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Simplified Micromechanics of Plain Weave Composites

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SUMMARY

A micromechanics based methodology to simulate the complete hygro-thermomechanical behavior of plain weave composites is developed. This methodology is based on micromechanics and the classical laminate theory. The methodology predicts a complete set of thermal, hygral and mechanical properties of plain woven composites, generates necessary data for use in a finite element structural analysis, and predicts stresses all the way from the laminate to the constituent level. This methodology is used in conjunction with a composite mechanics code to analyze and predict the properties/response of a generic graphite/epoxy woven textile composite and a plain weave ceramic composite. The fiber architecture, including the fiber waviness and fiber end distributions through the thickness, is properly accounted for. Predicted results compare reasonably well with those from detailed three-dimensional finite element analyses as well as available experimental data. However, the main advantage of the proposed methodology is its high computational efficiency as compared with three-dimensional finite element analyses.

INTRODUCTION

There is growing interest in the use of woven composites for structural applications. Such applications range from bio-medical components, aircraft and space structures to automotive and other applications. In the case of aircraft structures, woven or braided composites can be used for a wide variety of cross-sectional forms such as stiffeners, truss members, rotor blade and spars etc. to reduce the fabrication costs. Reinforcement of these composites are formed by various processes such as weaving, braiding or knitting, etc. Woven fabric composites, in particular, are constructed by weaving two fiber tows into each other to form a layer. These layers are then impregnated with a resin or matrix material, stacked in a desired orientation, and cured to obtain a composite laminate. The interlacing of fiber bundles has several advantages such as increasing the intra- and inter-laminar strength, greater damage tolerance, as well as providing a possibility to produce near net shape structural components. Such capabilities are very important for producing thick laminates. However, these advantages come at the expense of some loss in the in-plane stiffness and strength, which depends upon the weave architecture. There is certainly a need for sound engineering data as well as verified and efficient analytical/design methodologies to evaluate different parameters. These design methodologies must account for processing parameters and microstructural/geometrical features for accurate modeling of such composites.

This need has been addressed by many researchers (refs.1 to 9). There are certain models based on classical laminate theory which are used mainly to predict laminate level properties. These models include the mosaic model, the fiber undulation model, and the fiber bridging model. They are generally based on laminate theory. Then there are numerical models which are based on three-dimensional finite element analyses. Notable among these is the work of Whitcomb (ref. 5) for analyzing textile fabric composites. Whitcomb analyzed plain weave textile composites using brick elements and predicted properties of the unit cell for different waviness ratios and strain concentrations in the fiber cross-over regions. The moduli and the Poisson's ratios were predicted for a generic graphite/epoxy woven textile composite for various waviness ratios. Raju et al. (ref. 3) provided an overview of the analytical methods for woven composites. However, using the above analytical methods, it would be difficult to smoothly incorporate processing and environmental degradation effects. Furthermore, numerical analysis techniques such as finite element analyses are very tedious and cannot be used in a routine manner for woven composites. The model generation itself is very cumbersome and extremely time-consuming for such complex fiber architectures. Such numerical techniques should only be used either at the structural level or strictly for verification purposes at the micromechanical level.

NASA Lewis Research Center has been involved in the development of micromechanics based composite analysis codes for over two decades and several computer codes have been developed as part of that effort. One of these codes is ICAN (Integrated Composite Analyzer, ref. 10) that has been developed for a comprehensive analysis of continuous fiber reinforced polymer matrix composites. The program performs micromechanics, macromechanics and laminate analysis including the hygrothermal response of fiber composites. Fabrication-related issues and environmental degradation effects are also taken into account. Another code that is under development is CEMCAN (Ceramic Matrix Composite Analyzer, ref. 11) which performs a comprehensive analysis of ceramic matrix composites. The objective of the present work is to develop a methodology to predict the laminate properties and response of woven composites, that can be used in conjunction with composite mechanics codes such as ICAN and CEMCAN computer codes mentioned earlier. The intention of the present work is to develop a methodology that can make use of the capabilities that already exist for laminated composites, yet account for fiber waviness and fiber end distributions through the thickness accurately to simulate woven composite behavior. The present analysis parallels fiber crimp or undulation model (ref. 2). Micromechanics based techniques have certain advantages - the response can be decomposed down to the constituent level and since the micromechanics itself is based on closed-form equations, it is inherently much more efficient than a numerical analysis technique—both in terms of analysis time and the time required to generate a model. In the following, the methodology based on micromechanics for the analysis of woven composites, is explained briefly and is applied to a generic graphite/epoxy plain weave composite to predict the properties and the response to the applied in-plane tensile loading. These predictions are compared with the results obtained from a detailed three-dimensional finite element analyses and with some available experimental data. The properties of a SiC/SiC balanced fabric plain weave ceramic composite are also predicted and compared with measured values.

PLAIN WEAVE GEOMETRY

As mentioned before, there are several geometries/architectures for woven composites. In the case of two-dimensional woven fabric composites, two sets of mutually orthogonal sets of yarns of the same material (non-hybrid) or different material (hybrid) are interlaced with each other. The various types of architectures can be formed depending on how the pattern in the interlaced regions is repeated. Plain weave is a special case of two-dimensional woven fabric composites. In the case of plain woven composites, a "warp" or longitudinal fiber tow is interlaced with every second "fill" or width fiber tow as shown in figure 1. A representative volume element (RVE) or a unit cell for such a laminate construction is shown in figure 2 which has a dimension of a x a x h (only 1/4 of the actual unit cell is shown here). Symmetry is used and only this portion of the unit cell is used in the analyses. If one takes a section such as shown in figure 3, there is a portion where the tow is straight and the construction is like a [0/90] laminate and then there is a wavy portion of the tow. A useful parameter defined by Whitcomb (ref. 5) is the waviness ratio which is defined as the length of the wavy portion of the tow to the total fiber tow length (a_u/a). The other orthogonal tow is dispersed on either side of this wavy tow as shown in the figure and there is also a matrix rich area whose volume fraction depends upon material and geometry and can be a substantial fraction of the overall volume. A three-dimensional finite element mesh of the unit cell is also generated and various elastic analyses are carried out as explained in a later section.

SIMPLIFIED MICROMECHANICS

A typical section of the unit cell is shown in figure 3. and shows a warp fiber tow, a fill fiber tow in the orthogonal direction and a matrix rich region that arises due to the geometry of plain weave composites. The undulated shape of the fiber tows is chosen as follows, as suggested by Chou and Ishikawa (ref. 2) and shown in figure 3. For the warp fiber:

$$h_1(x) = \begin{cases} 0 & 0 \le x \le a_1 \\ \dfrac{h}{4}\left[1 + \sin\left(x - \dfrac{a}{2}\right)\dfrac{\pi}{a_u}\right] & a_1 \le x \le a_2 \\ \dfrac{h}{2} & a_2 \le x \le a \end{cases} \tag{1}$$

The sectional shape of the fill region:

$$\begin{array}{cc} \dfrac{h}{2} & 0 \le x \le a_1 \\ \dfrac{h}{4}\left[1 - \sin\left(x - \dfrac{a}{2}\right)\dfrac{\pi}{a_u}\right] & a_1 \le x \le \dfrac{a}{2} \\ -\dfrac{h}{4}\left[1 - \sin\left(x - \dfrac{a}{2}\right)\dfrac{\pi}{a_u}\right] & \dfrac{a}{2} \le x \le a_2 \\ -\dfrac{h}{2} & a_2 \le x \le a \end{array} \qquad (2)$$

where: a_u is the length of the undulated (wavy) fiber tow, h is the height, a_1 and a_2 are as shown in figure 3.

It is assumed that the laminate plate theory is applicable at each section of the model along the x-axis. The section (fig. 3) is divided into several slices. For a slice in the straight region, the equivalent properties of the slice can be obtained by running a [0/90] laminate analysis. For the undulated region, the following technique is used - a typical slice in the undulated region may look like the one shown in figure 4. In general, it will have three regions - fill fiber region, warp fiber region and a matrix rich area. The off-axis angle for the warp yarn is:

$$\theta(x) = \tan^{-1} \frac{dh_1(x)}{dx} \qquad (3)$$

Knowing θ for a particular slice (at the mid-point of the slice), the E_{xx} for the slice can be obtained by running a laminate analysis of a [90/θ/0] laminate. The E_{xx} of this "laminate" is same as the E_{xx} for the slice. The 90° "ply" in this laminate represents the fill yarn, θ "ply" represents the warp yarn and the 0 "ply" is the matrix or resin rich area. The matrix is assumed to be isotropic, while fibers can be transversely isotropic ($E_2 = E_3$). The thickness of each "ply" is properly accounted for depending upon the location of a particular slice in the section. Equivalent through-the-thickness modulus (E_{zz}) of the slice can be obtained as the E_{yy} of the [0/θ/0] laminate, where the first 0 "ply" now represents the fill fiber tow region. Since the ply orientation in laminate theory is in x-y plane, a proper orientation has to be taken into account to compute equivalent slice properties and the corresponding thickness of each region within a slice. Poisson's ratios and shear moduli are also computed in a similar manner (i.e. using laminate theory in a judicious manner). Knowing the equivalent properties of the slices, these are stacked as "plies" in a "laminate" and the computed laminate properties represent the equivalent properties of this section. For the stress analysis, a laminate analysis is carried out with an applied load (in-plane or out-of-plane) to obtain equivalent slice stresses in warp and fill regions. Using micromechanics analysis once again, these stresses in the fill and the warp regions can be divided into fiber and matrix microstresses if desired. Thus, this technique can provide a very detailed response at any level. All the features that are already built into a laminate analysis code such as ICAN (ref. 10) (e.g. incorporation of processing, effect of voids, environmental degradation, and cyclic load effects) can be easily incorporated in this analysis. Such detailed response can not be obtained from a numerical analysis technique in an efficient manner. The CEMCAN (Ceramic Matrix Composite Analyzer, ref. 11) computer code currently under development at NASA Lewis Research Center was used for composite mechanics computations in the case of predicting SiC/SiC plain weave properties, while the ICAN computer code also developed at NASA Lewis Research Center was used for laminate analyses in the case of woven polymeric composites.

FINITE ELEMENT ANALYSIS

A set of three-dimensional finite element analysis was also carried out to verify the predictions of the micromechanics analysis. Figure 5 shows a finite element mesh of the plain weave composite considered in this work. The waviness ratio is taken as 0.5. The unit cell is 30 mils × 30 mils (760 × 760 μm) in the planar dimension and is 10 mils (254 μm) thick (dimension of the unit cell depends upon the particular material and is generally provided as number of fiber tows per linear inch). This mesh has 1008 solid elements (mostly 8 noded bricks) and 1375 nodes. Both normal and shear loadings were considered for computing normal and shear moduli. Boundary conditions were applied in such a manner that if the face at x=0 has a specified displacement u=0 and the face at x=L has a specified displacement $u=u_1$, other faces are constrained to move in a planar manner through the use of conditions that mimic multi-point constraints (MPC). The details of the boundary conditions are provided in reference 5. The finite element mesh was generated using the MSC Patran computer code (ref. 12). Resulting nodal forces due to the applied displacements are computed and by dividing them by the cross-sectional area average stresses are computed. Equivalent modulus is computed by dividing this average stress by the applied strain. Equivalent moduli were also computed by equating the external work done to the internal strain energy. Poisson's ratios are also computed by computing the average strain in the transverse direction and dividing it by the applied strain. The analyses in this work were limited to linear elastic analyses.

RESULTS AND DISCUSSION

Two material systems were considered in this work as explained below -

Graphite/Epoxy Plain Weave Textile Composite.—The material used for this work is a generic graphite/epoxy composite. The tow properties were selected that correspond to a 62% fiber volume ratio (fvr) AS Graphite/Epoxy unidirectional tape prepreg material. The epoxy matrix is isotropic. The material properties for this composite system are shown in table I. The properties of a conventional [0/90] laminate fabricated from the same tape material (62%t fvr graphite/epoxy composite) were computed using laminate theory for comparison purposes. These properties are listed in table II for comparison purposes. One note worth mentioning again - there is some loss in axial stiffness due to the waviness of the fibers. Moreover, because of the matrix rich areas, overall fvr are somewhat lower than they are in the tow areas. Hence, the reduction in properties, as compared to a [0/90] laminate occurs due to both of the above factors. The results presented below should be viewed in that light.

Table II shows the normal and shear moduli and Poisson's ratios for this weave. The section was divided into 20 slices (each 1.5 mil or 38 μm wide). There is 20 to 30 percent drop in the in-plane longitudinal modulus as compared to a [0/90] laminate modulus., while the drop in through-the-thickness modulus is approximately 10 percent. Although, the fibers have a component in the z-direction, which will cause an increase in through-the-thickness stiffness, the matrix rich area causes the reverse effect and for this particular weave there is a drop in through-the-thickness modulus. There is a slight increase in the ν_{xy} value as compared to a [0/90] laminate value. Such observation compares well with the experimental observation in reference 6, which noted that there is an increase in ν_{xy} as the waviness ratio increases. In-plane shear modulus shows a slight decrease. The difference in micromechanical predictions and finite element analysis results is less than 10 percent. These results also compare quite favorably with the earlier work by Whitcomb (ref. 5) which used a three-dimensional finite element analyses to analyze these woven composites.

Figures 6 through 8 show the stresses in the fiber tows in the loading direction, fiber and matrix stresses in the various regions of the unit cell. The latter can only be obtained from a micromechanics based analysis as it has the capability to decompose fiber tow stresses into individual constituent values. Such detailed analysis will be useful for strength predictions. Stress predictions from the micromechanical analysis are also within 10 percent of the finite element predictions. At this time, no attempt was made to either refine the mesh or to increase the number of slices in the micromechanics model to determine the sensitivity of stresses. Work is continuing in this area. The user can divide the unit cell section in as many slices as desired or until a single slice will contain a single fiber in the width direction.

SiC/SiC Plain Weave Composite - The constituent material properties for the SiC/SiC 0/90 balanced fabric plain weave composite are shown in Table III. The fiber in this composite is Nicalon fiber and has 500 filaments/tow and fiber tow thickness is 152 μm (ref. 9) in the fabricated composite. These composites also have a high degree of porosity - about 11.5 percent closed porosity (i.e. the porosity in the fiber tow regions) and 8.5 percent as open porosity (i.e., porosity in the matrix rich area), for a total porosity of about 20 percent. The overall fiber volume ratio is 0.4. The thickness of the unit cell is 304 μm (12 mils), twice the thickness of the fiber tow. The section of the unit cell is 1168 μm (46 mils) wide and it was divided into 23 slices at 50 μm (2 mils) wide each. The interphase was assumed to be 2 percent of the fiber diameter in thickness and the modulus of the interphase was assumed to be a very low 3.5 GPa (0.5 Msi), almost a negligible value. The equivalent slice properties were computed by using the CEMCAN computer code. The predicted results and some available measured values (ref. 13) are shown in table IV. These values can also be predicted at different porosity levels as shown in figure 9 since voids are modeled explicitly in CEMCAN computer code. The predicted values of the elastic mechanical properties compare quite favorably with the measured values. However, there is some discrepancy between the predicted and measured values of thermal properties. Because of [0/90] laminate construction; a weak interphase and the matrix modulus being higher than the fiber modulus, fibers have little effect and the laminate thermal properties are controlled by matrix thermal properties. Hence, if the matrix has isotropic thermal properties, it will result in generally isotropic thermal properties for this laminate. There is some discrepancy either in the measured thermal properties or in the constituent properties provided. For example, the coefficient of thermal expansion for SiC matrix is known to be approximately $4 - 4.5 \times 10^{-6}$ °C. However, assuming this value for CTE of matrix, the resulting composite CTE turns out to be quite different and higher than the measured properties. This is being further investigated.

In any case, a micromechanics based model that can predict properties/stresses of woven composites was developed. The predicted results are within 10 percent of those from finite element analysis or measured values, except in the case of some thermal properties of SiC/SiC composite. Incorporating effects of voids, processing and environmental degradation effects on the response is rather straight forward since these features are already included in many composite mechanics codes and certainly in the NASA developed micromechanics codes such as ICAN (ref. 10), which was used for laminate analysis in the above computations. The analysis presented for the plain weave can also be extended in a fairly simple manner to other two-dimensional woven architectures.

CONCLUSIONS

A technique was presented that in combination with micromechanics based laminate analysis codes can efficiently predict the properties/response of the plain weave composites. Since this technique is based on micromechanics, any level of detail in the microstress/microstrain can be obtained in an efficient manner as compared to a numerical analysis technique. Limited verification with a set of detailed three-dimensional finite element analysis shows that the predicted results compare reasonably well with the predictions of the finite element analyses and compare well with the available limited experimental data. Further work is continuing to refine the model and evaluate other materials. Modifications to existing micromechanics based laminate analysis codes will be made that will incorporate features of the model presented here for the analysis of woven composites.

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Table I.—MATERIAL PROPERTIES FOR GRAPHITE/EPOXY COMPOSITE

	Graphite/epoxy	Epoxy
E_{11}	136 GPa	3.,45 GPa
E_{22} (= E_{33})	9 GPa	3.45 GPa
v_{12} (= v_{13})	0.26	0.35
v_{23}	0.41	0.35
G_{12} (=G_{13})	4.6 GPa	1.3 GPa
G_{23}	2.6GPa	1.3 GPa

Table II.—PROPERTIES OF GRAPHITE/EPOXYPLAIN WEAVE COMPOSITE

Property	Finite element results	0/90 laminate	Micromechanics
E_{xx} (GPa)	49.0	72.5	54.5
E_{zz} (GPa)	8.8	9.9	8.3
ν_{zx}	0.09	0.05	0.07
ν_{zy}	0.08	.05	0.07
ν_{yx}	0.04	.03	0.04
ν_{yz}	0.53	.38	0.5
G_{xy} (GPa)	4.1	4.6	4.4
G_{yz} (GPa)	3.9	3.6	3.5

Table III.—CONSTITUENT MATERIAL PROPERTIES FOR SIC/SIC COMPOSITE

Property	Nicalon fiber	SiC matrix
Density, gm/cm^3	2.57	3.22
E_1, GPa	200	350
E_2 (=E_3), Gpa	200	350
ν_{12}	0.25	0.2
ν_{23}	.25	2
C.T.E., 10^{-6}/C	3.0	2.2
Thermal conductivity, W/m-C	12.0	8.3

TABLE IV.—SiC/SiC COMPOSITE PROPERTIES
[fvr 0.4, void 0.2.]

Property	Predicted	Measured
Density, gm/cm^3	2.45	2.5
E_{xx}, GPa	214.4	214
E_{zz}, GPa	193	
G_{xy}, GPa	80	
G_{yz}, GPa	79.3	
ν_{xy}	0.18	0.17
ν_{yz}	0.2	
C.T.E.-x, 10^{-6}/C	2.2	3.0
C.T.E.-z, 10^{-6}/C	2.1	1.7
Ther. Cond.-x, W/m-C	8.7	19
Ther. Cond.-z, W/m-C	8.3	9.5

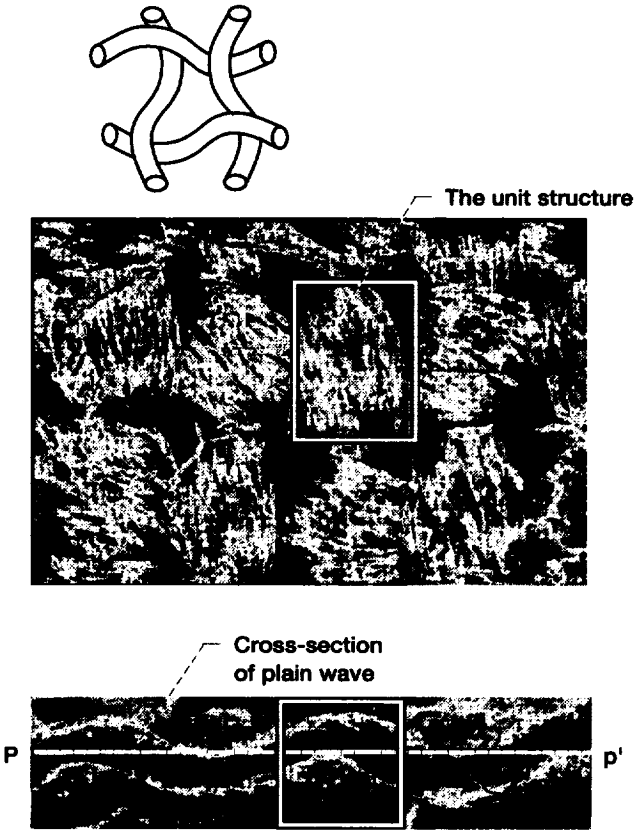

Figure 1.—Structure of a plain weave fabric.

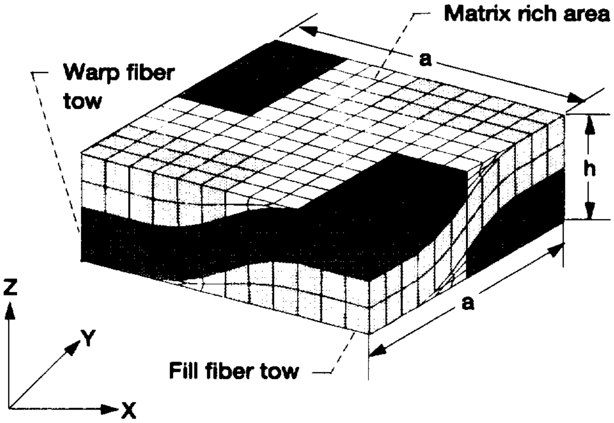

Figure 2.—1/4 portion of the "Unit Cell" or representation volume element (RVE).

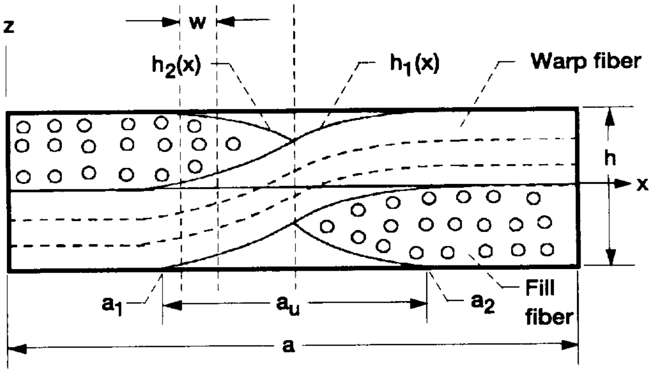

Figure 3.—Micromechanics model representation.

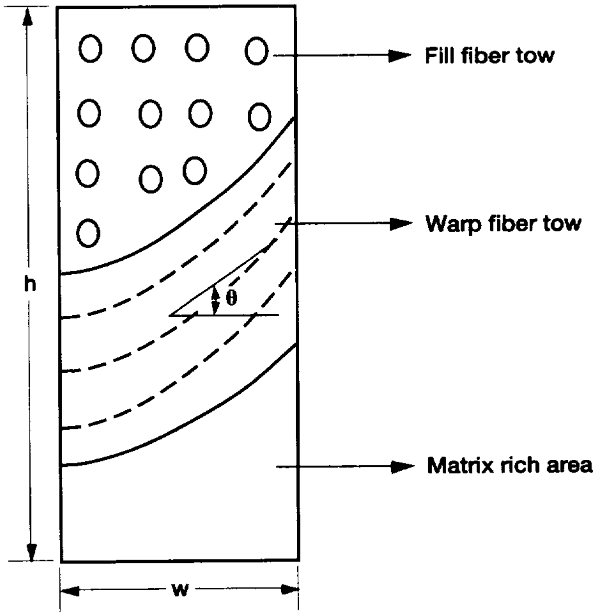

Figure 4.—A typical slice showing warp, fill and matrix regions.

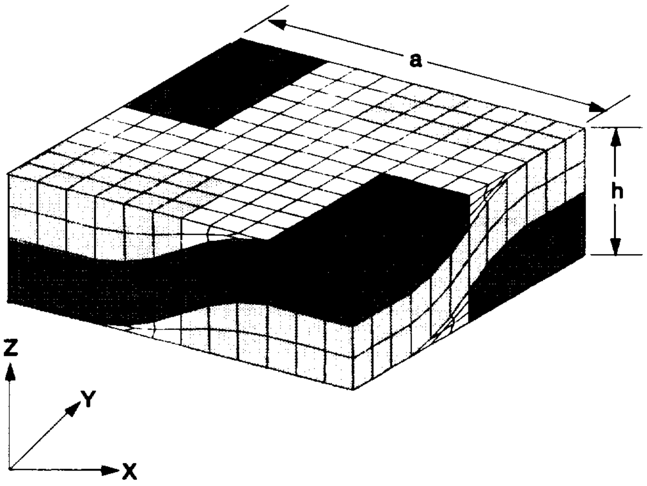

Figure 5.—Finite element mesh (1008 solid elements, 1375 nodes).

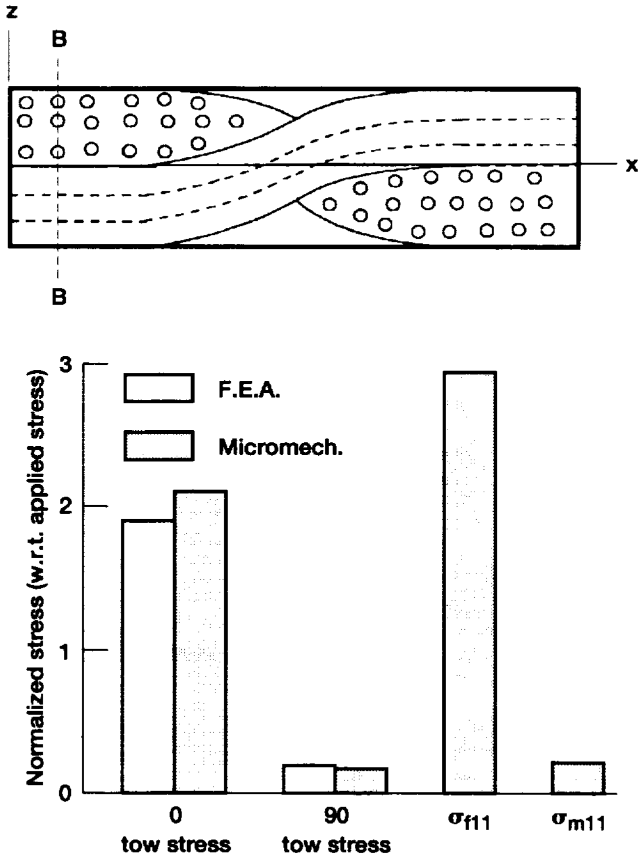

Figure 6.—Stresses in the straight fiber region (section B-B) due to tesile loading in the x-direction.

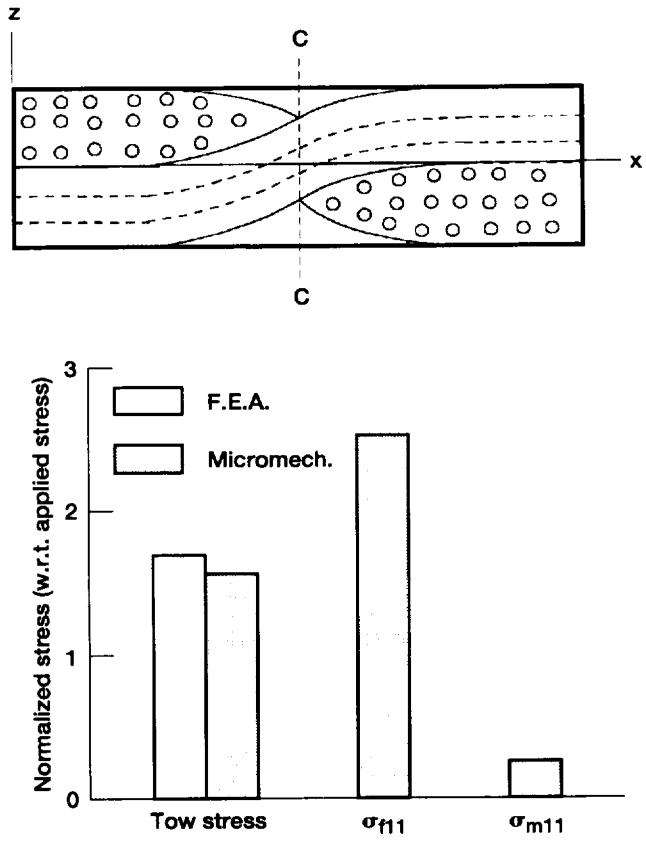

Figure 7.—Stresses in the undulated fiber region (section C-C) loading in x-direction.

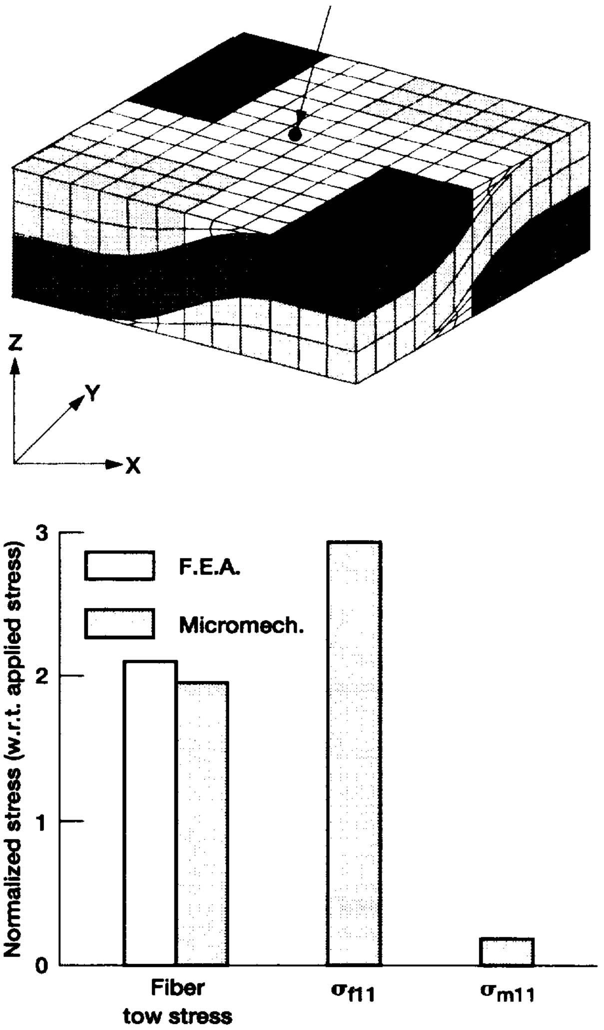

Figure 8.—Stresses in the undulated region in the middle of the unit cell (A); loading in the x-direction.

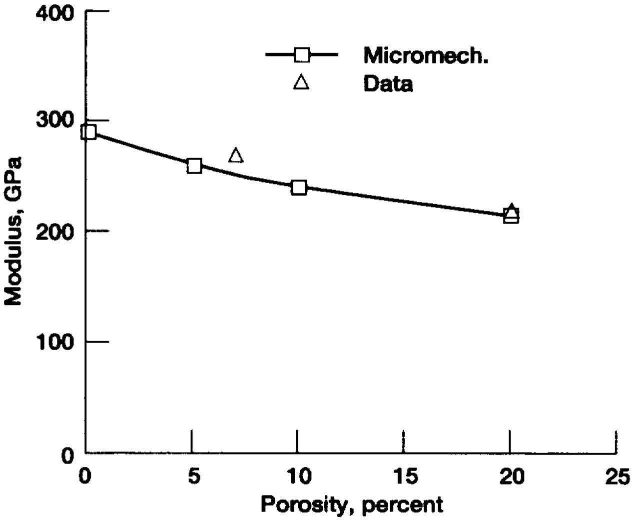

Figure 9.—In-plane modulus versus porosity (SiC/SiC composite; 0.4 fvr).

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