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Towards the Development of Micromechanics Equations for Ceramic Matrix Composites via Fiber Substructuring

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TOWARDS THE DEVELOPMENT OF MICROMECHANICS EQUATIONS FOR

CERAMIC MATRIX COMPOSITES VIA FIBER SUBSTRUCTURING

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ABSTRACT

A generic unit cell model which includes a unique fiber substructuring concept is proposed for the development of micromechanics equations for continuous fiber reinforced ceramic composites. The unit cell consists of three constituents: fiber, matrix and an interphase. In the present approach, the unit cell is further subdivided into several slices and the equations of micromechanics are derived for each slice. These are subsequently integrated to obtain ply level properties. A stand-alone computer code containing the micromechanics model as a module is currently being developed specifically for the analysis of ceramic matrix composites. Towards this development, equivalent ply property results for a SiC (silicon carbide fiber)/Ti-15-3 (Titanium matrix) composite with a 0.5 fiber volume ratio are presented and compared with those obtained from customary micromechanics models to illustrate the concept. Also, comparisons with limited experimental data for the ceramic matrix composite, SiC/RBSN (Reaction Bonded Silicon Nitride) with a 0.3 fiber volume ratio are given to validate the concepts.

SYMBOLS

C	heat capacity
d_f	fiber diameter
E,G	Young's (Normal) and shear moduli
f,m,i	subscripts for fiber, matrix, and interphase
K	thermal conductivity
k	volume fraction

ℓ	subscript for ply or slice (subply)
n	Poisson's ratio
$T, \Delta T$	melting temperature, temperature difference
1,2,3	subscripts for material axis. 1 along the fibers 2 and 3 are transverse to the fiber
α	coefficient of thermal expansion
ε	strain
ρ	density
σ	stress

INTRODUCTION

Composite micromechanics is an extensively explored field where the primary thrust is to evaluate the behavior of the composite as a function of the behavior and interaction of the constituents (fiber and matrix). There are two basic approaches to the micromechanics of composite materials: (1) mechanics of materials and (2) elasticity. The principles and the assumptions behind these approaches are well known and are standard topics of many text books [Ref. 1, for example].

In-house research over the past twenty years has focused on the mechanics of materials approach and has culminated into several computer codes for composite micromechanics and macromechanics. Notable among these are ICAN (Integrated Composite ANalyzer) and METCAN (METtal Matrix Composite ANalyzer). ICAN [Ref. 2] was primarily developed for predicting the behavior of polymer-matrix composites. The micromechanics of ICAN are based upon a unit cell consisting of the fiber and matrix that is arranged in a regular square array pattern (Fig. 1). A recently developed code using the same philosophy is METCAN [Ref. 3] which was tailored for analyzing micromechanical as well as macromechanical behavior of metal matrix composites. The unit cell model for METCAN is slightly different in that it consists of three distinct constituents fiber, matrix and an interphase. The third constituent, the

interphase is unique to this class of materials which can develop due to a possible chemical reaction between the fiber and matrix.

Currently, a unique fiber substructuring concept is being explored to further describe the micromechanics of fiber composites with finer local detail. In this approach the customary unit cell model is substructured into several slices (Fig. 2). Each slice is treated as the smallest representative unit and micromechanics equations are derived for each slice by applying the well known principles of the mechanics of materials approach. The basic philosophy is applicable to any type of continuous-fiber-reinforced matrix composite. However, the current emphasis is on the development of a dedicated stand-alone computer code using the above mentioned concepts for predicting the behavior of ceramic matrix composites (CMCs). The code is thus named CEMCAN for CEramic Matrix Composite ANalyzer.

The current approach has several advantages over other conventional methods. A few of these advantages provide the analyst/designer the capability to better distribute local stresses, the ability to specify various degrees of bond around the fiber circumference, and to account for the fiber breaks and matrix cracking. These are some of the issues that must be addressed to adequately describe the micromechanical behavior of ceramic matrix composites.

The objective of the present paper is twofold. First, to describe the fiber substructuring concepts and the micromechanics equations that are embedded in CEMCAN; and second, to describe the computer code CEMCAN, its current features and capabilities and some illustrative examples to demonstrate the versatility of the code.

FIBER SUBSTRUCTURING AND MICROMECHANICS

The primary objective of composite micromechanics is to determine the equivalent elastic moduli of a composite material in terms of the elastic moduli of the constituent materials. An additional and complementary objective of the micromechanics approaches is to determine the strengths of the composite material in terms of the strengths of the constituent materials. Other

properties of interest are the composite thermal expansion coefficients, thermal conductivities and heat capacity.

The derivation of equivalent composite ply properties using micromechanics theory starts with the identification of a representative volume element or unit cell. It is the smallest region or piece of material over which the stresses and strains are macroscopically uniform. However, within the unit cell the stresses and strains are nonuniform due to the heterogeneity of the material. The unit cell can consist of a fiber, matrix and/or an interphase. It is assumed that these cells are arranged in a regular pattern. Furthermore, it is assumed that the unit cell be either a square or a hexagon depending upon the chosen array pattern. Equivalent properties for the ply are then derived in terms of the constituent material properties based on the mechanics of materials approach. Other assumptions involved in this approach are: (1) fiber and matrix are subjected to the same strain in the fiber direction of a unidirectional fibrous composite, and (2) the same transverse stress is applied to both the fiber and matrix in the direction transverse to the fiber.

The details of the representative volume element chosen previously in the development of ICAN [Ref. 2] and METCAN [Ref. 3-5] are shown in Fig. 1. The unit cell for ICAN consists of two distinct regions A (matrix only) and B (fiber and matrix). The unit cell for METCAN, however, may consist of a maximum of three regions, A, B, and C. The region A consists of matrix only, the region B consists of a combination of matrix and interphase, and the region C consists of a combination of all three constituents: fiber, matrix and interphase. Note, that in the following discussion the interphase is treated as a separate constituent with distinct properties. Thus, it can either represent a zone formed due to a chemical reaction between the fiber and matrix or a separate layer provided intentionally to prevent such a reaction. The different regions facilitate the representation of the nonuniformity in the local stress distribution.

In the application of this approach to CMCs the same type of array pattern is assumed. However, the unit cell is further subdivided into several slices and the equations of micromechanics are derived for each slice. These are subsequently integrated to obtain unit cell/ply level properties. The modeling details of the substructured unit cell are illustrated in Fig. 2. To derive the equivalent slice properties consider a slice taken out from the unit cell. Let d_f, d_m, and d_i be the fiber, matrix, and interphase widths. Let h be the height of the slice and s be the total width of the slice. Since it is customary to express the equivalent properties in terms of the properties of each of the constituents and their respective volume ratios, let k_f, k_m, and k_i be the fiber, matrix and the interphase volume ratios respectively. Then by definition

$$k_f = \frac{d_f}{s}; \quad k_m = \frac{2d_m}{s}; \quad k_i = \frac{2d_i}{s} \tag{1}$$

Now that the preliminary parameters have been established; the mechanics of materials approach is applied to generate the composite mechanical and thermal properties.

Mechanical Properties

By applying the force equilibrium in the longitudinal direction the following equation can be written.

$$\sigma_{\ell 11} hs = \left(2\sigma_{m11}d_m + 2\sigma_{i11}d_i + \sigma_{f11}d_f\right)h \tag{2}$$

Also, based on the assumptions for the mechanics of the materials approach one can write the following equation.

$$\varepsilon_{\ell 11} = \varepsilon_{m11} = \varepsilon_{i11} = \varepsilon_{f11} \tag{3}$$

With the aid of Eqs. (1) to (3) the longitudinal modulus, $E_{\ell 11}$, can be written as

$$E_{\ell 11} = k_f E_{f11} + k_m E_{m11} + k_i E_{i11} \tag{4}$$

The Poisson's ratio in 1-2 direction can be derived by considering the strain in the transverse direction (22) as the sum of the individual strains in the constituents. Accordingly,

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$$\epsilon_{\ell22}s = 2\epsilon_{m22}d_m + 2\epsilon_{i22}d_i + \epsilon_{f22}d_f \tag{5}$$

Also, by definition

$$\nu_{j12} = \frac{\epsilon_{j22}}{\epsilon_{j11}} \tag{6}$$

where j can represent any of the subscripts ℓ, m, i, or f.

The combination of Eqs. (1), (5), and (6) leads to the following equation for the major Poisson's ratio

$$\nu_{\ell12} = k_f \nu_{f12} + k_m \nu_{m12} + k_i \nu_{i12} \tag{7}$$

The modulus in the transverse (2-2) direction can be derived by assuming that the same transverse stress, $\sigma_{\ell22}$, is applied to the fiber, matrix and interphase.

$$\sigma_{\ell22} = \sigma_{m22} = \sigma_{i22} = \sigma_{f22} \tag{8}$$

With the aid of Eqs. (5) and (8) and noting that

$$\epsilon_{j22} = \frac{\sigma_{j22}}{E_{j22}} \tag{9}$$

one can derive the following equation for the transverse modulus in the direction 2-2.

$$E_{\ell22} = \frac{E_{m22}E_{i22}E_{f22}}{k_m E_{i22}E_{f22} + k_i E_{f22}E_{m22} + k_f E_{m22}E_{i22}} \tag{10}$$

The in-plane shear modulus in (1-2) direction is determined by assuming that the shearing stresses on the fiber and the matrix are the same. In this respect the derivation of $G_{\ell12}$ is similar to that for $E_{\ell22}$. The equation for $G_{\ell12}$ can be shown as

$$G_{\ell12} = \frac{G_{m12}G_{i12}G_{f12}}{k_m G_{i12}G_{f12} + k_i G_{f12}G_{m12} + k_f G_{m12}G_{i12}} \tag{11}$$

The remaining mechanical properties can be derived in a similar fashion and are given by

$$E_{\ell33} = \frac{E_{m33}E_{i33}E_{f33}}{k_m E_{i33}E_{f33} + k_i E_{f33}E_{m33} + k_f E_{m33}E_{i33}} \tag{12}$$

$$G_{\ell 13} = \frac{G_{m13}G_{i13}G_{f13}}{k_m G_{i13}G_{f13} + k_i G_{f13}G_{m13} + k_f G_{m13}G_{i13}} \tag{13}$$

$$G_{\ell 23} = \frac{G_{m23}G_{i23}G_{f23}}{k_m G_{i23}G_{f23} + k_i G_{f23}G_{m23} + k_f G_{m23}G_{i23}} \tag{14}$$

$$\nu_{\ell 13} = k_f \nu_{f13} + k_m \nu_{m13} + k_i \nu_{i13} \tag{15}$$

$$\nu_{\ell 32} = k_f \nu_{f32} + k_m \nu_{m32} + k_i \nu_{i32} \tag{16}$$

The Poisson's ratios in 2-3, 2-1, and 3-1 directions are given by the reciprocity relations

$$\nu_{\ell 23} = \frac{\nu_{\ell 32}E_{\ell 22}}{E_{\ell 33}} \tag{17}$$

$$\nu_{\ell 21} = \frac{\nu_{\ell 12}E_{\ell 22}}{E_{\ell 11}} \tag{18}$$

$$\nu_{\ell 31} = \frac{\nu_{\ell 13}E_{\ell 33}}{E_{\ell 11}} \tag{19}$$

Thermal Properties

The equivalent thermal conductivity in the (1-1) direction can be derived by equating the total heat flow rate across the cross section to the sum of the individual rates in each constituent. The heat flow rate can be calculated using the Fourier's law of heat conduction. By following the above steps the heat flow rate equilibrium equation can be written as

$$K_{\ell 11}s\,h\frac{dT}{dL} = k_{f11}d_f h\frac{dT}{dL} + K_{m11}d_m h\frac{dT}{dL} + K_{i11}d_i h\frac{dT}{dL} \tag{20}$$

where (dT/dL) is the thermal gradient across a typical length of the cell L in the (1-1) direction (Fig. 3). Simplification of the above equation leads to the following:

$$K_{\ell 11} = k_f K_{f11} + k_m K_{m11} + k_i K_{i11} \tag{21}$$

The equivalent thermal conductivities in the (2-2) can be derived by noting that the total heat flow rate across each constituent in the (2-2) direction should be same. Thus from Fig. 3 the following can be written:

$$Q = K_{\ell 22}(Lh)\left[\frac{T_5 - T_0}{s}\right] = K_{m22}(Lh)\left[\frac{T_5 - T_4}{d_m}\right] = K_{i22}(Lh)\left[\frac{T_4 - T_3}{d_i}\right]$$

$$= K_{f22}(Lh)\left[\frac{T_3 - T_2}{d_f}\right] = K_{i22}(Lh)\left[\frac{T_2 - T_1}{d_i}\right] = K_{m22}(Lh)\left[\frac{T_1 - T_0}{d_m}\right] \tag{22}$$

where the T_0 through T_5 are the temperatures at various cross sections along the slice as shown in the Fig. 3. The above equation can be rearranged as

$$K_{\ell 22} = K_{m22}\left[\frac{T_5 - T_4}{T_5 - T_0}\right]\frac{s}{d_m}$$

$$= \left[\frac{T_5 - T_4}{\left(T_5 - T_4\right) + \left(T_4 - T_3\right) + \left(T_3 - T_2\right) + \left(T_2 - T_1\right) + \left(T_1 - T_0\right)}\right]\frac{s}{d_m} \tag{23}$$

By observing the fact that $(T_4 - T_3) = (T_2 - T_1)$ and $(T_5 - T_4) = (T_1 - T_0)$, the above can be further simplified into

$$K_{\ell 22} = \left[\frac{1}{2 + 2\left(\dfrac{T_4 - T_3}{T_5 - T_4}\right) + \left(\dfrac{T_3 - T_2}{T_5 - T_4}\right)}\right]K_{m22}\frac{s}{d_m} \tag{24}$$

With the aid of Eqs. (1) and (22), Eq. (24) can be written as $K_{\ell 22} = \dfrac{K_{m22}}{k_m + \dfrac{k_i K_{m22}}{K_{i22}} + \dfrac{k_f K_{m22}}{K_{f22}}}$ which leads to

$$K_{\ell 22} = \frac{K_{m22}K_{i22}K_{f22}}{k_m K_{i22}K_{f22} + k_i K_{f22}K_{m22} + k_f K_{m22}K_{i22}} \tag{25}$$

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The thermal conductivity along the (3-3) direction can be derived in a similar manner and is given by

$$K_{\ell 33} = \frac{K_{m33}K_{i33}K_{f33}}{k_m K_{i33}K_{f33} + k_i K_{f33}K_{m33} + k_f K_{m33}K_{i33}} \tag{26}$$

The equivalent heat capacity C_ℓ can be derived by equating the sum of the heat contained in the individual regions to the heat contained in the slice based on the equivalent heat capacity:

$$C_\ell = \frac{k_m \rho_m C_m + k_i \rho_i C_i + k_f \rho_f C_f}{\rho_\ell} \tag{27}$$

where ρ_ℓ is the equivalent density of the slice and ρ_m, ρ_i, and ρ_f are respectively the densities of the matrix, interphase and fiber. The equivalent density can be expressed in terms of the individual densities by the simple rule of mixtures:

$$\rho_\ell = k_f \rho_f + k_m \rho_m + k_i \rho_i \tag{28}$$

The longitudinal thermal expansion coefficient can be derived by noting that the sum of the forces in the longitudinal direction should be zero:

$$\begin{aligned}
\left(2d_m E_{m11} + 2d_i E_{i11} + d_f E_{f11}\right)\alpha_{\ell 11} \, \Delta T \\
= -\left(2d_m \alpha_{m11} E_{m11} + 2d_i \alpha_{i11} E_{i11} + d_f \alpha_{f11} E_{f11}\right)\Delta T = 0
\end{aligned} \tag{29}$$

where ΔT is the temperature difference. Simplification of Eq. (29) leads to the following expression for the longitudinal thermal expansion coefficient:

$$\alpha_{\ell 11} = \frac{k_m \alpha_{m11} E_{m11} + k_i \alpha_{i11} E_{i11} + k_f \alpha_{f11} E_{f11}}{E_{\ell 11}} \tag{30}$$

The transverse thermal expansion coefficient can be derived by equating the total strain in the (2-2) direction to the sum of the individual strains in each region:

$$\alpha_{\ell 22}s \, \Delta T = 2d_m \alpha_{m22} \, \Delta T + 2d_i \alpha_{i22} \, \Delta T + d_f \alpha_{f22} \, \Delta T \tag{31}$$

With the aid of Eqs. (1) and (31) $\alpha_{\ell 22}$ can be written as

$$\alpha_{\ell 22} = k_f \alpha_{f22} + k_m \alpha_{m22} + k_i \alpha_{i22} \tag{32}$$

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The expression for $\alpha_{\ell33}$ is similar to the above and is given by

$$\alpha_{\ell33} = k_f\alpha_{f33} + k_m\alpha_{m33} + k_i\alpha_{i33} \tag{33}$$

This set of equations define the equivalent properties for a typical slice with three regions. The procedure to obtain the equivalent properties of the representative volume element (unit cell) is analogous to that of obtaining the properties of a typical laminate from the ply properties. Here each slice is treated as a subply within the unit cell.

CEMCAN COMPUTER CODE

These new micromechanics equations have been programmed as a separate micromechanics module and integrated into a computer code similar to that of the earlier ICAN and METCAN codes. The new code is named CEMCAN and its flow chart is shown in Fig. 4. Not all aspects of the code as shown in the figure, are currently operational; a brief description follows.

The material behavior model depicted in the center describes the constituent property as a function of several independent variables such as the current temperature, stress and time. On the basis of the current properties, the equivalent properties for the slice are calculated using the micromechanics equations. The left side of the Fig. 4 shows the progressive integration or synthesis of the various stages in CEMCAN starting from the slice level properties and ending with the description of the laminate level properties. The details involved are described briefly in the following paragraphs. Some of these details are of text book nature and therefore the reader is advised to consult text books on composite mechanics [Ref. 1, for example] for a complete in depth discussion.

Step 1. Properties of a lamina from the slice level properties.

This involves integration of slice level properties through the unit cell to obtain the equivalent properties of the unit cell. Since it is the smallest representative volume element,

these properties can be considered as equivalent properties of a lamina. The integration from a slice to unit cell is achieved by using the classical laminate theory.

Step 2. Properties of a single ply from the lamina properties.

To obtain ply properties from lamina properties two cases must be considered. First, if there is a single fiber through the thickness of the ply, then the ply properties are identical to those of the lamina. However, if there are a number of fibers through the thickness of a single ply, then this ply is treated as a laminate made of a number of single fiber laminae. Consequently, the ply properties can be obtained by using once again the classical laminate theory.

Step 3. Properties of a laminate made of several plies.

The next step of integration involves the determination of global (laminate or structural level) properties from the single ply properties using macromechanics.

Step 4. Global or Laminate response to loads.

The global or laminate response at a point through the thickness consists of the strains and curvatures developed due to applied mechanical and thermal loads. This is accomplished using the well known principles of classical laminate theory.

The right hand side of the figure (Fig. 3) shows the successive reduction or decomposition of the laminate level response (strains and curvatures) to the slice level response. This involves going through the same steps as above in a reverse order.

Currently the micromechanics equations for the slice and integration to the ply level properties as well as decomposition of the ply response to the slice level response are completely programmed and are operational. In addition, the code can accommodate circular and arbitrarily shaped fibers by altering slicing in the horizontal and vertical directions (Fig. 5). Additional features including the consideration of material nonlinearities and constituent response within the slice are planned for the future.

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TYPICAL RESULTS AND DISCUSSION

The first set of results ensue from a verification exercise in which the proper formulation

of the equations is being checked using the established micromechanics in ICAN and METCAN.

To verify/illustrate the code's features and capabilities a typical composite system SiC (Silicon

carbide fiber)/Ti-15-3 (Titanium alloy matrix) is chosen. The reasons for this particular choice

are (1) the selected composite system is of current interest and (2) at this point the intention is

only to verify the micromechanics equations developed using the new fiber substructuring

concept. The typical properties for these constituents based upon the data given in Ref. [6] are

shown in Table I. Keeping a constant fiber volume ratio of 0.5, composite properties for the

SiC/Ti-15 are generated using CEMCAN as well as ICAN and METCAN. The resulting

predictions for composite moduli, Poisson's ratios, thermal conductivities and the coefficients of

thermal expansion are shown in Figs. 5 to 8.

Mechanical Properties

Unidirectional ply normal and shear moduli for the SiC/Ti15 composite system (with a

fiber volume ratio (FVR) of 0.5) are shown in Fig. 6. All three codes predicted almost the same

value for the ply longitudinal modulus. There appears to be much better agreement between

CEMCAN and METCAN for the remaining moduli. ICAN consistently over predicted with the

exception of the through the thickness shear modulus $G_{\ell 23}$. This is to be expected because, the

micromechanics equations embedded in ICAN are strictly for polymeric matrix composites which

involved certain simplifying assumptions [Ref. 7]. Similar trends are noticed in Fig. 7 also, where

the predictions of the Poisson's ratios for the same composite system are compared. However,

the differences, if any, are minimal.

Thermal Properties

Unidirectional ply thermal expansion coefficients for the composite system examined appear in

Fig. 8. With the exception of the longitudinal coefficient of thermal expansion α, all three

codes are in good agreement. The longitudinal thermal expansion coefficient predicted by METCAN is significantly higher (18 percent). The thermal conductivities predicted by all three codes are in excellent agreement as shown in Fig. 9.

Mechanical Response

The stress variation in a ply subjected to combined in plane loading is shown in Fig. 10. The benefits of fiber substructuring becomes clear from this example. The conventional micromechanics model in ICAN predicted a constant stress in the ply. In contrast, CEMCAN predicts a smooth variation of stresses through the ply thickness.

Thermal Response

The variation in the in plane stresses due to a 100 °F (311 K) increase in temperature is shown in Fig. 11. Once again, due to the fiber substructuring, CEMCAN is able to predict smooth variations in the in-plane stresses as opposed to a conventional model which predicts no stresses at all.

Verification of the CMC Micromechanics

The experimental data for a 0.3 FVR SiC/RBSN ceramic matrix composite system reported in Ref. [7] is used to conduct a limited validation study. More validation studies will be provided in future reports on the subject. Table II lists the properties of the constituents used for this study. The CEMCAN predictions are compared to the experimental data as shown in Fig. 12. Note that the properties are normalized with respect to the theoretically predicted value. As seen in the figure the longitudinal modulus as well as the major Poisson's ratio are in excellent agreement with the experimentally determined values. This is not very surprising because of the fiber dominated behavior in the longitudinal direction. The transverse modulus, the shear modulus and the minor Poisson's ratio are all over predicted. The experimentally observed values are about 50 percent or less than the theoretical predictions. Once again this should be expected because the theoretical model considered perfect bond between the fiber and

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matrix. In reality for CMC materials a very weak or nonexistent bond is quite common. To test this premise, a case was simulated utilizing an interphase with a thickness 5 percent of the diameter of the fiber and with negligible properties (listed in Table II). The results are shown in Fig. 11. The predicted properties now represent a lower bound for the composite. As seen from the figure, the experimentally measured values for the transverse direction clearly fall between the perfect bond and weak bond simulations. The experimental values are however much closer to the simulated results with weak bond. With the present model one can also try partial bonding as well as a host of other combinations.

SUMMARY AND FUTURE PLANS

Based on the results presented in this study, it can be concluded that:

1. The prediction of ply mechanical and thermal properties agreed very well with the existing models in ICAN and METCAN; lending credence to the fiber substructuring approach.

2. The verification case presented for SiC/RBSN composite system showed good agreement with the experimental results. Also, methods to establish upper and lower bounds to the mechanical properties are illustrated.

3. Fiber substructuring can capture greater local detail than conventional unit cell based micromechanical theories. Therefore, it offers promise in simulating complex aspects of micromechanics in ceramic matrix composites (CMC) such as (a) various degrees of bond around the fiber circumference and along the length, (b) fiber breaks and matrix cracking, (c) effects of these on ply thermal and mechanical properties/response.

4. The approach is general and versatile. It can be applied to any type of continuous fiber reinforced matrix composite.

The response decomposition from the slice (subply) level to the local (in each constituent) level is currently under development. This will enable predictions of local stresses (fiber, matrix, and interphase regions) within the slice. A nonlinear material behavior model to describe the

current constituent properties as a function of the reference properties and the current response is also under development.

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Table I. Properties Chosen in the Study for SiC Fiber and Ti-15 Matrix

SiC fiber properties			Ti-15 matrix properties		
E_f	62.0 Mpsi	427 GPa	E_m	12.3 Mpsi	85 GPa
G_f	23.8 Mpsi	164 GPa	G_m	4.7 Mpsi	32 GPa
ν_f	0.3		ν_m	0.32	
K_f	0.75 Btu/hr/in./°F	1.3 w.mK	K_f	0.39 Btu/hr/in./°F	0.67 w/mK
α_f	1.8 ppm/°F	3.2 ppm/K	α_m	4.5 ppm/°F	8.1 ppm/K
C_f	0.29 Btu/lb	1.2 kJ/kg K	C_m	0.12 Btu/lb	0.5 kJ/kg K
ρ_f	0.11 lb/in.³	3 Mg/m³	ρ_{in}	0.17 lb/in.³	4.8 Mg/m³
T_f	4870 °F	2961 K	T_m	1800 °F	1255 K
d_f	0.0056 in. (0.14 mm)				

Table II. Properties Chosen in the Study for SiC/RBSN Composite System

SiC fiber properties			RBSN matrix properties			Interphase		
E_f	56.6 Mpsi	390 GPa	E_m	15.9 Mpsi	110 GPa	E_i	100 psi	0.7 GPa
G_f	24.2 Mpsi	150 GPa	G_m	6.5 Mpsi	45 GPa	G_i	40 psi	0.27 GPa
ν_f	0.17		ν_m	0.22		ν_i	0.22	
d_f	0.0056 in. (0.14 mm)							

Square Array
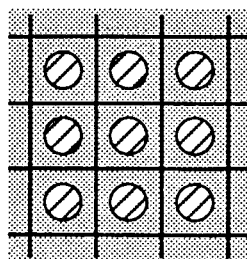
ICAN Unit Cell   METCAN Unit Cell
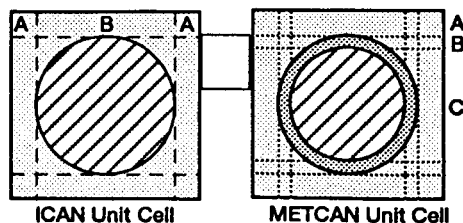
Figure 1.—Unit cell square array concepts in ICAN and METCAN codes.
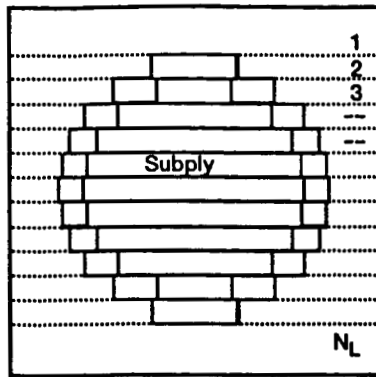
Unit cell with fiber, matrix, and
interphase divided into N_L slices
(subplies)

Individual slice showing three regions:
fiber, matrix, and interphase
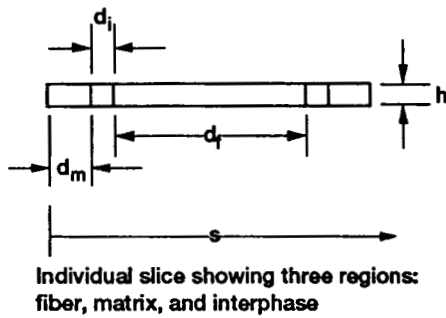
Figure 2.—Ply/fiber substructuring concept for
ceramic matrix composite micromechanics -
mechanics of materials approach.

(1-1) direction   (2-2) direction
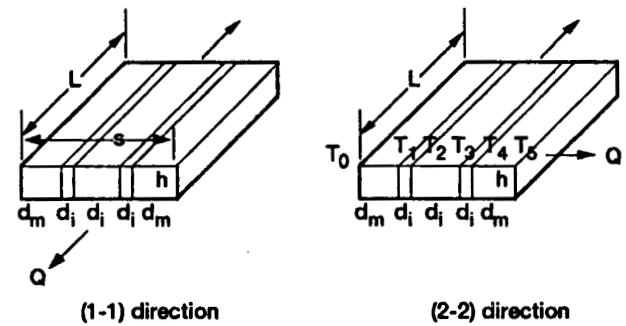
Figure 3.—Modeling details for the slice for deriving the equiv-
alent slice thermal conductivities.
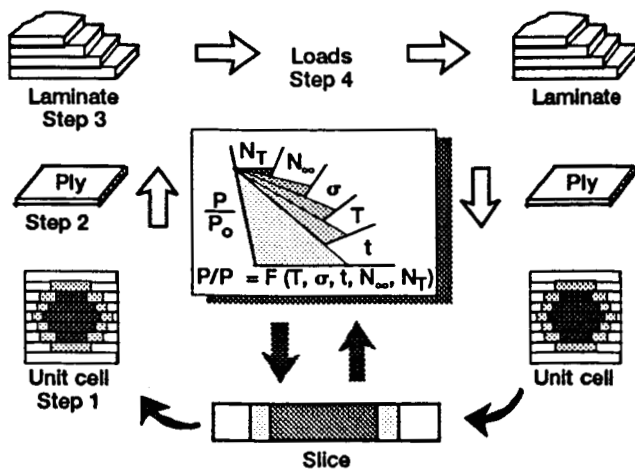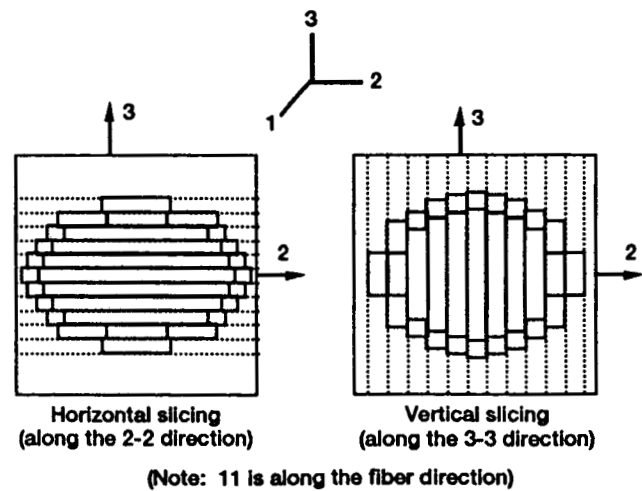

Figure 4.—Integrated analysis approach embedded in CEMCAN.

Horizontal slicing   Vertical slicing
(along the 2-2 direction)   (along the 3-3 direction)

(Note: 11 is along the fiber direction)

Figure 5.—Different fiber shapes and slicing arrangements
available in CEMCAN.
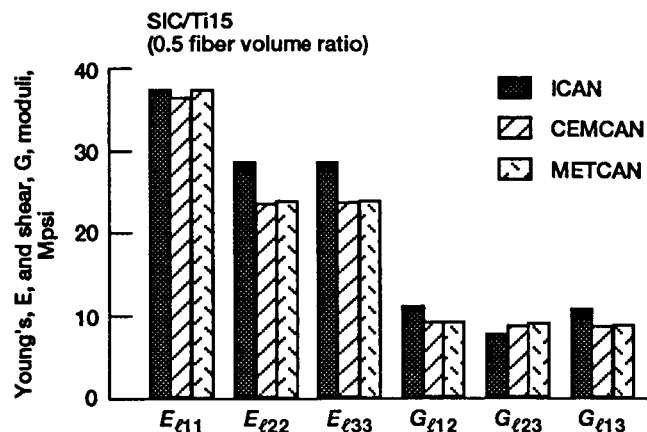
Figure 6.—Comparison of ICAN, CEMCAN, and METCAN predictions of Young's moduli and shear moduli for unidirectional SiC/Ti15-3 composite at .5 fvr.
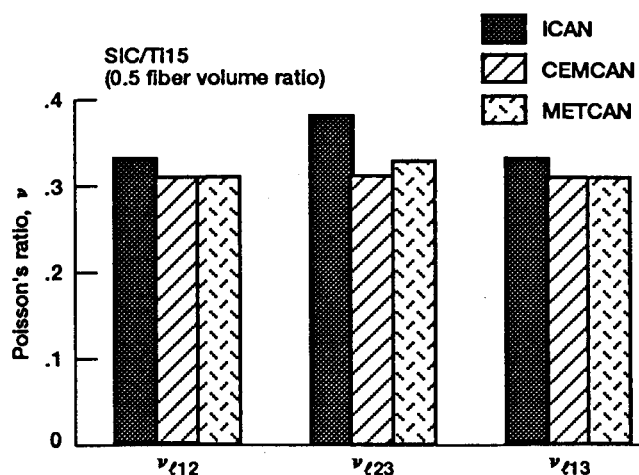
Figure 7.—Comparison of ICAN, CEMCAN, and METCAN predictions of Poisson's ratios for a unidirectional SiC/Ti15-3 composite at .5 fvr.
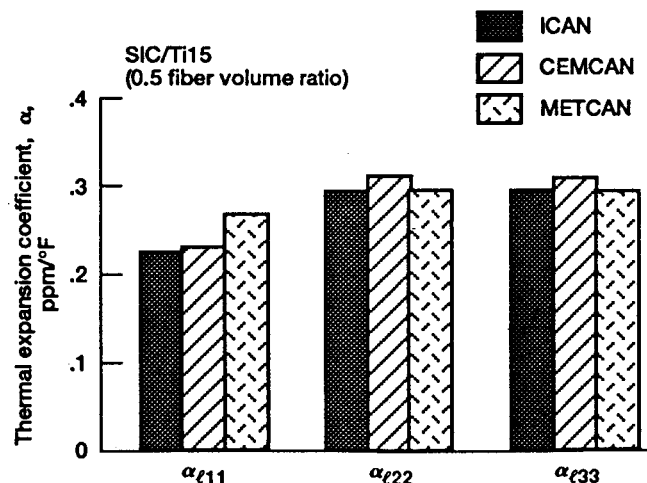
Figure 8.—Comparison of ICAN, CEMCAN, and METCAN predictions of thermal expansion coefficients for a unidirectional SiC/Ti15-3 at .5 fvr.
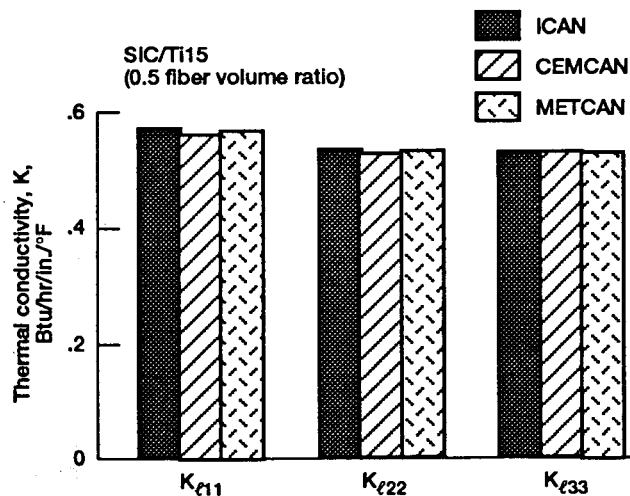

Figure 9.—Comparison of ICAN, CEMCAN, and METCAN predictions of thermal conductivities for a unidirectional SiC/Ti15-3 composite at .5 fvr.

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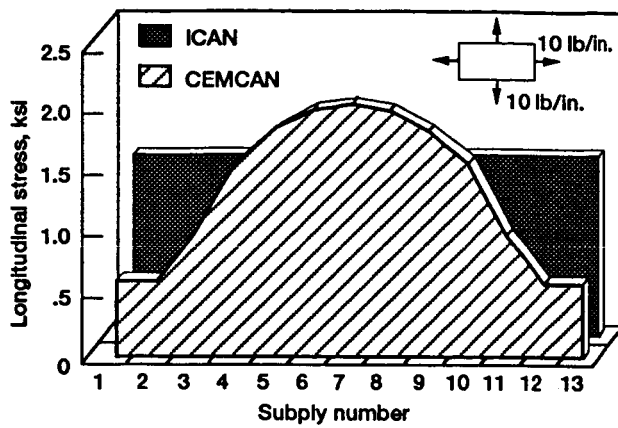
Figure 10.—Variation of longitudinal stress within the ply as predicted by CEMCAN for a unidirectional SiC/Ti15-3 composite at .5 fvr under a combined in-plane loading.
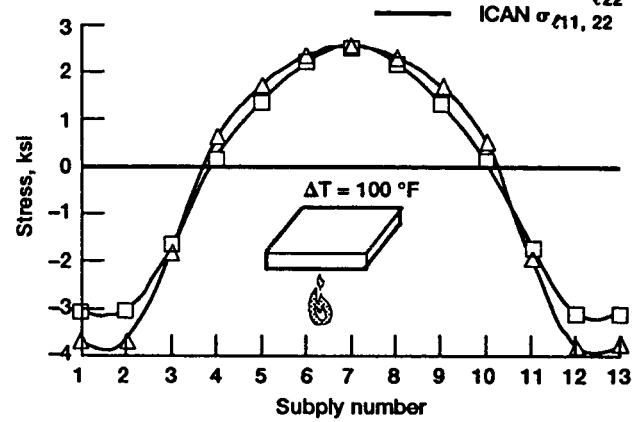
Figure 11.—Variation of the in-plane stresses within the ply as predicted by CEMCAN for a unidirectional SiC/Ti15-3 composite at .5 fvr under a 100 °F uniform heating.
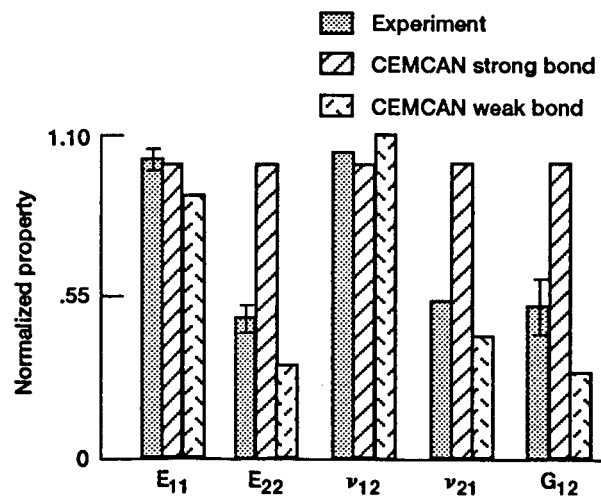

Figure 12.—Mechanical properties of SiC/RBSN composite (0.3 fvr): CEMCAN vs experiments.

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13. ABSTRACT (Maximum 200 words)

A generic unit cell model which includes a unique fiber substructuring concept is proposed for the development of micromechanics equations for continuous fiber reinforced ceramic composites. The unit cell consists of three constituents: fiber, matrix and an interphase. In the present approach, the unit cell is further subdivided into several slices and the equations of micromechanics are derived for each slice. These are subsequently integrated to obtain ply level properties. A stand alone computer code containing the micromechanics model as a module is currently being developed specifically for the analysis of ceramic matrix composites. Towards this development, equivalent ply property results for a SiC (silicon carbide fiber)/Ti-15-3 (Titanium matrix) composite with a 0.5 fiber volume ratio are presented and compared with those obtained from customary micromechanics models to illustrate the concept. Also, comparisons with limited experimental data for the ceramic matrix composite, SiC/RBSN (Reaction Bonded Silicon Nitride) with a 0.3 fiber volume ratio are given to validate the concepts.

14. SUBJECT TERMS

Micromechanics; Macromechanics; Fiber substructuring; Subply; Ceramic matrix composites; Unit cell; Mechanical properties; Thermal properties; Metal matrix composites; Polymer matrix composites; Interphase

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