be predicted by the application of the S-mixing rule for a particulate system with the apparent volume fractions of v_r' and v_p' for the resin and filler. These apparent volume fractions are related to the true volume fractions, v_r and v_p, through the relationships

$$v_r' = v_r/(v_r + v_p)$$

$$v_p' = v_p/(v_r + v_p)$$

so that $v_r' + v_p' = 1$.

The resulting properties for the isolated resin/filler systems are used to represent the behavior of a surrogate matrix material with properties $\underset{\approx}{C}_m$ as predicted by Eq. 5 with concentrations v_r' and v_p'. At this point, the computation follows steps (i) through (iv) for a two-component fiber/matrix system with the computed values for the surrogate matrix assuming the role of the resin phase. The volume fraction of the surrogate matrix phase is given by $v_m = v_r + v_p = 1-v_f$, where v_f is the volume fraction of the fiber phase.

FORTRAN PROGRAM

Introduction

The preceding sections have been concerned with developing a model for predicting the Engineering properties of sheet molding compounds. These ideas have been implemented in the FORTRAN program SMC-3. Use of SMC-3 is described in this section. Two examples using SMC-3 and a program listing follow. Finally, a few cautions which need to be noted when implementing SMC-3 on a computing system other than the DEC-system 10 for which this version was written are discussed.

Examples and use of SMC-3 will be illustrated by specific examples. In general the execution of the program requires the following input data:

1) number of components
2) properties of constitutive phases
3) volume or weight fractions of components
4) effective aspect ratio of fibers
5) orientation of fibers

To facilitate the use of SMC-3, the Engineering constants (in psi) for polyester resin, E-glass fibers, and calcium carbonate filler have been stored internally in the program. If these properties are to be used, no data regarding the engineering properties of the constitutive phases need be entered. If the properties of one or all the phases are to be changed, this can be accomplished by the user during program execution. For an isotropic phase, e.g., resin, filler and some fibers, Young's modulus, the Shear modulus and Poisson's ratio will need to be entered. For transversely isotropic fibers (e.g., Kevlar) two Young's moduli, two Shear moduli and two Poisson's ratios will need to be entered. Example 1 demonstrates how properties for isotropic phases are changed. Example 2a shows how the properties are changed for a transversely isotropic fiber.

The composition can be entered either as volume fractions or weight fractions. If volume fractions are used, the data are entered directly. Input using weight fractions also requires that the density of each phase must be entered. In examples 1 and 2, composition is input as weight and volume fractions, respectively.

The effective aspect ratio is entered directly upon request. The aspect ratio ranges from one to infinity. An aspect ratio of one corresponds to a spherical inclusion while an infinite aspect ratio corresponds to a continuous fiber.

Effect of fiber orientation on the Engineering constants can be investigated in either of two modes. First, the Engineering constants can be calculated for a single user selected fiber distribution. Orientation is specified by Herman's orientation function f. For random distribution f = 0. For perfectly aligned fibers f = 1.

Slightly oriented systems can be represented by "f" values in the range 0.2 to 0.3. Moderately oriented systems can be represented by "f" values of ~0.5. Significantly oriented systems can be represented by "f" values of 0.6 to 0.8

Second, a range of fiber orientations can be scanned. In this case the user specifies the initial and final values of the orientation parameter as well as the incremental step size.

For some input data it is possible to perform consistency checks. SMC-3 provides two such checks. The first is for composition fractions. If the fractions do not sum to unity, the user is instructed to re-enter the data.

The second consistency check is performed when one of the standard phases is replaced by an isotropic phase. In this case there are only two independent material descriptors, and it is possible to determine whether the input Young's modulus, Shear modulus and Poisson's ratio are self-consistent. The results of this check are as follows:

1) If input data are self-consistent, program execution continues.

2) If the input Poisson's ratio is inconsistent, an internally determined value is assigned and the user is informed of the change and asked for confirmation.

3) If the input Young's and Shear moduli require a negative Poisson's ratio or one larger than 0.5, the user is instructed to enter new moduli and Poisson's ratio.

Output from SMC-3 consists of two parts. The first is a summary of the input data. Included are the phase properties, composition as volume fractions, and the effective aspect ratio. Secondly, a tabular summary of the predicted material properties at specified orientations is printed. The table contains the predicted longitudinal, transverse, and perpendicular Young's moduli, the "1, 2", "1, 3" and "2, 3" Shear moduli and the "1, 2", "1, 3" and "2, 3" Poisson's ratios.

EXAMPLES

EXAMPLE 1

The purpose of this example is to illustrate the use of SMC3 for a three component system. The input data for the filler will be altered. An intentional error will be introduced to illustrate the operation of the self-consistancy check. After illustrating the checking feature, the data will be reset to the standard values.

☐ Data inputs by the user will be indicated by the symbol ✪.

☐ Comments are given in italics.

```
ENTER NUMBER OF COMPONENTS:
FOR RESIN/FIBER SYSTEM NUMB = 2
FOR RESIN/FIBER/FILLER SYSTEM NUMB = 3
✪3

TYPICAL PROPERTIES FOR A THREE COMPONENT
POLYESTER/E-GLASS/CALCIUM CARBONATE SYSTEM ARE:

            YOUNG'S MODULUS   SHEAR MODULUS   POISSON'S RATIO
-------------------------------------------------------------
RESIN         .5100E+06         .1960E+06          .301
FIBER         .1050E+08         .3940E+07          .333
FILLER        .6930E+07         .2620E+07          .323

IF THESE VALUES ARE ACCEPTABLE, ENTER A "0" (ZERO)
IF YOU WISH TO USE SIGNIFICANTLY DIFFERENT VALUES ENTER A "1" (ONE)
```

☐ *For illustrative purposes, the user elects to reduce the Young's Modulus of the filler from 6.93 X* 10^6 *to 4 X* 10^6 *while maintaining all other values for the properties. This will give inconsistant values for an isotropic material.*

```
✪1

 IF RESIN  PROPERTIES ARE ACCEPTABLE ENTER A "0" (ZERO)
 IF THEY ARE TO BE ALTERED ENTER A "1" (ONE)
✪0
```

```
   IF FIBER  PROPERTIES ARE ACCEPTABLE ENTER A "0" (ZERO)
   IF THEY ARE TO BE ALTERED ENTER A "1" (ONE)
✪0

   IF FILLER PROPERTIES ARE ACCEPTABLE ENTER A "0" (ZERO)
   IF THEY ARE TO BE ALTERED ENTER A "1" (ONE)
✪1

   ENTER YOUNG'S MODULUS FOR FILLER
✪4.E6

   ENTER SHEAR MODULUS FOR FILLER
✪2.62E6

   ENTER POISSON'S RATIO FOR FILLER
✪.323

   * * INPUT ERROR * *

   FOR INPUT VALUES OF THE YOUNG'S MODULUS AND SHEAR MODULUS
   POISSON'S RATIO WOULD BE NEGATIVE OR GREATER THAN 0.5

   RE-ENTER DATA
    ☐Return to standard values.

   ENTER YOUNG'S MODULUS FOR FILLER
✪6.93E6

   ENTER SHEAR MODULUS FOR FILLER
✪.262E7

   ENTER POISSON'S RATIO FOR FILLER
✪.323

   THE CURRENT SET OF PROPERTIES FOR THE THREE
   COMPONENT SYSTEM ARE:


               YOUNG'S MODULUS   SHEAR MODULUS   POISSON'S RATIO
   ------------------------------------------------------------
   RESIN        .5100E+06        .1960E+06          .301
   FIBER        .1050E+08        .3940E+07          .333
   FILLER       .6930E+07        .2620E+07          .323


   IF THESE VALUES ARE ACCEPTABLE, ENTER A "0" (ZERO)
   IF YOU WISH TO USE SIGNIFICANTLY DIFFERENT VALUES ENTER A "1" (ONE)
✪0
```

☐ *Weight fraction variables will be used. The use of weight fraction variables requires input for the density (or specific gravity) for each component.*

```
 IF THE COMPOSITION IS TO BE ENTERED AS VOLUME FRACTIONS,
 ENTER A "0" (ZERO)
 IF THE COMPOSITION IS TO BE ENTERED AS WEIGHT FRACTIONS,
 ENTER A "1" (ONE)
✪1

 WEIGHT FRACTION OF RESIN
✪.332

 DENSITY OF RESIN
✪1.2

 WEIGHT FRACTION OF FIBER
✪.25

 DENSITY OF FIBER
✪2.55

 WEIGHT FRACTION OF FILLER
✪.418

 DENSITY OF FILLER
✪2.40

 ENTER ASPECT RATIO OF THE FIBER
✪500.
```

☐ *This value for an aspect ratio is associated with relatively long and straight fibers.*

```
THE STATE OF ORIENTATION OF THE FIBER IS SPECIFIED
BY THE HERMANS ORIENTATION FACTOR, F.
FOR PLANAR RANDOM F = 0
FOR PERFECTLY ALIGNED F = 1.

IF YOU WISH DATA FOR A SPECIFIED ORIENTATION ENTER A "0" (ZERO)
IF YOU WISH TO SCAN OVER A RANGE OF ORIENTATIONS ENTER A "1" (ONE)
✪0

ENTER SPECIFIC STATE OF ORIENTATION
✪0.
```

☐ *The input data is summarized for convenience and the predicted properties displayed for the various orientations.*

```
INPUT DATA
          YOUNG'S MODULUS   SHEAR MODULUS   POISSON'S RATIO
------------------------------------------------------------
RESIN        .5100E+06        .1960E+06          .301
FIBER        .1050E+08        .3940E+07          .333
FILLER       .6930E+07        .2620E+07          .323

VOLUME FRACTIONS:
          RESIN    .504
          FIBER    .179
          FILLER   .317

ASPECT RATIO    500.0


CALCULATED DATA

ORIENTATION                           0.00
LONGITUDINAL YOUNG'S MODULUS       .2011E+07
TRANSVERSE YOUNG'S MODULUS         .2011E+07
PERPENDICULAR YOUNG'S MODULUS      .1615E+07
2,3 SHEAR MODULUS                  .6183E+06
1,3 SHEAR MODULUS                  .6183E+06
1,2 SHEAR MODULUS                  .7789E+06
1,2 POISSON'S RATIO                   .291
1,3 POISSON'S RATIO                   .287
2,3 POISSON'S RATIO                   .287

STOP

END OF EXECUTION
CPU TIME: 0.77  ELAPSED TIME: 3:15.28
EXIT
```

EXAMPLE 2a

The purpose of this example is to illustrate the use of SMC3 for a two component system. In this example, the fiber properties will be altered to reflect fiber anisotropy (e.g., KEVLAR 49).

☐Data inputs by the user will be indicated by the symbol ✪.

☐Comments are given in italics.

```
  ENTER NUMBER OF COMPONENTS:
  FOR RESIN/FIBER SYSTEM NUMB = 2
  FOR RESIN/FIBER/FILLER SYSTEM NUMB = 3
✪2

  TYPICAL PROPERTIES FOR A TWO COMPONENT
  POLYESTER/E-GLASS FIBER SYSTEM ARE:

              YOUNG'S MODULUS   SHEAR MODULUS   POISSON'S RATIO
  ------------------------------------------------------------
  RESIN        .5100E+06         .1960E+06          .301
  FIBER        .1050E+08         .3940E+07          .333
```

☐*The stored values for the fiber properties are to be altered. The resin properties will be maintained.*

```
 IF THESE VALUES ARE ACCEPTABLE, ENTER A "0" (ZERO)
 IF YOU WISH TO USE SIGNIFICANTLY DIFFERENT VALUES ENTER A "1" (ONE)
✪1

 IF RESIN  PROPERTIES ARE ACCEPTABLE ENTER A "0" (ZERO)
 IF THEY ARE TO BE ALTERED ENTER A "1" (ONE)
✪0

 IF FIBER  PROPERTIES ARE ACCEPTABLE ENTER A "0" (ZERO)
 IF THEY ARE TO BE ALTERED ENTER A "1" (ONE)
✪1
```

```
 IF FIBER IS ISOTROPIC ENTER A "0" (ZERO)
 IF FIBER IS ANISOTROPIC (E.G. GRAPHITE) ENTER A "1" (ONE)
```

☐ *The fiber is transversely isotropic*

```
✪1

 ENTER LONGITUDINAL YOUNG'S MODULUS
✪18.3E6

 ENTER TRANSVERSE YOUNG'S MODULUS
✪1.83E6

 ENTER SHEAR MODULUS, G12
✪6.88E6

 ENTER SHEAR MODULUS, G23
✪.688E6

 ENTER POISSON'S RATIO, POS12
✪.3

 ENTER POISSON'S RATIO, POS23
✪.3
```

☐ *The new properties are displayed for verification by the user.*

```
THE CURRENT SET OF PROPERTIES FOR THE TWO
COMPONENT SYSTEM ARE:


             RESIN          FIBER
-------------------------------------
E1        .5100E+06      .1830E+08
E2        .5100E+06      .1830E+07
E3        .5100E+06      .1830E+07
G12       .1960E+06      .6880E+07
G13       .1960E+06      .6880E+07
G23       .1960E+06      .6880E+06
POS12        .301           .300
POS13        .301           .300
POS23        .301           .300


IF THESE VALUES ARE ACCEPTABLE, ENTER A "0" (ZERO)
IF YOU WISH TO USE SIGNIFICANTLY DIFFERENT VALUES ENTER A "1" (ONE)
✪0
```

```
 IF THE COMPOSITION IS TO BE ENTERED AS VOLUME FRACTIONS,
 ENTER A "0" (ZERO)
 IF THE COMPOSITION IS TO BE ENTERED AS WEIGHT FRACTIONS,
 ENTER A "1" (ONE)
✪0

 VOLUME FRACTION RESIN
✪.53

 VOLUME FRACTION FIBER
✪.47

 ENTER ASPECT RATIO OF THE FIBER
✪2.
```

☐*This low value for the aspect ratio is associated with pronounced fiber curvature and/or very short fiber lengths.*

```
 THE STATE OF ORIENTATION OF THE FIBER IS SPECIFIED
 BY THE HERMANS ORIENTATION FACTOR, F.
 FOR PLANAR RANDOM F = 0
 FOR PERFECTLY ALIGNED F = 1.

 IF YOU WISH DATA FOR A SPECIFIED ORIENTATION ENTER A "0" (ZERO)
 IF YOU WISH TO SCAN OVER A RANGE OF ORIENTATIONS ENTER A "1" (ONE)
```

☐*The user elects to scan over the possible range of orientation.*

```
✪1

 ENTER THE STARTING VALUE FOR "F"
✪0.

 ENTER THE FINAL VALUE FOR "F"
✪1.

 ENTER THE INCREMENTS FOR STEPPING VALUES OF "F"
✪.25
```

☐ *The input data is summarized for convenience and the predicted properties displayed for the various orientations.*

```
INPUT DATA
               RESIN          FIBER
-----------------------------------
E1          .5100E+06      .1830E+08
E2          .5100E+06      .1830E+07
E3          .5100E+06      .1830E+07
G12         .1960E+06      .6880E+07
G13         .1960E+06      .6880E+07
G23         .1960E+06      .6880E+06
POS12          .301           .300
POS13          .301           .300
POS23          .301           .300

VOLUME FRACTIONS:
          RESIN    .530
          FIBER    .470

ASPECT RATIO      2.0


CALCULATED DATA

ORIENTATION                            0.00
LONGITUDINAL YOUNG'S MODULUS       .3065E+07
TRANSVERSE YOUNG'S MODULUS         .3065E+07
PERPENDICULAR YOUNG'S MODULUS      .1158E+07
2,3 SHEAR MODULUS                  .8269E+06
1,3 SHEAR MODULUS                  .8269E+06
1,2 SHEAR MODULUS                  .1300E+07
1,2 POISSON'S RATIO                   .178
1,3 POISSON'S RATIO                   .439
2,3 POISSON'S RATIO                   .439


ORIENTATION                            0.25
LONGITUDINAL YOUNG'S MODULUS       .3547E+07
TRANSVERSE YOUNG'S MODULUS         .2563E+07
PERPENDICULAR YOUNG'S MODULUS      .1155E+07
2,3 SHEAR MODULUS                  .7211E+06
1,3 SHEAR MODULUS                  .9327E+06
1,2 SHEAR MODULUS                  .1304E+07
1,2 POISSON'S RATIO                   .215
1,3 POISSON'S RATIO                   .455
2,3 POISSON'S RATIO                   .418
```

```
ORIENTATION                              0.50
LONGITUDINAL YOUNG'S MODULUS          .4027E+07
TRANSVERSE YOUNG'S MODULUS            .2065E+07
PERPENDICULAR YOUNG'S MODULUS         .1149E+07
2,3 SHEAR MODULUS                     .6152E+06
1,3 SHEAR MODULUS                     .1039E+07
1,2 SHEAR MODULUS                     .1300E+07
1,2 POISSON'S RATIO                     .266
1,3 POISSON'S RATIO                     .466
2,3 POISSON'S RATIO                     .395


ORIENTATION                              0.75
LONGITUDINAL YOUNG'S MODULUS          .4505E+07
TRANSVERSE YOUNG'S MODULUS            .1576E+07
PERPENDICULAR YOUNG'S MODULUS         .1135E+07
2,3 SHEAR MODULUS                     .5094E+06
1,3 SHEAR MODULUS                     .1144E+07
1,2 SHEAR MODULUS                     .1285E+07
1,2 POISSON'S RATIO                     .341
1,3 POISSON'S RATIO                     .470
2,3 POISSON'S RATIO                     .373


ORIENTATION                              1.00
LONGITUDINAL YOUNG'S MODULUS          .4987E+07
TRANSVERSE YOUNG'S MODULUS            .1107E+07
PERPENDICULAR YOUNG'S MODULUS         .1107E+07
2,3 SHEAR MODULUS                     .4036E+06
1,3 SHEAR MODULUS                     .1250E+07
1,2 SHEAR MODULUS                     .1250E+07
1,2 POISSON'S RATIO                     .459
1,3 POISSON'S RATIO                     .459
2,3 POISSON'S RATIO                     .352

STOP

END OF EXECUTION
CPU TIME: 0.99  ELAPSED TIME: 3:52.92
EXIT
```

EXAMPLE 2b

The purpose of this example is to illustrate the use of SMC3 to obtain the properties of a two component unidirectional laminate of continuous glass fibers. In this example, stored properties will be used.

☐ Data input by the user will be indicated by the symbol ✪.

☐ Comments are given in italics.

```
 ENTER NUMBER OF COMPONENTS:
 FOR RESIN/FIBER SYSTEM NUMB = 2
 FOR RESIN/FIBER/FILLER SYSTEM NUMB = 3
✪2

 TYPICAL PROPERTIES FOR A TWO COMPONENT
 POLYESTER/E-GLASS FIBER SYSTEM ARE:

           YOUNG'S MODULUS   SHEAR MODULUS   POISSON'S RATIO
 ----------------------------------------------------------
 RESIN        .5100E+06        .1960E+06           .301
 FIBER        .1050E+08        .3940E+07           .333

 IF THESE VALUES ARE ACCEPTABLE, ENTER A "0" (ZERO)
 IF YOU WISH TO USE SIGNIFICANTLY DIFFERENT VALUES ENTER A "1" (ONE)
✪0

 IF THE COMPOSITION IS TO BE ENTERED AS VOLUME FRACTIONS,
 ENTER A "0" (ZERO)
 IF THE COMPOSITION IS TO BE ENTERED AS WEIGHT FRACTIONS,
 ENTER A "1" (ONE)
✪0

 VOLUME FRACTION RESIN
✪.6

 VOLUME FRACTION FIBER
✪.4
```

```
 ENTER ASPECT RATIO OF THE FIBER
✪1000000.
```

☐*The value of 1000000 for the aspect ratio is used to represent a continuous fiber.*

```
 THE STATE OF ORIENTATION OF THE FIBER IS SPECIFIED
 BY THE HERMANS ORIENTATION FACTOR, F.
 FOR PLANAR RANDOM F = 0
 FOR PERFECTLY ALIGNED F = 1.
```

☐*Since the properties of a unidirectional laminate are desired, the orientation factor is set at unity to represent aligned fibers.*

```
 IF YOU WISH DATA FOR A SPECIFIED ORIENTATION ENTER A "0" (ZERO)
 IF YOU WISH TO SCAN OVER A RANGE OF ORIENTATIONS ENTER A "1" (ONE)
✪0

 ENTER SPECIFIC STATE OF ORIENTATION
✪1.
```

☐*The input data is summarized for convenience and the predicted properties displayed. (Note that the "star field" for the aspect ratio indicates a continuous fiber with an infinite aspect ratio.)*

```
 INPUT DATA
              YOUNG'S MODULUS   SHEAR MODULUS   POISSON'S RATIO
 ----------------------------------------------------------------
 RESIN         .5100E+06         .1960E+06          .301
 FIBER         .1050E+08         .3940E+07          .333

 VOLUME FRACTIONS:
              RESIN    .600
              FIBER    .400

 ASPECT RATIO  *******
```

```
CALCULATED DATA

ORIENTATION                          1.00
LONGITUDINAL YOUNG'S MODULUS      .4506E+07
TRANSVERSE YOUNG'S MODULUS        .1249E+07
PERPENDICULAR YOUNG'S MODULUS     .1249E+07
2,3 SHEAR MODULUS                 .4574E+06
1,3 SHEAR MODULUS                 .5589E+06
1,2 SHEAR MODULUS                 .5589E+06
1,2 POISSON'S RATIO                 .319
1,3 POISSON'S RATIO                 .319
2,3 POISSON'S RATIO                 .365

STOP

END OF EXECUTION
CPU TIME: 0.54  ELAPSED TIME: 1:19.02
```

```
CALCULATED DATA

ORIENTATION                             1.00
LONGITUDINAL YOUNG'S MODULUS         .4506E+07
TRANSVERSE YOUNG'S MODULUS           .1249E+07
PERPENDICULAR YOUNG'S MODULUS        .1249E+07
2,3 SHEAR MODULUS                    .4574E+06
1,3 SHEAR MODULUS                    .5589E+06
1,2 SHEAR MODULUS                    .5589E+06
1,2 POISSON'S RATIO                     .319
1,3 POISSON'S RATIO                     .319
2,3 POISSON'S RATIO                     .365

STOP

END OF EXECUTION
CPU TIME: 0.54  ELAPSED TIME: 1:19.02
```

FORTRAN Listing

Internal documentation for SMC-3 is provided by "Comment" statements to define variables, specify operations, and indicate program flow at the appropriate locations.

```
C            -------------
C            PROGRAM SMC-3
C            -------------
C
C    THIS PROGRAM WRITTEN BY:
C
C    DR. R. L. MCCULLOUGH
C    UNIVERSITY OF DELAWARE
C    NEWARK, DELAWARE
C
C    STUART MCGEE
C    UNIVERSITY OF DELAWARE
C    NEWARK, DELAWARE
C
C    JUNE 4, 1979  (LAST REVISION)
C
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C      THIS PROGRAM USES THE WU-MCCULLOUGH RELATIONSHIP IN
C    CONJUNCTION WITH THE AGGREGATE MODEL TO PREDICT PROPERTIES
C    FOR TWO COMPONENT (RESIN/FIBER) OR THREE COMPONENT
C    (RESIN/FIBER/FILLER) SHEET MOLDING COMPOUNDS.
C
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C           MATERIAL SPECIFICATION
C
C      THE MINIMUM DATA REQUIRED FOR THE EXECUTION OF THE
C    PROGRAM IS:
C
C      V2(K) THE VOLUME FRACTION OF PHASE K (K=1,RESIN,
C            K=2,FIBER, K=3,FILLER)
C      AA2   THE EFFECTIVE ASPECT RATIO OF THE FIBER
C      F     THE STATE OF ORIENTATION OF THE FIBERS
C
```

```
C         STANDARD VALUES FOR THE YOUNG'S MODULUS, SHEAR MODULUS,
C       AND POISSON'S RATIO FOR POLYESTER RESIN, E-GLASS FIBERS,
C       AND CALCIUM CARBONATE FILLER ARE STORED INTERNALLY.
C       THESE VALUES MAY BE ALTERED UNDER CONTROL OF THE USER
C       DURING EXECUTION OF THE PROGRAM.  PROVISION IS MADE TO
C       ACCEPT WEIGHT FRACTION VARIABLES IN LIEU OF VOLUME
C       FRACTION VARIABLES.  THE USE OF WEIGHT FRACTION
C       VARIABLES REQUIRES INPUT FOR THE DENSTIY OF EACH
C       COMPONENT.
C
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C                       PROGRAM SUBROUTINES
C
C         THE PROGRAM IS SEGMENTED UNDER THE FOLLOWING SUB-
C       ROUTINES:
C
C       INPUT   THIS SUBROUTINE PROVIDES AN INTERACTIVE MODE FOR
C               DATA ACQUISITION.  CONSISTENCY CHECKS ARE
C               PROVIDED ON VOLUME FRACTION (OR WEIGHT FRACTION)
C               VARIABLES.
C
C               CALLS:  ALTER, PRINT1, PRINT2
C
C       ALTER   THIS SUBROUTINE PROVIDES FOR REPLACING ANYONE
C               OR ALL OF THE STORED VALUES FOR THE PROPERTIES
C               OF THE RESIN, FIBER, AND/OR FILLER PHASE WITH A
C               SET SELECTED BY THE USER.  ALTERED VALUES OF
C               YOUNG'S MODULUS, SHEAR MODULUS AND POISSON'S
C               RATIO ARE CHECKED FOR CONSISTENCY WHEN THE
C               INTPUT IS FOR AN ISOTROPIC MATERIAL.
C
C               CALLS:  CHECK
C
C       CHECK   THIS SUBROUTINE CHECKS ALTERED VALUES OF YOUNG'S
```

```
      DIMENSION RESIN(6,6),FIBER(6,6),FILLER(6,6),CZERO(6,6)
      COMMON /B1/ NREAD,NWRITE
      COMMON /B3/ E1(3),E2(3),E3(3),G12(3),G13(3),G23(3),POS12(3),
     CPOS13(3),POS23(3),V2(3),AA2,FSTART,FSTOP,FADD
C---THE FOLLOWING DATA FILES CONTAIN THE TYPICAL VALUES FOR
C-- THE PROPERTIES OF THE COMPONENTS IN THE ORDER RESIN/FIBER/
C-- FILLER
      DATA E1/.51E6,.105E8,.693E7/,G12/.196E6,.394E7,.262E7/
      DATA E2/.51E6,.105E8,.693E7/,G13/.196E6,.394E7,.262E7/
      DATA E3/.51E6,.105E8,.693E7/,G23/.196E6,.394E7,.262E7/
      DATA POS12/.301,.333,.323/,POS13/.301,.333,.323/
      DATA POS23/.301,.33,.323/,ISO/0/
C---DATA FILE FOR OUTPUT TALBES AND DEVICE NUMBERS FOR INPUT
C-- (NREAD) AND FOR OUTPUT (NWRITE)
      DATA PHASE/5HRESIN,5HFIBER,5HFILLE,2*1H ,1HR/
      DATA NREAD,NWRITE/5,5/
C---CALL ON THE SUBROUTINE INPUT TO ENTER THE DATA INTO THE
C-- PROGRAM
C---ALL MAJOR VARIABLES ARE TRANSFERED THROUGH COMMON BLOCKS
      CALL INPUT(NUMB,ISO)
C---PRINT A SUMMARY OF THE INPUT DATA
      WRITE(NWRITE,10)
   10 FORMAT(//2X,10HINPUT DATA)
      IF(ISO .EQ. 0) CALL PRINT1(NUMB)
      IF(ISO .EQ. 1) CALL PRINT2(NUMB)
      WRITE(NWRITE,20) (PHASE(I),PHASE(I+3),V2(I),I=1,NUMB)
   20 FORMAT(/2X,17HVOLUME FRACTIONS:/(12X,A5,A1,1X,F5.3))
      WRITE(NWRITE,30) AA2
   30 FORMAT(/2X,12HASPECT RATIO,2X,F7.1)
C---CONVERT ENGINEERING CONSTANTS TO ELASTIC CONSTANTS
      CALL ELAST(1,RESIN)
      CALL ELAST(2,FIBER)
      CALL ELAST(3,FILLER)
C---CONSTRUCT SURROGATE MATRIX PHASE WHICH HAS THE PROPERTIES
C-- OF THE RESIN/FILLER SYSTEM
```

```
      CALL AMATIN(AAA,TRANS,NDUM)
      DO 80 K=1,6
      DO 80 J=1,6
       CSTAR(K,J)=CZERO(K,J)+TRANS(K,J)
C---CSTAR IS THE ELASTIC CONSTANT ARRAY FOR THE MICROLAMINATE
   80 CONTINUE
      WRITE(NWRITE,90)
   90 FORMAT(//2X,15HCALCULATED DATA)
      DO 120 L=1,50
      F=FSTART+FADD*FLOAT(L-1)
      IF(F .GT. FSTOP) GO TO 130
C---COMPUTE ORIENTATION AVERAGE OF AN AGGREGATE OF MICRO-
C-- LAMINATES
      CALL PLANAR(1.,F,CSTAR,TRANS)
      CALL AMATIN(TRANS,S,NDUM)
C---CONVERT TO ENGINEERING CONSTANTS
       DO 100 K=1,6
        EC(K)=1./S(K,K)
  100  CONTINUE
       EC(7)=- EC(1)*S(1,2)
       EC(8)=- EC(1)*S(1,3)
       EC(9)=- EC(2)*S(2,3)
C---PRINT THE CALCULATED DATA
      WRITE(NWRITE,110) F,(EC(J),J=1,9)
  110 FORMAT(/2X,11HORIENTATION,24X,F5.2/2X,12HLONGITUDINAL,
     C1X,15HYOUNG'S MODULUS,4X,E10.4/2X,10HTRANSVERSE,1X
     C15HYOUNG'S MODULUS,6X,E10.4/2X,13HPERPENDICULAR,1X
     C15HYOUNG'S MODULUS,3X,E10.4/2X,17H2,3 SHEAR MODULUS,15X
     CE10.4/2X,17H1,3 SHEAR MODULUS,15X,E10.4/2X,3H1,2,1X,
     C13HSHEAR MODULUS,15X,E10.4/2X,13H1,2 POISSON'S,1X
     C5HRATIO,16X,F5.3/2X,19H1,3 POISSON'S RATIO,16X,F5.3/
     C2X,19H2,3 POISSON'S RATIO,16X,F5.3/)
  120 CONTINUE
  130 STOP
      END
```

```
C                   MODULUS, SHEAR MODULUS, AND POISSON'S RATIO
C                   FOR SELF-CONSISTENCY
C
C           PRINT1  THIS ROUTINE IS USED TO PRINT THE PROPERTY
C                   DATA FOR ISOTROPIC MATERIALS.
C
C           PRINT2  THIS ROUTINE IS USED TO PRINT THE PROPERTY
C                   DATA FOR ANISOTROPIC MATERIALS.
C
C           ELAST   THIS SUBROUTINE CONVERTS ENGINEERING CONSTANTS
C                   (YOUNG'S MODULUS, SHEAR MODULUS, AND POISSON'S
C                   RATIO) INTO THE 6X6 ARRAY OF ELASTIC CONSTANTS,
C                   "C(K)", FOR THE K'TH PHASE COMPONENT.
C
C           SMIX    THIS SUBROUTINE IS USED TO GENERATE PROPERTIES
C                   FOR THE SPECIAL CASE OF PARTICULATE SYSTEMS.
C                   (THE ASPECT RATIO IS SET TO 1.)
C
C                   CALLS:  EMAKE,COMP,AMATIN
C
C           COMP    THIS SUBROUTINE COMPENSATES THE PROPERTIES OF
C                   EACH PHASE COMPONENT FOR CORRELATION EFFECTS.
C
C                   CALLS:  AMATIN
C
C           AMATIN  A SPECIAL MATRIX INVERSION ROUTINE WHICH
C                   MAKES USE OF SYMMETRY FOR MORE EFFICIENT
C                   INVERSIONS.
C
C           PLANAR  THIS SUBROUTINE GENERATES THE AVERAGE PROPERTIES
C                   OF A SYSTEM IN THE STATE OF PLANAR ORIENTATION
C                   CHARACTERIZED BY THE ORIENTATION FACTOR, F.
C
          DIMENSION CM(6,6),EZERO(6,6),BIGM(6,6),TRANS(6,6),CSTAR(6,6)
          DIMENSION AAA(6,6),S(6,6),EC(9),NDUM(4),PHASE(6)
```

```
      VS=V2(1)+V2(3)
      VHI=V2(3)/VS
C---VHI IS THE APPARENT VOLUME FRACTION OF FILLER IF NO FIBER
C-- WERE PRESENT
      CALL SMIX(VHI,RESIN,FILLER,CM)
C---CM IS THE 6X6 ELASTIC CONSTANT ARRAY FOR THE SURROGATE
C-- MATRIX PHASE
C---COMPUTE REFERENCE PHASE CZERO
      VX=V2(2)
      CALL SMIX(VX,CM,FIBER,CZERO)
C---COMPUTE PROPERTIES OF MICROLAMINATE FROM
C--      CSTAR = CZERO + (BIGM**-1 + EZERO)**-1
      CALL EMAKE(EZERO,CZERO,AA2)
      DO 40 K=1,6
      DO 40 J=1,6
       BIGM(K,J)=0.
   40 CONTINUE
C---COMPUTE COMPENSATED PROPERTIES OF SURROGATE MATRIX
      CALL COMP(CZERO,CM,EZERO,TRANS)
      DO 50 K=1,6
      DO 50 J=1,6
       BIGM(K,J)=BIGM(K,J)+(1.-VX)*TRANS(K,J)
   50 CONTINUE
C---COMPUTE COMPENSATED PROPENTIES OF FIBER PHASE
      CALL COMP(CZERO,FIBER,EZERO,TRANS)
      DO 60 K=1,6
      DO 60 J=1,6
       BIGM(K,J)=BIGM(K,J)+VX*TRANS(K,J)
   60 CONTINUE
C---TRANS IS THE INVERSE OF BIGM
      CALL AMATIN(BIGM,TRANS,NDUM)
      DO 70 K=1,6
      DO 70 J=1,6
       AAA(K,J)=TRANS(K,J)+EZERO(K,J)
   70 CONTINUE
```

```
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE INPUT(NUMB,ISO)
C
C         THIS SUBROUTINE IS AN INTERACTIVE ROUTINE FOR OBTAINING
C       INPUT DATA.
C
C         TYPICAL PROPERTIES FOR POLYESTER RESIN, E-GLASS FIBERS
C       AND CALCIUM CARBONATE FILLER ARE STORED INTERNALLY.
C       THESE VALUES CAN BE ALTERED BY THE USER DURING PROGRAM
C       EXECUTION.  THE ALTERED VALUES WILL BE CHECKED FOR
C       SELF-CONSISTENCY.
C
C         PHASE CONCENTRATIONS MAY BE ENTERED EITHER AS VOLUME
C       OR WEIGHT FRACTIONS.  CONCENTRATIONS ENTERED AS WEIGHT
C       FRACTIONS WILL BE CONVERTED INTERNALLY TO VOLUME
C       FRACTIONS.  BOTH VOLUME AND WEIGHT FRACTION VARIABLES
C       WILL BE TESTED FOR CONSISTENCY.
C
C         THE EFFECTIVE ASPECT RATIO IS ENTERED AS A UNITLESS
C       QUANTITY IN THE RANGE OF 0. TO 100,000.  THE ASPECT
C       RATIO OF A SPHERICAL INCLUSION IS 1.
C
C         THE STATE OF ORIENTATION IS SPECIFIED BY THE HERMANS
C       ORIENTATION FACTOR "F".  PROVISIONS ARE AVAILABLE
C       TO ACCEPT A SINGLE VALUE FOR "F" OR TO CONDUCT
C       A SCAN FROM 0 (RANDOM) TO 1 (PERFECT ALIGNMENT) IN
C       SPECIFIED STEPS.
C
C         ROUTINES CALLED:
C               ALTER
C               PRINT1
C               PRINT2
C
      COMMON /B1/ NREAD,NWRITE
      COMMON /B3/ E1(3),E2(3),E3(3),G12(3),G13(3),G23(3),POS12(3),
```

```
     CPOS13(3),POS23(3),V2(3),AA2,FSTART,FSTOP,FADD
      DIMENSION PHASE(6),DELT(3),DEN(3),DX(3)
C---SET HEADINGS FOR OUTPUT TABLES
      DATA PHASE/5HRESIN,5HFIBER,5HFILLE,2*1H ,1HR/
C---ENTER NUMBER OF COMPONENTS (NUMB)
      WRITE(NWRITE,10)
   10 FORMAT(2X,27HENTER NUMBER OF COMPONENTS:/2X,9HFOR RESIN
     C22H/FIBER SYSTEM NUMB = 2/2X,22HFOR RESIN/FIBER/FILLER,1X
     C15HSYSTEM NUMB = 3)
   20 READ(NREAD,30) NUMB
   30 FORMAT(I1)
      IF(NUMB .EQ. 2 .OR. NUMB .EQ. 3) GO TO 50
      WRITE(NWRITE,40)
   40 FORMAT(2X,19H* * INPUT ERROR * *//2X,16HRE-ENTER NUMBER
     C13HOF COMPONENTS  )
      GO TO 20
C---PRINT THE STANDARD PROPERTIES FOR THE PROPER SYSTEM
   50 IF(NUMB .EQ. 2) WRITE(NWRITE,60)
      IF(NUMB .EQ. 3) WRITE(NWRITE,70)
   60 FORMAT(2X,38HTYPICAL PROPERTIES FOR A TWO COMPONENT/
     C2X,35HPOLYESTER/E-GLASS FIBER SYSTEM ARE:  //)
   70 FORMAT(2X,40HTYPICAL PROPERTIES FOR A THREE COMPONENT  /
     C2X47HPOLYESTER/E-GLASS/CALCIUM CARBONATE SYSTEM ARE:  //)
      CALL PRINT1(NUMB)
C---CHECK TO SEE IF THESE ARE ACCEPTABLE VALUES
      WRITE(NWRITE,80)
   80 FORMAT(//2X,44HIF THESE VALUES ARE ACCEPTABLE, ENTER A "0"
     C6H(ZERO)/2X,43HIF YOU WISH TO USE SIGNIFICANTLY DIFFERENT
     C24HVALUES ENTER A "1" (ONE)  )
      READ (5,30) MALTER
      IF(MALTER .EQ. 0) GO TO 120
   90 CALL ALTER(NUMB,ISO)
C---PRINT THE ALTERED PROPERTIES FOR THE BENEFIT OF THE USER
      IF(NUMB .EQ. 2) WRITE(NWRITE,100)
  100 FORMAT(2X,42HTHE CURRENT SET OF PROPERTIES FOR THE TWO  /
```

```
      C2X,21HCOMPONENT SYSTEM ARE:  //)
       IF(NUMB .EQ. 3) WRITE(NWRITE,110)
  110 FORMAT(2X,44HTHE CURRENT SET OF PROPERTIES FOR THE THREE /
      C2X,21HCOMPONENT SYSTEM ARE:  //)
       IF(ISO .EQ. 0) CALL PRINT1(NUMB)
       IF(ISO .EQ. 1) CALL PRINT2(NUMB)
       WRITE(NWRITE,80)
       READ(NREAD,30) MALTER
       IF(MALTER .EQ. 1) GO TO 90
C---DETERMINE HOW COMPOSITION IS TO BE ENTERED
  120 WRITE(NWRITE,130)
  130 FORMAT(//2X,45HIF THE COMPOSITION IS TO BE ENTERED AS VOLUME
      C11H FRACTIONS,/2X,18HENTER A "0" (ZERO)/2X,7HIF THE
      C49HCOMPOSITION IS TO BE ENTERED AS WEIGHT FRACTIONS,
      C/2X,17HENTER A "1" (ONE)  )
       READ(NREAD,30) MCOMP
       IF(MCOMP .EQ. 1) GO TO 180
C---ENTER COMPOSITION AS VOLUME FRACTIONS
  140 TEST=0.
       DO 160 K=1,NUMB
       WRITE(NWRITE,150) PHASE(K),PHASE(K+3)
  150 FORMAT(2X,16HVOLUME FRACTION ,A5,A1)
       READ(NREAD,*) V2(K)
       TEST=TEST+V2(K)
  160 CONTINUE
C---TEST TO SEE IF THE FRACTIONS SUM TO ONE
       TI=ABS(TEST-1.)
       IF(TI .LT. .001) GO TO 250
       WRITE(NWRITE,170)
  170 FORMAT(2X,19H* * INPUT ERROR * *//2X,13HTHE FRACTIONS
      C20H DO NOT SUM TO UNITY /2X,17HRE-ENTER THE DATA   )
       GO TO 140
C---ENTER COMPOSITION AS WEIGHT FRACTIONS
  180 TEST=0.
       DO 210 K=1,NUMB
```

```
      WRITE(NWRITE,190) PHASE(K),PHASE(K+3)
  190 FORMAT(2X,19HWEIGHT FRACTION OF ,A5,A1)
      READ(NREAD,*) DX(K)
      WRITE(NWRITE,200) PHASE(K),PHASE(K+3)
  200 FORMAT(2X,10HDENSITY OF,1X,A5,A1)
      READ(NREAD,*) DEN(K)
      TEST=TEST+DX(K)
  210 CONTINUE
C---TEST TO SEE IF THE FRACTIONS SUM TO ONE
      TI=ABS(1.-TEST)
      IF(TI .LT. .001) GO TO 220
      WRITE(NWRITE,170)
      GO TO 180
  220 CONTINUE
C---CONVERT THE WEIGHT FRACTIONS TO VOLUME FRACTIONS
      SUM=0.
      DO 230 K=1,NUMB
      DELT(K)=DX(K)/DEN(K)
      SUM=SUM+DELT(K)
  230 CONTINUE
      DO 240 K=1,NUMB
      V2(K)=DELT(K)/SUM
  240 CONTINUE
  250 CONTINUE
C---ENTER FIBER'S ASPECT RATIO
      WRITE(NWRITE,260)
  260 FORMAT(2X,31HENTER ASPECT RATIO OF THE FIBER )
      READ(NREAD,*) AA2
C---ENTER PARAMETERS CONCERNING THE ORIENTATION PARAMETER "F"
      WRITE(NWRITE,270)
  270 FORMAT(2X,41HTHE STATE OF ORIENTATION OF THE FIBER IS
     C9HSPECIFIED/2X,34HBY THE HERMANS ORIENTATION FACTOR,1X
     C2HF./2X,23HFOR PLANAR RANDOM F = 0/2X,13HFOR PERFECTLY,1X
     C14HALIGNED F = 1.//2X,33HIF YOU WISH DATA FOR A SPECIFIED
     C30HORIENTATION ENTER A "0" (ZERO)/2X,15HIF YOU WISH TO
```

```
     C51HSCAN OVER A RANGE OF ORIENTATIONS ENTER A "1" (ONE) )
      READ(NREAD,30) MORN
      IF(MORN .EQ. 1) GO TO 290
      WRITE(NWRITE,280)
  280 FORMAT(2X,35HENTER SPECIFIC STATE OF ORIENTATION)
      READ(NREAD,*) FSTART
      FSTOP=FSTART
      FADD=.1
      GO TO 330
  290 WRITE(NWRITE,300)
  300 FORMAT(2X,32HENTER THE STARTING VALUE FOR "F")
      READ(NREAD,*) FSTART
      WRITE(NWRITE,310)
  310 FORMAT(2X,29HENTER THE FINAL VALUE FOR "F")
      READ(NREAD,*) FSTOP
      WRITE(NWRITE,320)
  320 FORMAT(2X,47HENTER THE INCREMENTS FOR STEPPING VALUES OF "F")
      READ(NREAD,*) FADD
  330 CONTINUE
      RETURN
      END
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE ALTER(NUMB,ISO)
C
C         THIS SUBROUTINE PROVIDES FOR REPLACING THE STORED
C       VALUES OF YOUNG'S MODULUS, SHEAR MODULUS, AND POISSON'S
C       RATIO FOR ANYONE OR ALL OF THE COMPONENTS BY A SET OF
C       VALUES SELECTED BY THE USER.  IF THE NEW SET OF
C       VALUES IS TO BE USED TO REPRESENT A TRANSVERSELY
C       ISOTROPIC FIBER, THE USER WILL BE REQUIRED TO SUPPLY
C       TWO VALUES FOR THE YOUNG'S MODULUS (LONGITUDINAL AND
C       TRANSVERSE), TWO VALUES FOR THE SHEAR MODULUS, AND
C       TWO VALUES FOR THE POISSON'S RATIO.  ALTERED VALUES
C       WILL BE TESTED FOR SELF-CONSISTENCY.
C
```

```
C        INPUT:
                 NUMB    NUMBER OF COMPONENTS
                 MALT    FLAG TO INDICATE THAT THE STORED
                         VALUES ARE TO ALTERED
                 ISO     FLAG WHICH INDICATES WHETHER THE
                         FIBER PHASE IS ISOTROPIC (ISO=0)
                         OR ANISOTROPIC (ISO=1)
C
C        INPUT/OUTPUT:
C                E1(I)   THE LONGITUDINAL YOUNG'S MODULUS FOR
C                        PHASE I
C                E2(I)   THE TRANSVERSE YOUNG'S MODULUS FOR
C                        PHASE I
C                E3(I)   THE PERPENDICULAR YOUNG'S MODULUS FOR
C                        PHASE I
C               G12(I)   THE "1,2" SHEAR MODULUS FOR PHASE I
C               G13(I)   THE "1,3" SHEAR MODULUS FOR PHASE I
C               G23(I)   THE "2,3" SHEAR MODULUS FOR PHASE I
C             POS12(I)   THE "1,2" POISSON'S RATIO FOR PHASE I
C             POS13(I)   THE "1,3" POISSON'S RATIO FOR PHASE I
C             POS23(I)   THE "2,3" POISSON'S RATIO FOR PHASE I
C
C        FOR THE ABOVE ARRAYS:
C           I=1, RESIN PHASE
C           I=2, FIBER PHASE
C           I=3, FILLER PHASE
C
C        ROUTINES CALLED:
C           CHECK
C
      COMMON /B1/ NREAD,NWRITE
      COMMON /B3/ E1(3),E2(3),E3(3),G12(3),G13(3),G23(3),POS12(3),
     CPOS13(3),POS23(3),V2(3),AA2,FSTART,FSTOP,FADD
      DIMENSION PHASE(6)
      DATA PHASE/5HRESIN,5HFIBER,5HFILLE,2*1H ,1HR/
```

```
      DO 160 I=1,NUMB
C---DETERMINE IF THE I-TH PHASE PROPERTIES ARE TO BE CHANGED
      WRITE(NWRITE,10) PHASE(I),PHASE(I+3)
   10 FORMAT(2X,3HIF ,A5,A1,27H PROPERTIES ARE ACCEPTABLE
     C18HENTER A "0" (ZERO)/2X,25HIF THEY ARE TO BE ALTERED
     C18H ENTER A "1" (ONE))
      READ(NREAD,20) MALT
   20 FORMAT(I1)
      IF(MALT .EQ. 0) GO TO 160
      IF(I .EQ. 1 .OR. I .EQ. 3) GO TO 100
C---ENTER SYMMETRY OF FIBER
      WRITE(NWRITE,30)
   30 FORMAT(2X,40HIF FIBER IS ISOTROPIC ENTER A "0" (ZERO)/
     C2X,51HIF FIBER IS ANISOTROPIC (E.G. GRAPHITE) ENTER A "1"
     C,6H (ONE))
      READ(NREAD,35) ISO
   35 FORMAT(I1)
      IF(ISO .EQ. 0) GO TO 100
C---DETERMINE PROPERTIES FOR AN ANISOTROPIC FIBER
      WRITE(NWRITE,40)
   40 FORMAT(2X,34HENTER LONGITUDINAL YOUNG'S MODULUS)
      READ(NREAD,*) E1(2)
      WRITE(NWRITE,50)
   50 FORMAT(2X,32HENTER TRANSVERSE YOUNG'S MODULUS)
      READ(NREAD,*) E2(2)
      E3(2)=E2(2)
      WRITE(NWRITE,60)
   60 FORMAT(2X,24HENTER SHEAR MODULUS, G12)
      READ(NREAD,*) G12(2)
      G13(2)=G12(2)
      WRITE(NWRITE,70)
   70 FORMAT(2X,24HENTER SHEAR MODULUS, G23)
      READ(NREAD,*) G23(2)
      WRITE(NWRITE,80)
   80 FORMAT(2X,28HENTER POISSON'S RATIO, POS12  )
```

```
      READ(NREAD,*) POS12(2)
      POS13(2)=POS12(2)
      WRITE(NWRITE,90)
   90 FORMAT(2X,28HENTER POISSON'S RATIO, POS23   )
      READ(NREAD,*) POS23(2)
      GO TO 160
C---ENTER THE PROPERTIES FOR AN ISOTROPIC PHASE
  100 WRITE(NWRITE,110)PHASE(I),PHASE(I+3)
  110 FORMAT(2X,26HENTER YOUNG'S MODULUS FOR ,A5,A1)
      READ(NREAD,*) E1(I)
      E2(I)=E1(I)
      E3(I)=E1(I)
      WRITE(NWRITE,120) PHASE(I),PHASE(I+3)
  120 FORMAT(2X,24HENTER SHEAR MODULUS FOR ,A5,A1)
      READ(NREAD,*) G12(I)
      G13(I)=G12(I)
      G23(I)=G12(I)
      WRITE(NWRITE,130) PHASE(I),PHASE(I+3)
  130 FORMAT(2X,26HENTER POISSON'S RATIO FOR ,A5,A1)
      READ(NREAD,*) POS
C---CHECK FOR SELF-CONSISTENCY OF NEW INPUT DATA
  140 CALL CHECK(POS,G12(I),E1(I),P,MK)
      IF(MK .EQ. 1) GO TO 100
  150 POS12(I)=P
      POS13(I)=P
      POS23(I)=P
  160 CONTINUE
      RETURN
      END
```

```
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE CHECK(POS,G,E,P,MK)
C---THIS SUBROUTINE CHECKS THE INPUT POISSON'S RATIO, POS,
C-- AGAINST POS=.5*(E/G)-1. TO ASSURE THAT THE INPUT IS
C-- CONSISTANT WITH AN ISOTROPIC MATERIAL
C
C       INPUT:
C               POS     INPUT POISSON'S RATIO
C               G       INPUT SHEAR MODULUS
C               E       INPUT YOUNG'S MODULUS
C
C       OUTPUT:
C               P       VALUE OF POISSON'S RATIO CONSISTANT
C                       WITH THE INPUT YOUNG'S MODULUS AND
C                       INPUT SHEAR MODULUS
C               MK      FLAG INDICATING SUCCESS OF NEW INPUT
C                       OPERATION
C
      COMMON /B1/ NREAD,NWRITE
      P=0.5*(E/G)-1.0
      IF(P.GT. 0. .AND. P .LT. .5) GO TO 20
C---THERE HAS BEEN AN INPUT ERROR, VALUES ARE UNACCEPTABLE
      WRITE(NWRITE,10)
   10 FORMAT(2X,19H* * INPUT ERROR * *//2X,9HFOR INPUT,1X
     C47HVALUES OF THE YOUNG'S MODULUS AND SHEAR MODULUS/2X,
     C44HPOISSON'S RATIO WOULD BE NEGATIVE OR GREATER,1X
     C8HTHAN 0.5//2X,13HRE-ENTER DATA)
      MK=1
      P=.3
      RETURN
   20 W=ABS(POS-P)
      IF(W .GT. .003) GO TO 30
C---THE ENTERED VALUE FOR POISSON'S RATIO IS ACCEPTABLE AND
C-- NEEDS NOT BE CHANGED
      MK=0
```

```
      P=POS
      RETURN
C---THE ENTERED POISSON'S RATIO IS INCONSISTENT WITH THE
C-- ENTERED YOUNG'S AND SHEAR MODULI, ASK IF VALUES ARE TO
C-- BE RE-ENTERED OR IF THE ESTIMATED VALUE IS ACCEPTABLE
   30 WRITE(NWRITE,40) P
   40 FORMAT(2X,19H* * INPUT ERROR * *//2X,10HTHE VALUES,1X
     C34HFOR THE MODULI AND POISSON'S RATIO/2X,3HARE,1X
     C38HINCONSISTENT FOR AN ISOTROPIC MATERIAL/2X,3HTHE,1X
     C41HPOISSON'S RATIO HAS BEEN ASSIGNED A VALUE,1X,F5.3)
      WRITE(NWRITE,50)
   50 FORMAT(2X,39HIF THIS ASSIGNMENT IS ACCEPTABLE, ENTER ,1X
     C13HA "0" (ZERO);/2X,27HOTHERWISE ENTER A "1" (ONE)/
     C2X,42HAND PREPARE TO RE-ENTER THE VALUES FOR THE/2X
     C51HYOUNG'S MODULUS, SHEAR MODULUS, AND POISSON'S RATIO)
      READ(NREAD,60) MK
   60 FORMAT(I1)
      RETURN
      END
C* * * * * * * * * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE PRINT1(NUMB)
C---THIS SUBROUTINE IS USED TO PRINT THE INPUT DATA WHEN
C-- ALL PHASES ARE ISOTROPIC
      COMMON /B1/ NREAD,NWRITE
      COMMON /B3/ E1(3),E2(3),E3(3),G12(3),G13(3),G23(3),POS12(3),
     CPOS13(3),POS23(3),V2(3),AA2,FSTART,FSTOP,FADD
      DIMENSION PHASE(6)
      DATA PHASE/5HRESIN,5HFIBER,5HFILLE,2*1H ,1HR/
      WRITE(NWRITE,10) (PHASE(I),PHASE(I+3),E1(I),G12(I),POS12(I),
     CI=1,NUMB)
   10 FORMAT(11X,15HYOUNG'S MODULUS,3X,13HSHEAR MODULUS,3X,
     C15HPOISSON'S RATIO/2X,29(2H--)/(2X,A5,A1,5X,E10.4,
     C7X,E10.4,9X,F5.3))
      RETURN
      END
```

```
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE PRINT2(NUMB)
C---THIS ROUTINE IS USED TO PRINT THE INPUT DATA WHEN
C-- THE FIBER PHASE IS ANISOTROPIC
      COMMON /B1/ NREAD,NWRITE
      COMMON /B3/ DATA(3,10),AA2,FSTART,FSTOP,FADD
C---SET HEADINGS FOR OUTPUT
      DIMENSION TITLE(9),DASH(6),PHASE(6)
      DATA PHASE/5HRESIN,5HFIBER,5HFILLE,2*1H ,1HR/
      DATA DASH/2*5H-----,3H---,2*5H-----,3H---/
      DATA TITLE/2HE1,2HE2,2HE3,3HG12,3HG13,3HG23,5HPOS12,
     C5HPOS13,5HPOS23/
      WRITE(NWRITE,10) (PHASE(I),PHASE(I+3),I=1,NUMB)
   10 FORMAT(13X,A5,A1,7X,A5,A1,6X,A5,A1)
      NDASH=3
      IF(NUMB .EQ. 3) NDASH=6
      WRITE(NWRITE,20) (DASH(L),L=1,NDASH)
   20 FORMAT(2X,9(2H--),2(2A5,A3))
C---TYPE YOUNG'S AND SHEAR MODULI
      DO 40 L=1,6
      WRITE(NWRITE,30) TITLE(L),(DATA(J,L),J=1,NUMB)
   30 FORMAT(2X,A5,3X,3(E10.4,3X))
   40 CONTINUE
C---TYPE POISSON'S RATIOS
      DO 60 L=7,9
      WRITE(NWRITE,50) TITLE(L),(DATA(J,L),J=1,NUMB)
   50 FORMAT(2X,A5,6X,3(F5.3,8X))
   60 CONTINUE
      RETURN
      END
```

```
C* * * * * * * * * ** * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE ELAST(I,C)
C---CONVERTS THE ENGINEERING CONSTANTS (E=YOUNG'S MODULUS,
C-- G=SHEAR MODULUS, POS=POISSON'S RATIO) FOR PHASE "I" TO THE
C-- ARRAY OF ELASTIC CONSTANTS "C(J,K)"
      COMMON /B3/ E1(3),E2(3),E3(3),G12(3),G13(3),G23(3),POS12(3),
     CPOS13(3),POS23(3),V2(3),AA2,FSTART,FSTOP,FADD
      DIMENSION C(6,6)
C---CLEAR THE REGISTARS
      DO 10 K=1,6
      DO 10 J=1,6
      C(K,J)=0.
   10 CONTINUE
      AD=1.-2.*E3(I)/E1(I)*POS12(I)*POS23(I)*POS13(I)
     C-POS13(I)**2*E3(I)/E1(I)-POS23(I)**2*E3(I)/E2(I)-
     CPOS12(I)**2*E2(I)/E1(I)
      D=1./AD
      C(1,1)=E1(I)*D*(1.-((E3(I)/E2(I))*POS23(I)**2))
      C(1,2)=D*(E2(I)*POS12(I)+E3(I)*POS13(I)*POS23(I))
      C(2,2)=D*E2(I)*(1.-((POS13(I)**2)*(E3(I)/E1(I))))
      C(1,3)=D*E3(I)*(POS12(I)*POS23(I)+POS13(I))
      C(2,3)=D*(E3(I)/E1(I))*(E1(I)*POS23(I)+E2(I)*POS
     C12(I)*POS13(I))
      C(3,3)=D*E3(I)*(1.-(E2(I)/E1(I))*(POS12(I)**2))
      C(4,4)=G23(I)
      C(5,5)=G13(I)
      C(6,6)=G12(I)
      C(3,2)=C(2,3)
      C(3,1)=C(1,3)
      C(2,1)=C(1,2)
      RETURN
      END
```

```
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE AMATIN(A,B,NWARN)
C---THIS SUBROUTINE INVERTS A 6X6 MATRIX WHICH HAS THE
C-- FOLLOWING PROPERTIES
C
C         A(I,J)=A(J,I)
C         A(I,J)=0.      FOR I NOT EQUAL J AND
C                        I OR J GREATER THAN 3
      DIMENSION NWARN(4),A(6,6),B(6,6)
      DO 10 K=1,4
       NWARN(K)=0.
   10 CONTINUE
C---CLEAR THE REGISTARS
      DO 20 K=1,6
      DO 20 J=1,6
       B(K,J)=0.
   20 CONTINUE
C---CALCULATE THE DETERMINANT OF THE MATRIX TO BE INVERTED
      DETER=A(1,1)*(A(2,2)*A(3,3)-A(3,2)*A(2,3))-A(1,2)*(A(2,1)
     C*A(3,3)-A(1,3)*A(3,2))+A(1,3)*(A(2,1)*A(3,2)-A(3,1)*
     CA(2,2))
C---CALCULATE THE ELEMENTS OF THE INVERTED MATRIX
   30 B(1,1)=(A(2,2)*A(3,3)-A(3,2)*A(2,3))/DETER
      B(2,2)=(A(1,1)*A(3,3)-A(3,1)*A(1,3))/DETER
      B(3,3)=(A(1,1)*A(2,2)-A(2,1)*A(1,2))/DETER
      B(1,2)=-(A(2,1)*A(3,3)-A(3,1)*A(2,3))/DETER
      B(1,3)=(A(2,1)*A(3,2)-A(2,2)*A(3,1))/DETER
      B(2,3)=-(A(1,1)*A(3,2)-A(3,1)*A(1,2))/DETER
      B(2,1)=B(1,2)
      B(3,1)=B(1,3)
      B(3,2)=B(2,3)
      DO 50 K=4,6
      IF(A(K,K) .NE. 0.) GO TO 40
      KK=K-2
      NWARN(KK)=1
```

```
      B(K,K)=9.99E10
      GO TO 50
   40 B(K,K)=1./A(K,K)
   50 CONTINUE
      RETURN
      END
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE COMP(CZERO,PHASE,EZERO,PHASEM)
C---SUBROUTINE TO COMPUTE PHASE PROPERTIES COMPENSATED FOR
C-- CORRELATIONS
C
C       INPUT:
C               CZERO   THE 6X6 ARRAY OF ELASTIC CONSTANTS FOR
C                       THE REFERENCE PHASE
C               PHASE   THE 6X6 ARRAY OF ELASTIC CONSTANTS FOR
C                       THE CURRENT PHASE
C               EZERO   THE 6X6 ARRAY OF THE CORRELATION TENSOR
C
C       OUTPUT:
C               PHASEM  THE 6X6 ARRAY OF ELASTIC CONSTANTS FOR
C                       THE CURRENT PHASE COMPENSATED FOR
C                       CORRELATIONS
C
C       ROUTINES CALLED:
C               AMATIN
C
      DIMENSION CZERO(6,6),PHASE(6,6),EZERO(6,6),PHASEM(6,6)
      DIMENSION NDUM(4),NWARN(4),AAA(6,6),R(6,6),H(6,6)
C---CLEAR THE REGISTARS
      DO 5 J=1,6
      DO 5 K=1,6
       PHASEM(K,J)=0.
       R(K,J)=0.
       H(K,J)=0.
       AAA(K,J)=0.
```

```
    5 CONTINUE
      DO 10 K=1,6
      DO 10 J=1,6
      R(K,J)=PHASE(K,J)-CZERO(K,J)
   10 CONTINUE
      CALL AMATIN(R,AAA,NWARN)
C---DEVELOP THE INVERTED CORRELATION TENSOR
      DO 20 K=1,6
      DO 20 J=1,6
      H(K,J)=AAA(K,J)-EZERO(K,J)
   20 CONTINUE
      CALL AMATIN(H,PHASEM,NDUM)
C---CHECK TO SEE IF THE SHEAR MODULUS IN "R" WAS ZERO
      DO 30 K=4,6
      KK=K-2
      IF(NWARN(KK) .NE. 0) PHASEM(K,K)=0.
   30 CONTINUE
      RETURN
      END
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE EMAKE(EZERO,CZERO,AA)
C---THIS SUBROUTINE CREATES THE MATRIX EZERO
C
C       INPUT:
C               AA      THE CURRENT ASPECT RATIO
C               CZERO   THE 6X6 ARRAY OF ELASTIC CONSTANTS FOR
C                       THE REFERENCE PHASE
C
C       OUTPUT:
C               EZERO   THE 6X6 ARRAY OF THE CORRELATION TENSOR
C
      DIMENSION EZERO(6,6),CZERO(6,6)
C---CLEAR THE REGISTARS
      DO 5 K=1,6
      DO 5 J=1,6
```

```
         EZERO(K,J)=0.
       5 CONTINUE
         IF(AA-1.) 10,50,60
C---SET THE H-I VALUES WHEN A IS LESS THAN ONE
C-
      10 IF(AA-.99) 30,30,20
C---DETERMINE THE H-I VALUES WHEN .99 < A < 1. USING
C-- APPROXIMATING POLYNOMIALS
      20 YSQ=(1.-AA*AA)/AA/AA
         Y4=YSQ*YSQ
         H1=2./3.-2.*YSQ/15.+2.*Y4/35.
         H2=1.-H1
         H3=8./15.-4.*YSQ/35.+Y4/10.
         H5=.2+4.*YSQ/35.+9.*Y4/10.
         H4=.5*(1.-H3-H5)
         GO TO 70
      30 IF(AA .GT. .025) GO TO 40
C---DETERMINE THE H-I VALUES WHEN 0. < A < .025 USING
C-- APPROXIMATING POLYNOMIALS
         PIE=ACOS(-1.)
         YSQI=AA*AA/(1.-AA*AA)
         YI=SQRT(YSQI)
         Y3I=YI**3
         Y4I=YSQI*YSQI
         H1=PIE*YI/2.-YSQI+(PIE-2.)*Y3I/2.+Y4I/3.
         H2=1.-H1
         H3=PIE*YI/4.-3.*Y3I*PIE/2.+4.*Y4I
         H5=1.-.75*PIE*YI+4.*YSQI-1.5*PIE*Y3I+4.*Y4I
         H4=.5*(1.-H3-H5)
         GO TO 70
C---WHEN .025 < A < .99 USING THE EXACT EQUATIONS AS DEVELOPED
C-- BY WU
      40 ASQ=AA**2
         B1=ASQ/(1.-ASQ)
         B1SQRT=SQRT(B1)
```

```
      B2=1./B1
      B2SQRT=SQRT(B2)
      B3=ATAN(B2SQRT)
      H1=B1*((B2SQRT+B1SQRT)*B3-1.)
      H2=1.-H1
      H3=B1**2*(.5/ASQ+1.+(B2**(1.5)/2.-B2SQRT-3.*B1SQRT/
     C2.)*B3)
      H5=(1.+ASQ/2.-3.*B1SQRT/2.*B3)/(1.-ASQ)**2
      H4=.5*(1.-H3-H5)
      GO TO 70
C---CALCULATE THE H-I VALUES FOR AN ASPECT RATIO OF ONE
   50 H1=2./3.
      H2=1./3.
      H3=8./15.
      H4=2./15.
      H5=1./5.
      GO TO 70
C---SET THE H-I VALUES WHEN A IS GREATER THAN ONE USING
C-- THE EXACT EQUATIONS DEVELOPED BY WU FOR 1.0 < A < 25.
   60 IF(AA .GT. 25.) GO TO 65
      X=(AA**2-1.)/AA**2
      XRT=SQRT(X)
      Z=ALOG((1.+XRT)/(1.-XRT))/XRT
      H1=(1.-.5*(1.-X)*Z)/X
      H2=1.-H1
      H3=(1.5-.5*X+.25*(X**2+2.*X-3.)*Z)/X**2
      H5=(((1.-X)/X)**2)*(((3.-2.*X)/(2.*(1.-X)))-.75*Z)
      H4=.5*(1.-H3-H5)
      GO TO 70
C---WHEN 25 < A < 150 USE THE APPROXIMATING POLYNOMILAL
   65 IF(AA .GT. 150.) GO TO 85
      XSQ=(AA*AA-1.)/AA/AA
      HG=.2+XSQ*(1./7.+XSQ/9.)
      B1=(1.-XSQ)*XSQ*HG
      H1=(2.+XSQ)/3.-B1
      H2=1.-H1
```

```
      H3=(16.+XSQ*(11.+3.*XSQ))/30.-(3.+2.*XSQ)*B1/2.
      H5=(1.-XSQ)*(2.+3.*XSQ)/10.-3.*B1/2.
      H4=.5*(1.-H3-H5)
C---CALCULATE THE CONSTANTS WHICH CAN BE COMBINED TO GIVE
C-- THE MATRIX EZERO
   70 ALPHA=(CZERO(2,2)-CZERO(4,4))/(4.*CZERO(4,4)*CZERO(2,2))
      BETA=.25/CZERO(6,6)
      AKE=ALPHA*H3-BETA*H1
      AMUE=.5*ALPHA*H3-BETA*H1
      ALAMBE=2.*ALPHA*H4
      DELTA=2.*ALPHA*H4-BETA*(.5*H1+H2)
      RNE=4.*ALPHA*H5-4.*BETA*H2
C---CALCULATE THE COMPONENTS OF THE EZERO MATRIX
      EZERO(1,1)=RNE
      EZERO(1,2)=ALAMBE
      EZERO(1,3)=EZERO(1,2)
      EZERO(2,1)=EZERO(1,2)
      EZERO(2,2)=AKE+AMUE
      EZERO(2,3)=AKE-AMUE
      EZERO(3,1)=EZERO(1,3)
      EZERO(3,2)=EZERO(2,3)
      EZERO(3,3)=EZERO(2,2)
      EZERO(4,4)=4.*AMUE
      EZERO(5,5)=4.*DELTA
      EZERO(6,6)=EZERO(5,5)
      GO TO 90
C---COMPUTE EZERO FOR A APPROACHING INFINITY FOR THE GENERAL
C-- CASE OF TRANSVERSELY ISOTROPIC REFERENCE
   85 EKT=-.25/CZERO(2,2)
      EMUT=-(CZERO(2,2)+CZERO(4,4))/(8.*CZERO(4,4)*CZERO(2,2))
      EMUA=-.125/CZERO(5,5)
      EZERO(2,2)=EKT+EMUT
      EZERO(2,3)=EKT-EMUT
      EZERO(3,3)=EZERO(2,2)
      EZERO(3,2)=EZERO(2,3)
```

```
      EZERO(4,4)=4.*EMUT
      EZERO(5,5)=4.*EMUA
      EZERO(6,6)=EZERO(5,5)
   90 CONTINUE
      RETURN
      END
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE PLANAR(B,F,A,AA)
C---CONSTRUCTS THE PLANAR AVERAGE "AA" OF ARRAY "A" FOR EITHER
C-- ELASTIC CONSTANTS (B=1.0) OR COMPLIANCE CONSTANTS (B=4.)
C-- FOR THE STATE OF ORIENTATION "F"
      DIMENSION A(6,6),AA(6,6),AD(6,6),AZ(6,6)
C---CLEAR THE REGISTERS
      DO 10 K=1,6
      DO 10 J=1,6
      AA(K,J)=0.
      AD(K,J)=0.
      AZ(K,J)=0.
   10 CONTINUE
C---COMPUTE ASSOCIATED VALUE OF ORIENTATION PARAMETER "G"
      G=2.*F*(7.-2.*F)/(5.*(4.-2.*F))
C---SET UP INVARIANTS
      AZ(1,1)=(3.*A(1,1)+3.*A(2,2)+2.*A(1,2)+4./B*A(6,6))/8.
      AZ(2,2)=AZ(1,1)
      AZ(1,2)=(A(1,1)+A(2,2)+6.*A(1,2)-4./B*A(6,6))/8.
      AZ(1,3)=(A(1,3)+A(2,3))/2.
      AZ(2,3)=AZ(1,3)
      AZ(3,1)=AZ(1,3)
      AZ(3,2)=AZ(2,3)
      AZ(3,3)=A(3,3)
      AZ(4,4)=(A(4,4)+A(5,5))/2.
      AZ(5,5)=AZ(4,4)
      AZ(6,6)=B*(A(1,1)+A(2,2)-2.*A(1,2)+4./B*A(6,6))/8.
      DO 20 K=1,6
      DO 20 J=1,6
```

```
      AD(K,J)=AZ(K,J)-A(K,J)
   20 CONTINUE
C---CONSTRUCT AVERAGES
      DO 30 K=1,6
      DO 30 J=1,6
      AA(K,J)=AZ(K,J)-F*AD(K,J)
   30 CONTINUE
C---COMPLETE CONSTRUCTION WITH "G" DEPENDENT TERMS
      AA(1,1)=AA(1,1)+(5.*(G-F)*AD(6,6))/B
      AA(1,2)=AA(1,2)-5.*(G-F)*AD(1,2)
      AA(2,1)=AA(1,2)
      AA(2,2)=AA(2,2)+(5.*(G-F)*AD(6,6))/B
      AA(6,6)=AA(6,6)-5.*(G-F)*AD(6,6)
      RETURN
      END
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE SMIX(VHI,CLO,CHI,CM)
C
C         THIS ROUTINE USES THE WU-MCCULLOUGH RELATIONSHIP IN
C       CONJUNCTION WITH THE S-MIXING RULE TO GENERATE PROPERTIES
C       FOR PARTICULATE SYSTEMS (ASPECT RATIO = 1).
C
C       INPUT:
C               VHI     VOLUME FRACTION OF RIGID PHASE
C               CLO     6X6 ARRAY OF ELAXTIC CONSTANTS FOR SOFT
C                       PHASE
C               CHI     6X6 ARRAY OF ELASTIC CONSTANTS FOR
C                       RIGID PHASE
C
C       OUTPUT:
C               CM      6X6 ARRAY OF ELASTIC CONSTANTS FOR A
C                       PARTICULATE SYSTEM
C
C       ROUTINES CALLED:
C               EMAKE
```

```
C                   COMP
C                   AMATIN
C
      DIMENSION CLO(6,6),CHI(6,6),CM(6,6),BIGM(6,6),TRANS(6,6)
      DIMENSION AAA(6,6),SL(6,6),SH(6,6),EZERO(6,6),CSTAR(6,6)
      DIMENSION NDUM(4)
C---CLEAR THE REGISTARS
      DO 10 K=1,6
      DO 10 J=1,6
       CM(K,J)=0.
       BIGM(K,J)=0.
       TRANS(K,J)=0.
       AAA(K,J)=0.
       SL(K,J)=0.
       SH(K,J)=0.
   10 CONTINUE
      IF(VHI .EQ. 0.) GO TO 40
C---COMPUTE LOWER BOUND FOR A PARTICULATE SYSTEM (AA=1)
      CALL EMAKE(EZERO,CLO,1.)
      CALL COMP(CLO,CHI,EZERO,TRANS)
      DO 20 K=1,6
      DO 20 J=1,6
       BIGM(K,J)=VHI*TRANS(K,J)
   20 CONTINUE
      CALL AMATIN(BIGM,TRANS,NDUM)
      DO 30 K=1,6
      DO 30 J=1,6
       AAA(K,J)=TRANS(K,J)+EZERO(K,J)
   30 CONTINUE
      CALL AMATIN(AAA,TRANS,NDUM)
   40 DO 50 K=1,6
      DO 50 J=1,6
       CSTAR(K,J)=CLO(K,J)+TRANS(K,J)
   50 CONTINUE
      CALL AMATIN(CSTAR,SL,NDUM)
C---COMPUTE UPPER BOUND FOR A PARTICULATE SYSTEM (AA=1)
```

```
      CALL EMAKE(EZERO,CHI,1.)
      CALL COMP(CHI,CLO,EZERO,TRANS)
      DO 60 K=1,6
      DO 60 J=1,6
       BIGM(K,J)=(1.-VHI)*TRANS(K,J)
   60 CONTINUE
      CALL AMATIN(BIGM,TRANS,NDUM)
      DO 70 K=1,6
      DO 70 J=1,6
       AAA(K,J)=TRANS(K,J)+EZERO(K,J)
   70 CONTINUE
      CALL AMATIN(AAA,TRANS,NDUM)
      DO 80 K=1,6
      DO 80 J=1,6
       CSTAR(K,J)=CHI(K,J)+TRANS(K,J)
   80 CONTINUE
      CALL AMATIN(CSTAR,SH,NDUM)
C---COMPUTE ELASTIC CONSTANTS BY MIXING RULE
      VOL=1.-VHI
      DO 90 K=1,6
      DO 90 J=1,6
       TRANS(K,J)=VOL*SL(K,J)+VHI*SH(K,J)+.5*VHI*VOL*
     C (SL(K,J)-SH(K,J))
   90 CONTINUE
C---CONVERT COMPLIANCE TO ELASTIC CONSTANTS
      CALL AMATIN(TRANS,CM,NDUM)
      RETURN
      END
```

Anticipated Modifications

The program SMC-3 was constructed from basic FORTRAN statements in order to facilitate its transferability. The program could be made more efficient by using statements unique to specific computers.

Currently SMC-3 is executed on a DEC-10 system. For this system, no "job" control cards are required. Consequently, there are no file or tape declaration statements, no calls to specific compilers, and no memory or time limit specifications. The following items are summarized for the benefit of users concerned with such requirements.

- Tapes Declared:	SMC-3 uses only input and output tapes
- Compiler:	SMC-3 is FORTRAN-10 compatible
- Memory Requirements:	SMC-3 uses less than the default memory limit on the DEC-10
- Time Limit:	CPU time is usually less than one second

It was recognized that the READ and WRITE device number would vary with the user's computer system. In order to facilitate transfer, SMC-3 has incorporated integer variables for input and output device numbers. Both variables, NREAD for input device, NWRITE for output device, are assigned values using a DATA statement (line 12100 of the program). The typical input/output commands in SMC-3 are of the form

```
DATA NREAD,NWRITE/5,5/
.
.
.
READ(NREAD,10)A
.
.
.
.
WRITE(NWRITE,100)A
```

To assign the correct device numbers to the READ and WRITE statements, it is only necessary to change the DATA statement (line 12100). The variables NREAD and NWRITE are transferred to the required subroutines through COMMON/B1/. For ease of data entry, SMC-3 was written using free formatted READ statements. The free format READ symbol for the DEC-10 is the star, "*". These READ statements are of the form:

```
READ(NREAD,*)B
```

If the computing system on which SMC-3 is being implemented has free format READ capabilities, the correct symbol will need to be used in place of the star. For systems which do not have the free format READ options, it will be necessary to format each of the existing free format READ commands. Young's and Shear moduli could be read using the exponential field format--an E10.5 field would suffice. All other formats could be replaced by a floating point field. For example, a F20.10 would suffice. If this is done, all data should be entered including decimal points. <u>Statement numbers for the added FORMAT statements should be 500 or longer</u> to prevent any duplication of existing statement numbers.

To replace the free formatted READ statements, the following changes will be necessary:

1) change free format symbol, "*", to FORMAT statement numbers

2) insert corresponding FORMAT statement

For example, the READ statement which reads the volume fractions (program line 30300) could be changed to:

```
    READ(NREAD,500) V2(K)
500 FORMAT(F20.10)
```

The READ command for Young's modulus (program line 46500) could be rewritten as:

```
    READ(NREAD,510) E1(I)
510 FORMAT (E10.5)
```

A listing of each line where the free format has been utilized is summarized below. Lines 30300 through 36800 are all contained in SUBROUTINE INPUT. All these lines can be replaced with a single floating point FORMAT statement. The remaining free formatted READ statements occur in SUBROUTINE ALTER. Both exponential field and floating point field FORMAT statements will need to be used in this subroutine. POS12(2), POS23(2) and POS should be read using the floating point field while the remaining variables can be read using the suggested exponential field.

(From SUBROUTINE INPUT)

```
30300          READ(NREAD,*) V2(K)
31800          READ(NREAD,*) DX(K)
32100          READ(NREAD,*) DEN(K)
34300          READ(NREAD,*) AA2
35600          READ(NREAD,*) FSTART
36200          READ(NREAD,*) FSTART
36500          READ(NREAD,*) FSTOP
36800          READ(NREAD,*) FADD
```

(From SUBROUTINE ALTER)

```
44200          READ(NREAD,*) E1(2)
44500          READ(NREAD,*) E2(2)
44900          READ(NREAD,*) G12(2)
45300          READ(NREAD,*) G23(2)
45600          READ(NREAD,*) POS12(2)
46000          READ(NREAD,*) POS23(2)
46500          READ(NREAD,*) E1(I)
47000          READ(NREAD,*) G12(I)
47500          READ(NREAD,*) POS
*
```

Another change which may be necessary deals with continuation cards. In two FORMAT statements, the number of continuation cards has exceeded four. Seven were used starting at line 20000 while six were used starting at line 34600. For computers/compilers which are limited to fewer continuation cards, the output at these two locations will need to be rewritten using two WRITE statements.

SPECIALIZED TI-59 ROUTINES

Introduction

This section describes the operation of a TI-59 calculator/ PC-100 printer programmed to predict properties for two-component (fiber/resin) and three component (fiber/filler/resin) sheet molding materials.

The program is segmented on four magnetic cards:

Card I	-- Reads input and generates reference phase
Card II	-- Generates CSTAR
Card III	-- Planar averaging
Card IV	-- Generates Engineering constants and controls output.

The procedures for reading magnetic cards are reviewed at the end of this section.

A PC-100 printer is required for the operation of the program.

The current version of the program is restricted to isotropic fibers with aspect ratios in excess of 150. Supplementary cards will be provided at a future date to deal with low aspect ratio fibers and platelet reinforcing agents.

The following input data is required:

E_j = Young's modulus of component "j"

ν_j = Poisson's ratio of component "j"

G_j = Shear modulus of component "j"

v_j = volume fraction of component "j"

f = orientation parameter, $0 \leq f \leq 1$
(f=0 is random, f=1 is perfectly aligned)

The operating procedures for two-phase and three-phase systems are summarized in the following section. Sample calculations are given in the subsequent section.

Preprogrammed magnetic cards will be provided. However, difficulty has been encountered in reading magnetic cards programmed on other machines. Consequently, a program listing is provided so that cards can be generated.

OPERATING PROCEDURES FOR TWO-PHASE SYSTEMS

- ☐Enter physical properties
  - ☐Read sides 1 and 2 of card I

	Press	Display	Printer
☐Enter resin properties			
☐E_R	A	E_R	E_R
☐ν_R	B	ν_R	ν_R
☐G_R	C	G_R	G_R
☐Enter fiber properties			
☐E_F	2nd A'	E_F	E_F
☐ν_F	2nd B'	ν_F	ν_F
☐G_F	2nd C'	G_F	G_F
☐Enter volume fraction fiber	D	v_F	v_F
☐Generate reference phase properties	E	0	E_{Ref} ν_{Ref} G_{Ref}

- ☐Card II
  - ☐Read sides 1 and 2 of card II
  - ☐Press A

    Printer will respond with a print and advance when finished
- ☐Planar averaging
  - ☐Read sides 1 and 2 of card III

	Press	Display	Printer
☐ Enter orientation parameter f	A	f	f F
Planar averaging	B	0	Will advanc when completed
☐ Output			
☐ Read sides 1 only of Card IV			
☐ Generate output	A	0	E1 E2 E3 V12 V13 V23 G23 G13 G12

SUMMARY OF RESULTS

▷ To vary f, the orientation parameter: Run the program as before, with the first value of f.

▷ After obtaining the necessary output, read side 1 (only) of card III

▷ Enter orientation parameter, f, and continue with planar averaging operation

OPERATING PROCEDURES FOR THREE-PHASE SYSTEMS

☐ Enter physical properties of resin and filler

☐ Read sides 1 and 2 of card I

	Press	Display	Printer
☐ Enter resin properties			
☐ E_R	A	E_R	E_R
☐ ν_R	B	ν_R	ν_R
☐ G_R	C	G_R	G_R
☐ Enter filler properties			
☐ E_{Fill}	2nd A'	E_{Fill}	E_{Fill}
☐ ν_{Fill}	2nd B'	ν_{Fill}	ν_{Fill}
☐ G_{Fill}	2nd C'	G_{Fill}	G_{Fill}
☐ Enter modified volume fraction filler $v'_{Fill} = \frac{v_{Fill}}{v_{Fill}+v_R}$	D	v'_{Fill}	v'_{Fill}
☐ Generate surrogate matrix properties	E		E_m ν_m G_m
☐ Enter physical properties of surrogate matrix and fiber			
☐ Enter surrogate matrix properties			
☐ E_m	A	E_m	E_m
☐ ν_m	B	ν_m	ν_m
☐ G_m	C	G_m	G_m

	Press	Display	Printer
☐Enter fiber properties			
☐E_F	2nd A'	E_F	E_F
☐ν_F	2nd B'	F	F
☐G_F	2nd C'	G_F	G_F
☐Enter volume fraction fiber	D	V_F	V_F
☐Generate reference phase properties	E		E_{Ref} ν_{Ref} G_{Ref}

✫ AT THIS POINT, CONTINUE WITH CARD II
AS IN THE TWO-PHASE PROGRAM

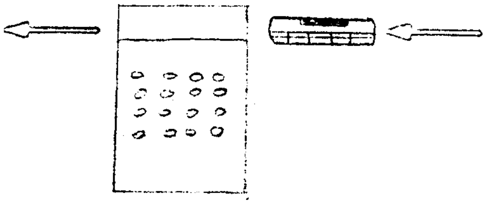
REVIEW OF CARD READING PROCEDURES

I. Reading Cards

All program cards need both sides read except the output program. When an instruction tells you to read both sides of a card:

A. Press CLR

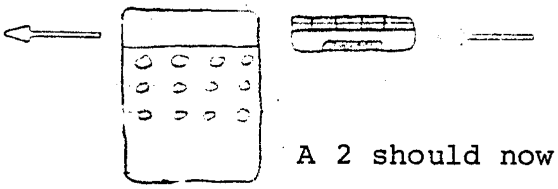
B. Slide card through lower slot in calculator, printed side up:



The card-reader motor will start. Push the card in until the gears catch it and pull it through. Pull the card out from the other side. A 1 should be in the display.

C. Press CLR

D. Turn card around and slide through again (printed side still up.



A 2 should now be in the display.

E. If display flashes, press CLR and try again.

F. If motor continues to run and display is blank after reading a card, press R/S. There wasn't anything on the side you read. Make sure the card was supposed to have both sides read.

EXAMPLES

EXAMPLES RUN WITH A TWO-PHASE COMPOSITE

SMC-65 Properties (in psi)

	E	ν	G	Vol. Fraction
Resin	5.1×10^5	.301	1.96×10^5	.6
Fiber	1.05×10^7	.333	3.94×10^6	.4

	Press	Display	Printer
☐Read sides 1 and 2 of card I			
Enter resin properties			
☐5.1 EE 5	A	5.1 05	5.1 05
☐ .301	B	3.01 -01	3.01-01
☐1.96 EE 5	C	1.96 05	1.96 05
Enter fiber properties			
☐1.05 EE7	2nd A'	1.05 07	1.05 07
☐ .333	2nd B'	3.33 -01	3.33-01
☐3.94 EE 6	2nd C'	3.94 06	3.94 06
Volume fraction fiber			
☐ .4	D	4. -01	4. -01
☐Generate reference phase properties	E	0	1.340 06 2.821-01 5.225 05
☐Read sides 1 and 2 of card II			
☐Run program on this card	A	0.	0.
☐Read sides 1 and 2 of card III			
Enter f			
☐0.	A	0	0. F
☐Planar averaging	B	0	Printer advance when done

	Press	Display	Printer
☐Read side 1 of card IV			
☐Generate output	A	0	2.377 06 E1 2.377 06 E2 1.319 06 E3 2.950-01 V12 3.010-01 V13 3.010-01 V23 5.082 05 G23 5.082 05 G13 9.176 05 G12
SUMMARY OF RESULTS			
☐Read side 1 of card III			
Enter new f value			
☐.25	A	.25	0.25 F
☐Planar averaging	B	0	
☐Read side 1 of card IV			
☐Generate output	A	0	2.705 06 E1 1.949 06 E2 1.315 06 E3 3.680-01 V12 2.770-01 V13 3.070-01 V23 4.955 05 G23 5.209 05 G13 9.432 05 G12
SUMMARY OF RESULTS			

SAMPLE RUN WITH A THREE-PHASE COMPOSITE

SMC-25 Properties (in psi)

	E	ν	G	Vol. Fraction
Resin	5.1×10^5	.301	1.96×10^5	.504
Fiber	1.05×10^7	.333	3.94×10^6	.179
Filler	3×10^6	.402	1.07×10^6	.317

☐Read sides 1 and 2 of card I

	Press	Display	Printer
Enter resin properties			
☐5.1 EE5	A	5.1 05	5.1 05
☐ .301	B	3.01 -01	3.01-01
☐1.96 EE5	C	1.96 05	1.96 05
Enter filler properties			
☐ 3 EE6	2nd A'	3. 06	3. 06
☐ .042	2nd B'	4.02 -01	4.02-01
☐1.07 EE 6	2nd C'	1.07 06	1.07 06

Enter modified volume fraction filler:

$$v_{Fill} = \frac{v_{Fill}}{v_{Fill} + v_R}$$

	Press	Display	Printer
☐ $v'_{Fill} = \frac{.317}{.317 + .504} = .3861$	D	3.861-01	3.861-01
☐Generate surrogate matrix properties	E	0	9.582 05 3.117-01 3.652 05
Enter surrogate matrix properties			
☐9.582 EE5	A	9.582 05	9.582 05
☐ .3117	B	3.117-01	3.117-01
☐3.652 EE5	C	3.652 05	3.652 05
Enter fiber properties			
☐1.05 EE 7	2nd A'	1.05 07	1.05 07
☐ .333	2nd B'	3.33 -01	3.33-01
☐3.94 EE 6	2nd C'	3.94 06	3.94 06

	Press	Display	Printer
Volume fraction fiber			
☐ .179	D	1.79 -01	1.79-01
☐ Generate reference phase properties	E	0	1.348 06 3.021-01 5.175 05
☐ Read sides 1 and 2 of card II			
☐ Run program on this card	A	0.	0.
☐ Read sides 1 and 2 of card III			
Enter f			
☐ 0	A	0	0. F
☐ Planar averaging	B	0	1 advance
☐ Read side 1 of card IV			
☐ Generate output *SUMMARY OF RESULTS* (f=0)	A		1.756 06 E1 1.756 06 E2 1.356 06 E3 3.080-01 V12 3.110-01 V13 3.110-01 V23 4.975 05 G23 4.975 05 G13 6.710 05 G12
☐ Read side 1 of card III			
Enter new f value			
☐ .25	A	.25	0.25 F
☐ Planar averaging	B	0	
☐ Read side 1 of card IV			
☐ Generate output *SUMMARY OF RESULTS* (f=0.25)	A	0	1.894 06 E1 1.576 06 E2 1.353 06 E3 3.480-01 V12 2.960-01 V13 3.170-01 V23 4.936 05 G23 5.014 05 G13 6.823 05 G12

TI-59
PROGRAM LISTINGS

The key strokes associated with cards I-IV are listed on the following pages.

It is recommended that upon entering the routines, duplicate magnetic cards should be recorded. The spare card serves as a replacement for a damaged card. If a card is damaged, a second duplicate should be recorded from the spare card.

C A R D I

Data Input and Generation of Reference Phase

Labels Used

```
001   22  INV
043   11   A
051   12   B
067   13   C
086   16  A'
094   17  B'
110   18  C'
129   14   D
137   15   E
176   52  EE
247   57  ENG
256   33  X²
277   34  ΓX
316   89   π
327   68  NOP
391   78  Σ+
414   70  RAD
```

Program

```
000   76  LBL
001   22  INV
002   73  RC*
003   10   10
004   33  X²
005   85   +
006   73  RC*
007   10   10
008   65   ×
009   73  RC*
010   11   11
011   75   -
012   02   2
013   65   ×
014   73  RC*
015   11   11
016   33  X²
017   95   =
018   42  STO
019   13   13
020   35  1/X
021   65   ×
022   53   (
023   73  RC*
024   11   11
025   85   +
026   73  RC*
027   10   10
```

```
028   54   )
029   95   =
030   72  ST*
031   10   10
032   73  RC*
033   11   11
034   55   ÷
035   43  RCL
036   13   13
037   94  +/-
038   95   =
039   72  ST*
040   11   11
041   92  RTN
042   76  LBL
043   11   A
044   35  1/X
045   42  STO
046   30   30
047   35  1/X
048   99  PRT
049   91  R/S
050   76  LBL
051   12   B
052   65   ×
053   43  RCL
054   30   30
055   94  +/-
056   95   =
057   42  STO
058   31   31
059   55   ÷
060   43  RCL
061   30   30
062   94  +/-
063   95   =
064   99  PRT
065   91  R/S
066   76  LBL
067   13   C
068   42  STO
069   32   32
070   03   3
071   00   0
072   42  STO
073   10   10
074   03   3
075   01   1
076   42  STO
```

```
077   11   11
078   71  SBR
079   22  INV
080   43  RCL
081   32   32
082   99  PRT
083   98  ADV
084   91  R/S
085   76  LBL
086   16  A'
087   35  1/X
088   42  STO
089   33   33
090   35  1/X
091   99  PRT
092   91  R/S
093   76  LBL
094   17  B'
095   65   ×
096   43  RCL
097   33   33
098   94  +/-
099   95   =
100   42  STO
101   34   34
102   55   ÷
103   43  RCL
104   33   33
105   94  +/-
106   95   =
107   99  PRT
108   91  R/S
109   76  LBL
110   18  C'
111   42  STO
112   35   35
113   03   3
114   03   3
115   42  STO
116   10   10
117   03   3
118   04   4
119   42  STO
120   11   11
121   71  SBR
122   22  INV
123   43  RCL
124   35   35
125   99  PRT
```

CARD I
-continued-

```
126  98 ADV
127  91 R/S
128  76 LBL
129  14  D
130  42 STO
131  42  42
132  42 STO
133  50  50
134  99 PRT
135  91 R/S
136  76 LBL
137  15  E
138  43 RCL
139  33  33
140  75  -
141  43 RCL
142  30  30
143  95  =
144  42 STO
145  43  43
146  43 RCL
147  34  34
148  75  -
149  43 RCL
150  31  31
151  95  =
152  42 STO
153  44  44
154  43 RCL
155  35  35
156  75  -
157  43 RCL
158  32  32
159  95  =
160  35 1/X
161  42 STO
162  45  45
163  04  4
164  03  3
165  42 STO
166  10  10
167  04  4
168  04  4
169  42 STO
170  11  11
171  71 SBR
172  22 INV
173  61 GTO
174  57 ENG
```

```
175  76 LBL
176  52 EE
177  73 RC*
178  00  00
179  75  -
180  73 RC*
181  02  02
182  95  =
183  55  ÷
184  04  4
185  55  ÷
186  73 RC*
187  00  00
188  55  ÷
189  73 RC*
190  02  02
191  95  =
192  42 STO
193  46  46
194  04  4
195  65  ×
196  73 RC*
197  02  02
198  95  =
199  35 1/X
200  42 STO
201  47  47
202  65  ×
203  04  4
204  55  ÷
205  03  3
206  94 +/-
207  85  +
208  04  4
209  55  ÷
210  05  5
211  65  ×
212  43 RCL
213  46  46
214  95  =
215  72 ST*
216  06  06
217  04  4
218  55  ÷
219  01  1
220  05  5
221  65  ×
222  43 RCL
223  46  46
```

```
             224  95  =
             225  72 ST*
             226  07  07
             227  01  1
             228  06  6
             229  55  ÷
             230  01  1
             231  05  5
             232  65  ×
             233  43 RCL
             234  46  46
             235  75  -
             236  08  8
             237  55  ÷
             238  03  3
end side 1-  239  65  ×
             240  43 RCL
             241  47  47
             242  95  =
             243  72 ST*
             244  08  08
             245  92 RTN
             246  76 LBL
             247  57 ENG
             248  03  3
             249  08  8
             250  42 STO
             251  00  00
             252  08  8
             253  42 STO
             254  09  09
             255  76 LBL
             256  33 X²
             257  43 RCL
             258  00  00
             259  72 ST*
             260  09  09
             261  01  1
             262  94 +/-
             263  44 SUM
             264  00  00
             265  97 DSZ
             266  09  09
             267  33 X²
             268  71 SBR
             269  52 EE
             270  08  8
             271  42 STO
             272  09  09
```

CARD I
-continued-

```
273  03   3
274  44  SUM
275  00   00
276  76  LBL
277  34  ΓX
278  03   3
279  74  SM*
280  09   09
281  97  DSZ
282  09   09
283  34  ΓX
284  71  SBR
285  52  EE
286  01   1
287  94  +/-
288  44  SUM
289  42   42
290  43  RCL
291  42   42
292  35  1/X
293  85   +
294  01   1
295  95   =
296  42  STO
297  46   46
298  71  SBR
299  68  NOP
300  01   1
301  44  SUM
302  42   42
303  43  RCL
304  46   46
305  35  1/X
306  42  STO
307  46   46
308  08   8
309  42  STO
310  09   09
311  03   3
312  94  +/-
313  44  SUM
314  00   00
315  76  LBL
316  89   π
317  74  SM*
318  09   09
319  97  DSZ
320  09   09
321  89   π
```

```
322  71  SBR
323  68  NOP
324  61  GTO
325  78  Σ+
326  76  LBL
327  68  NOP
328  43  RCL
329  46   46
330  64  PD*
331  06   06
332  64  PD*
333  07   07
334  64  PD*
335  08   08
336  43  RCL
337  43   43
338  55   ÷
339  43  RCL
340  42   42
341  95   =
342  74  SM*
343  06   06
344  43  RCL
345  44   44
346  55   ÷
347  43  RCL
348  42   42
349  95   =
350  74  SM*
351  07   07
352  43  RCL
353  45   45
354  55   ÷
355  43  RCL
356  42   42
357  85   +
358  73  RC*
359  08   08
360  95   =
361  35  1/X
362  85   +
363  73  RC*
364  02   02
365  95   =
366  35  1/X
367  72  ST*
368  08   08
369  43  RCL
370  06   06
```

```
371  42  STO
372  10   10
373  43  RCL
374  07   07
375  42  STO
376  11   11
377  71  SBR
378  22  INV
379  73  RC*
380  00   00
381  74  SM*
382  06   06
383  73  RC*
384  01   01
385  74  SM*
386  07   07
387  71  SBR
388  22  INV
389  92  RTN
390  76  LBL
391  78  Σ+
392  01   1
393  75   -
394  43  RCL
395  42   42
396  95   =
397  42  STO
398  46   46
399  55   ÷
400  02   2
401  65   ×
402  43  RCL
403  42   42
404  95   =
405  42  STO
406  47   47
407  03   3
408  42  STO
409  09   09
410  01   1
411  44  SUM
412  08   08
413  76  LBL
414  70  RAD
415  43  RCL
416  46   46
417  65   ×
418  73  RC*
419  06   06
```

CARD I
-continued-

```
420  85   +
421  43  RCL
422  42   42
423  65   ×
424  73  RC*
425  08   08
426  85   +
427  43  RCL
428  47   47
429  65   ×
430  53   (
431  73  RC*
432  06   06
433  75   -
434  73  RC*
435  08   08
436  54   )
437  95   =
438  72  ST*
439  06   06
440  01   1
441  44  SUM
442  06   06
443  44  SUM
444  08   08
445  97  DSZ
446  09   09
447  70  RAD
```

```
448  58  FIX
449  03   03
450  52  EE
451  95   =
452  98  ADV
453  43  RCL
454  36   36
455  35  1/X
456  99  PRT
457  65   ×
458  43  RCL
459  37   37
460  94  +/-
461  95   =
462  99  PRT
463  43  RCL
464  38   38
465  35  1/X
466  99  PRT
467  98  ADV
468  42  STO
469  38   38
470  71  SBR
471  22  INV
472  58  FIX
473  09   09
474  25  CLR
475  91  R/S
```

NOTE: Intermediate results for CZERO are stored in the following registers

Reg 36: $C_{11} = C_{22} = C_{33}$

37: $C_{12} = C_{13} = C_{23}$

38: $C_{44} = C_{55} = C_{66}$

CARD II

Calculation of CSTAR

```
Labels used
 001   22  INV
 043   11   A
 126   85   +
 148   49  PRD
 249   24  CE
 254   53   (
 298   54   )
 351   78  Σ+
 370   35  1/X

Program
 000   76  LBL
 001   22  INV
 002   43  RCL
 003   10   10
 004   33  X²
 005   85   +
 006   43  RCL
 007   10   10
 008   65   ×
 009   43  RCL
 010   11   11
 011   75   -
 012   02   2
 013   65   ×
 014   43  RCL
 015   11   11
 016   33  X²
 017   95   =
 018   42  STO
 019   12   12
 020   35  1/X
 021   65   ×
 022   53   (
 023   43  RCL
 024   11   11
 025   85   +
 026   43  RCL
 027   10   10
 028   54   )
 029   95   =
 030   42  STO
 031   10   10
 032   43  RCL
 033   11   11
 034   55   ÷
 035   43  RCL
 036   12   12
 037   94  +/-
 038   95   =
 039   42  STO
 040   11   11
 041   92  RTN
 042   76  LBL
 043   11   A
 044   01   1
 045   75   -
 046   43  RCL
 047   50   50
 048   95   =
 049   42  STO
 050   40   40
 051   04   4
 052   94  +/-
 053   35  1/X
 054   55   ÷
 055   43  RCL
 056   36   36
 057   95   =
 058   42  STO
 059   23   23
 060   42  STO
 061   24   24
 062   55   ÷
 063   02   2
 064   55   ÷
 065   43  RCL
 066   38   38
 067   65   ×
 068   53   (
 069   43  RCL
 070   36   36
 071   85   +
 072   43  RCL
 073   38   38
 074   54   )
 075   95   =
 076   44  SUM
 077   23   23
 078   22  INV
 079   44  SUM
 080   24   24
 081   65   ×
 082   04   4
 083   95   =
 084   42  STO
 085   25   25
 086   02   2
 087   35  1/X
 088   94  +/-
 089   55   ÷
 090   43  RCL
 091   38   38
 092   95   =
 093   42  STO
 094   26   26
 095   03   3
 096   03   3
 097   42  STO
 098   04   04
 099   04   4
 100   07   7
 101   42  STO
 102   07   07
 103   71  SBR
 104   24  CE
 105   03   3
 106   06   6
 107   42  STO
 108   04   04
 109   05   5
 110   07   7
 111   42  STO
 112   07   07
 113   71  SBR
 114   24  CE
 115   71  SBR
 116   78  Σ+
 117   71  SBR
 118   35  1/X
 119   04   4
 120   42  STO
 121   00   00
 122   01   1
 123   00   0
 124   94  +/-
 125   76  LBL
 126   85   +
 127   74  SM*
 128   00   00
 129   97  DSZ
 130   00   00
 131   85   +
 132   71  SBR
 133   78  Σ+
 134   71  SBR
```

CARD II
-continued-

```
135  35  1/X
136  04   4
137  06   6
138  42  STO
139  05   05
140  06   6
141  42  STO
142  00   00
143  01   1
144  06   6
145  42  STO
146  07   07
147  76  LBL
148  49  PRD
149  73  RC*
150  05   05
151  65   X
152  43  RCL
153  40   40
154  85   +
155  73  RC*
156  06   06
157  65   X
158  43  RCL
159  50   50
160  95   =
161  72  ST*
162  07   07
163  72  ST*
164  05   05
165  01   1
166  94  +/-
167  44  SUM
168  05   05
169  44  SUM
170  06   06
171  44  SUM
172  07   07
173  97  DSZ
174  00   00
175  49  PRD
176  71  SBR
177  35  1/X
178  43  RCL
179  41   41
180  42  STO
181  11   11
182  43  RCL
183  42   42

184  42  STO
185  12   12
186  43  RCL
187  43   43
188  85   +
189  43  RCL
190  23   23
191  95   =
192  42  STO
193  13   13
194  43  RCL
195  44   44
196  85   +
197  43  RCL
198  24   24
199  95   =
200  42  STO
201  14   14
202  71  SBR
203  35  1/X
204  43  RCL
205  36   36
206  44  SUM
207  41   41
208  44  SUM
209  43   43
210  43  RCL
211  37   37
212  44  SUM
213  42   42
214  44  SUM
215  44   44
216  43  RCL
217  45   45
218  35  1/X
219  85   +
220  43  RCL
221  25   25
222  95   =
223  35  1/X
224  85   +
225  43  RCL
226  38   38
227  95   =
228  42  STO
229  45   45
230  43  RCL
231  46   46
232  35  1/X

             233  85   +
             234  43  RCL
             235  26   26
             236  95   =
             237  35  1/X
             238  85   +
end side 1-239  43  RCL
             240  38   38
             241  95   =
             242  42  STO
             243  46   46
             244  25  CLR
             245  99  PRT
             246  98  ADV
             247  91  R/S
             248  76  LBL
             249  24  CE
             250  03   3
             251  42  STO
             252  00   00
             253  76  LBL
             254  53   (
             255  43  RCL
             256  04   04
             257  75   -
             258  01   1
             259  95   =
             260  72  ST*
             261  00   00
             262  42  STO
             263  04   04
             264  97  DSZ
             265  00   00
             266  53   (
             267  73  RC*
             268  01   01
             269  75   -
             270  43  RCL
             271  36   36
             272  95   =
             273  42  STO
             274  10   10
             275  73  RC*
             276  02   02
             277  75   -
             278  43  RCL
             279  37   37
             280  95   =
             281  42  STO
```

CARD II
-continued-

```
282   11   11
283   71  SBR
284   22  INV
285   73  RC*
286   03   03
287   75   -
288   43  RCL
289   38   38
290   95   =
291   35  1/X
292   42  STO
293   13   13
294   06   6
295   42  STO
296   00   00
297   76  LBL
298   54   )
299   43  RCL
300   07   07
301   75   -
302   01   1
303   95   =
304   72  ST*
305   00   00
306   42  STO
307   07   07
308   97  DSZ
309   00   00
310   54   )
311   43  RCL
312   10   10
313   72  ST*
314   01   01
315   75   -
316   43  RCL
317   23   23
318   95   =
319   72  ST*
320   03   03
321   43  RCL
322   11   11
323   72  ST*
324   02   02
325   75   -
326   43  RCL
327   24   24
328   95   =
329   72  ST*
330   04   04
331   43  RCL
332   13   13
333   75   -
334   43  RCL
335   25   25
336   95   =
337   35  1/X
338   72  ST*
339   05   05
340   43  RCL
341   13   13
342   75   -
343   43  RCL
344   26   26
345   95   =
346   35  1/X
347   72  ST*
348   06   06
349   92  RTN
350   76  LBL
351   78  Σ+
352   73  RC*
353   01   01
354   42  STO
355   11   11
356   73  RC*
357   02   02
358   42  STO
359   12   12
360   73  RC*
361   03   03
362   42  STO
363   13   13
364   73  RC*
365   04   04
366   42  STO
367   14   14
368   92  RTN
369   76  LBL
370   35  1/X
371   43  RCL
372   13   13
373   85   +
374   43  RCL
375   14   14
376   95   =
377   42  STO
378   07   07
379   65   ×
380   43  RCL
381   11   11
382   75   -
383   43  RCL
384   12   12
385   33  X²
386   42  STO
387   08   08
388   65   ×
389   02   2
390   95   =
391   42  STO
392   09   09
393   35  1/X
394   65   ×
395   43  RCL
396   07   07
397   95   =
398   72  ST*
399   01   01
400   43  RCL
401   12   12
402   94  +/-
403   55   ÷
404   43  RCL
405   09   09
406   95   =
407   72  ST*
408   02   02
409   43  RCL
410   11   11
411   65   ×
412   43  RCL
413   13   13
414   75   -
415   43  RCL
416   08   08
417   95   =
418   55   ÷
419   53   (
420   53   (
421   43  RCL
422   13   13
423   75   -
424   43  RCL
425   14   14
426   54   )
427   65   ×
428   43  RCL
```

CARD II
-continued-

```
429   09  09
430   54  )
431   42 STO
432   09  09
433   95  =
434   72 ST*
435   03  03
436   43 RCL
437   08  08
438   75  -
439   43 RCL
440   11  11
441   65  ×
442   43 RCL
443   14  14
444   95  =
445   55  ÷
446   43 RCL
447   09  09
448   95  =
449   72 ST*
450   04  04
451   92 RTN
```

NOTE: Intermediate results are stored in the following registers.

EZERO		CSTAR	
Reg 21:	$E_{11} = E_{22} = 0$	Reg 41:	C_{11}
22:	$E_{12} = E_{13} = 0$	42:	$C_{12} = C_{13}$
23:	E_{33}	43:	$C_{22} = C_{33}$
24	E_{23}	44:	C_{23}
25	E_{44}	45:	C_{44}
26	$E_{55} = E_{66}$	46:	$C_{55} = C_{66}$

CARD III

Input Orientation Factor (f) and Planar Averaging

Labels Used

```
001   11   A
014   12   B
266   22  INV
```

Program

```
000   76  LBL
001   11   A
002   42  STO
003   17   17
004   02   2
005   01   1
006   69  OP
007   04   04
008   43  RCL
009   17   17
010   69  OP
011   06   06
012   91  R/S
013   76  LBL
014   12   B
015   02   2
016   65   ×
017   43  RCL
018   17   17
019   95   =
020   42  STO
021   18   18
022   94  +/-
023   85   +
024   07   7
025   95   =
026   65   ×
027   43  RCL
028   18   18
029   55   ÷
030   05   5
031   55   ÷
032   53   (
033   04   4
034   75   -
035   43  RCL
036   18   18
037   54   )
038   95   =
039   42  STO
040   18   18
041   94  +/-
042   85   +
043   43  RCL
044   17   17
045   95   =
046   42  STO
047   19   19
048   01   1
049   75   -
050   43  RCL
051   17   17
052   95   =
053   42  STO
054   20   20
055   53   (
056   43  RCL
057   41   41
058   85   +
059   43  RCL
060   42   42
061   65   ×
062   02   2
063   85   +
064   43  RCL
065   43   43
066   54   )
067   55   ÷
068   04   4
069   95   =
070   42  STO
071   10   10
072   53   (
073   43  RCL
074   41   41
075   85   +
076   43  RCL
077   43   43
078   75   -
079   02   2
080   65   ×
081   43  RCL
082   42   42
083   85   +
084   04   4
085   65   ×
086   43  RCL
087   46   46
088   54   )
089   55   ÷
090   08   8
091   95   =
092   42  STO
093   09   09
094   53   (
095   43  RCL
096   42   42
097   85   +
098   43  RCL
099   44   44
100   54   )
101   55   ÷
102   02   2
103   65   ×
104   43  RCL
105   20   20
106   95   =
107   42  STO
108   08   08
109   85   +
110   43  RCL
111   42   42
112   65   ×
113   43  RCL
114   17   17
115   95   =
116   42  STO
117   13   13
118   43  RCL
119   08   08
120   85   +
121   43  RCL
122   44   44
123   65   ×
124   43  RCL
125   17   17
126   95   =
127   42  STO
128   15   15
129   43  RCL
130   45   45
131   85   +
132   43  RCL
133   46   46
134   95   =
135   55   ÷
136   02   2
137   65   ×
138   43  RCL
139   20   20
```

CARD III
-continued-

```
140  95  =              189  43  RCL                    238  95  =
141  42  STO            190  41   41   end side 1-      239  42  STO
142  07   07            191  65  ×                      240  12   12
143  85  +              192  43  RCL                    241  43  RCL
144  43  RCL            193  17   17                    242  09   09
145  45   45            194  95  =                      243  75  -
146  65  ×              195  42  STO                    244  43  RCL
147  43  RCL            196  11   11                    245  46   46
148  17   17            197  43  RCL                    246  95  =
149  95  =              198  06   06                    247  65  ×
150  42  STO            199  85  +                      248  43  RCL
151  27   27            200  43  RCL                    249  05   05
152  43  RCL            201  43   43                    250  85  +
153  07   07            202  65  ×                      251  43  RCL
154  85  +              203  43  RCL                    252  09   09
155  43  RCL            204  17   17                    253  95  =
156  46   46            205  95  =                      254  42  STO
157  65  ×              206  42  STO                    255  29   29
158  43  RCL            207  14   14                    256  43  RCL
159  17   17            208  43  RCL                    257  43   43
160  95  =              209  17   17                    258  42  STO
161  42  STO            210  65  ×                      259  16   16
162  28   28            211  04  4                      260  71  SBR
163  43  RCL            212  75  -                      261  22  INV
164  46   46            213  43  RCL                    262  25  CLR
165  75  -              214  18   18                    263  98  ADV
166  43  RCL            215  65  ×                      264  91  R/S
167  09   09            216  05  5                      265  76  LBL
168  95  =              217  95  =                      266  22  INV
169  65  ×              218  42  STO                    267  43  RCL
170  05  5              219  05   05                    268  12   12
171  65  ×              220  43  RCL                    269  75  -
172  43  RCL            221  10   10                    270  43  RCL
173  19   19            222  75  -                      271  14   14
174  85  +              223  43  RCL                    272  65  ×
175  43  RCL            224  09   09                    273  43  RCL
176  20   20            225  75  -                      274  11   11
177  65  ×              226  43  RCL                    275  55  ÷
178  53  (              227  42   42                    276  43  RCL
179  43  RCL            228  95  =                      277  12   12
180  10   10            229  65  ×                      278  95  =
181  85  +              230  43  RCL                    279  42  STO
182  43  RCL            231  05   05                    280  07   07
183  09   09            232  85  +                      281  55  ÷
184  54  )              233  43  RCL                    282  53  (
185  95  =              234  10   10                    283  43  RCL
186  42  STO            235  75  -                      284  12   12
187  06   06            236  43  RCL                    285  75  -
188  85  +              237  09   09                    286  43  RCL
```

CARD III
-continued-

```
287  11   11
288  65   ×
289  43  RCL
290  15   15
291  55   ÷
292  43  RCL
293  13   13
294  54   )
295  42  STO
296  08   08
297  95   =
298  42  STO
299  10   10
300  94  +/-
301  85   +
302  01   1
303  95   =
304  55   ÷
305  53   (
306  53   (
307  43  RCL
308  13   13
309  75   -
310  43  RCL
311  11   11
312  65   ×
313  43  RCL
314  15   15
315  55   ÷
316  43  RCL
317  12   12
318  54   )
319  42  STO
320  09   09
321  75   -
322  43  RCL
323  10   10
324  65   ×
325  53   (
326  43  RCL
327  13   13
328  75   -
329  43  RCL
330  11   11
331  65   ×
332  43  RCL
333  16   16
334  55   ÷
335  43  RCL
336  13   13
337  54   )
338  54   )
339  95   =
340  42  STO
341  23   23
342  65   ×
343  43  RCL
344  09   09
345  94  +/-
346  85   +
347  01   1
348  95   =
349  55   ÷
350  43  RCL
351  07   07
352  95   =
353  42  STO
354  22   22
355  65   ×
356  43  RCL
357  12   12
358  94  +/-
359  85   +
360  01   1
361  75   -
362  43  RCL
363  13   13
364  65   ×
365  43  RCL
366  23   23
367  95   =
368  55   ÷
369  43  RCL
370  11   11
371  95   =
372  42  STO
373  21   21
374  01   1
375  75   -
376  43  RCL
377  22   22
378  65   ×
379  43  RCL
380  07   07
381  95   =
382  55   ÷
383  53   (
384  43  RCL
385  15   15
386  75   -
387  43  RCL
388  13   13
389  65   ×
390  43  RCL
391  14   14
392  55   ÷
393  43  RCL
394  12   12
395  54   )
396  95   =
397  42  STO
398  25   25
399  94  +/-
400  65   ×
401  43  RCL
402  13   13
403  75   -
404  43  RCL
405  11   11
406  65   ×
407  43  RCL
408  22   22
409  95   =
410  55   ÷
411  43  RCL
412  12   12
413  95   =
414  42  STO
415  24   24
416  43  RCL
417  11   11
418  94  +/-
419  65   ×
420  43  RCL
421  23   23
422  75   -
423  43  RCL
424  12   12
425  65   ×
426  43  RCL
427  25   25
428  95   =
429  55   ÷
430  43  RCL
431  13   13
432  95   =
433  42  STO
434  26   26
435  92  RTN
```

CARD III
-continued-

NOTE: Intermediate results for the Average CSTAR are stored in the following registers

Reg 21: C_{11}

22: C_{12}

23: C_{13}

24: C_{22}

25: C_{23}

26: C_{33}

27: C_{44}

28: C_{55}

29: C_{66}

CARD IV

Conversion of C^* to Engineering Constants

Program

```
000  76  LBL
001  11   A
002  43  RCL
003  21   21
004  35  1/X
005  42  STO
006  11   11
007  94  +/-
008  65   x
009  43  RCL
010  22   22
011  95   =
012  42  STO
013  12   12
014  43  RCL
015  11   11
016  94  +/-
017  65   x
018  43  RCL
019  23   23
020  95   =
021  42  STO
022  13   13
023  43  RCL
024  24   24
025  35  1/X
026  42  STO
027  14   14
028  65   x
029  43  RCL
030  25   25
031  94  +/-
032  95   =
033  42  STO
034  15   15
035  43  RCL
036  26   26
037  35  1/X
038  42  STO
039  16   16
040  01   1
041  07   7
042  00   0
043  02   2
044  69  OP
045  04   04
046  43  RCL
047  11   11
048  71  SBR
049  95   =
050  01   1
051  07   7
052  00   0
053  03   3
054  69  OP
055  04   04
056  43  RCL
057  14   14
058  71  SBR
059  95   =
060  01   1
061  07   7
062  00   0
063  04   4
064  69  OP
065  04   04
066  43  RCL
067  16   16
068  71  SBR
069  95   =
070  98  ADV
071  04   4
072  02   2
073  00   0
074  02   2
075  00   0
076  03   3
077  69  OP
078  04   04
079  43  RCL
080  12   12
081  71  SBR
082  95   =
083  04   4
084  02   2
085  00   0
086  02   2
087  00   0
088  04   4
089  69  OP
090  04   04
091  43  RCL
092  13   13
093  71  SBR
094  95   =
095  04   4
096  02   2
097  00   0
098  03   3
099  00   0
100  04   4
101  69  OP
102  04   04
103  43  RCL
104  15   15
105  71  SBR
106  95   =
107  98  ADV
108  02   2
109  02   2
110  00   0
111  03   3
112  00   0
113  04   4
114  69  OP
115  04   04
116  43  RCL
117  27   27
118  71  SBR
119  95   =
120  02   2
121  02   2
122  00   0
123  02   2
124  00   0
125  04   4
126  69  OP
127  04   04
128  43  RCL
129  28   28
130  71  SBR
131  95   =
132  02   2
133  02   2
134  00   0
135  02   2
136  00   0
137  03   3
138  69  OP
139  04   04
140  43  RCL
141  29   29
142  71  SBR
143  95   =
144  98  ADV
145  98  ADV
```

CARD IV
-continued-

```
146   25 CLR
147   92 RTN
148   76 LBL
149   95  =
150   58 FIX
151   03  03
152   52 EE
153   95  =
154   69 OP
155   06  06
156   58 FIX
157   09  09
158   22 INV
159   52 EE
160   95  =
161   92 RTN
```

side 1 only