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Computational Simulation of Intermingled–Fiber Hybrid Composite Behavior

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SUMMARY

Three-dimensional finite-element analysis and a micromechanics based computer code ICAN (Integrated Composite Analyzer) are used to predict the composite properties and microstresses of a unidirectional graphite/epoxy primary composite with varying percentages of S-glass fibers used as hybridizing fibers at a total fiber volume ratio of 0.54. The three-dimensional finite-element model used in the analyses consists of a group of nine fibers, all unidirectional, in a three-by-three unit cell array. There is generally good agreement between the composite properties and microstresses obtained from both methods. The results indicate that the finite-element methods and the micromechanics equations embedded in the ICAN computer code can be used to obtain the properties of intermingled fiber hybrid composites needed for the analysis/design of hybrid composite structures. However, the finite-element model should be big enough to be able to simulate the conditions assumed in the micromechanics equations.

1. INTRODUCTION

The incorporation of two or more fibers within a single matrix is known as hybridization, and the resulting material is referred to as a hybrid composite. The hybrid composites can be classified either as intraply hybrid, having more than one type of fiber within a ply, or as interply hybrids, where only one type of fiber is placed in a single ply and then the different plies are dispersed through the laminate.

In recent years, high modulus fibers such as boron and graphite have been widely used in many aerospace applications because of their exceptionally high stiffness to weight ratios. However, the impact strength of these composites have been found to be generally low. An effective method of improving the impact properties of graphite fiber reinforced composites is to add a small percentage of a low-modulus high-strength fiber. Glass fibers are generally used for this purpose. The incorporation of glass fiber not only improves the impact properties, it can also reduce the overall cost, as many times cost is a limitation for using graphite fiber composites (ref. 1).

The objective of this paper is to evaluate a commingled or intermingled-fiber hybrid composite consisting of 54 percent high modulus graphite (P–75) fiber in an epoxy (R–930) matrix with varying percentages of S-glass fibers used as hybridizing fibers. The composite properties are evaluated using three-dimensional finite-element analysis and a micromechanics based computer code ICAN (ref. 2). The microstresses for one hybrid composite obtained from both methods are also compared.

2. ICAN COMPUTER CODE

The research in the area of composite micromechanics and macromechanics over the last two decades at NASA Lewis Research Center has resulted in several computer codes for composite mechanics and structural analysis. The primary intention of this research is to develop composite mechanics theories and analysis methods that range in scale from micromechanics to global structural analysis in one integrated code. The micromechanics theories are represented by simplified equations and have been corroborated by detailed three-dimensional finite-element analysis (ref. 3).

ICAN (Integrated Composite Analyzer) is primarily designed to describe the hygrothermomechanical properties/response of polymer matrix composites. It can analyze standard composites, i.e., consisting of one type of fiber in a matrix forming a lamina. In addition to that, the code can also analyze an interply or intraply hybrid composite system. In an interply hybrid composite, each layer/lamina is made by different fiber/matrix combinations. An intraply hybrid composite system, on the other hand, consists of two or more different fibers embedded in a matrix within each layer/lamina in a prescribed manner. These layers/laminae are then arranged with prescribed orientations to form a composite laminate. The ICAN computer code simulates a commingled tow fiber reinforced composite. The micromechanics equations embedded in the ICAN computer code take into account the effects of temperature and moisture including the temperature and/or moisture gradients through-the-thickness. However, within each layer the temperature or moisture is assumed to be constant. Another unique feature of the ICAN computer code is its own data base of material properties for commonly used fiber and matrix materials. The user needs to specify only the code names for the constituents, and the program searches and selects the appropriate properties from the data base. It is an open-ended program, in that, the material properties for new materials as they become available as well as new analyses modules pertaining to the composite mechanics can be easily added. More detailed information about ICAN can be found in reference 2. This program is available for public distribution through COSMIC, Suite 112, Barrow Hall, Athens, GA 30602.

3. FINITE-ELEMENT MODEL

The finite-element model used in the computational simulation procedure consists of a group of nine fibers, all unidirectional, in a three-by-three unit cell array ("nine cell model") as shown in figure 1. The primary composite system consists of high modulus (P–75) graphite fiber in an epoxy (R–930) matrix with a fiber volume ratio of 0.54. The S-glass fibers are used as hybridizing fibers in varying percentages. The properties of the constituent materials are shown in table I. There are 10 elements (bays) along the length of the fiber. Each unit cell, as shown in figure 1, consists of 32 hexahedron (six-sided) solid elements and eight pentahedron (five-sided) solid elements for a total of 3600 elements and 3707 nodes (approx. 11 000 degrees of freedom) in the model. Perfect bonding, i.e., no interphase has been assumed to exist between the fiber and the matrix.

4. RESULTS AND DISCUSSION

4.1 Composite Properties

Four hybrid composites were evaluated for composite properties as shown in figure 2: (a) No hybridizing S-glass fibers added, resulting in a P–75/R–930 composite, (b) one S-glass fiber and the remaining eight fibers are graphite fibers, i.e., 1/9 or 11.1 percent hybridizing fibers. For the micromechanics analysis, it means that the middle ply will have one out of three or 33.3 percent S-glass hybridizing fibers, (c) two out of nine fibers are S-glass fibers, and (d) four fibers out of nine are S-glass hybridizing fibers.

The ICAN computer code was used to predict the composite properties for these configurations and ply-layups. In the case of finite-element analysis (FEA), fiber elements are assigned appropriate material properties, i.e., S-glass or graphite fiber properties as the case may be. The composite properties from the finite-element analysis are computed as described below. The procedure is illustrated by computing the longitudinal modulus, $E_{\ell 11}$. The procedure to determine other composite properties via FEA is similar and is discussed in detail elsewhere (ref. 3). For the case of $E_{\ell 11}$, a uniform displacement field, u, is applied in the X direction (along the fiber) on the front face (X/L = 1) and the back face (X/L = 0) is fixed in the X direction (u = 0.0) as shown in figure 3. Constraints are also applied to prevent rigid body motion in the 2 and 3 directions. Three-dimensional finite-element analysis is carried out with this applied displacement field using the MSC/NASTRAN finite-element code (ref. 4). Resulting nodal forces corresponding to those applied displacements are obtained from the finite-element analysis. From the sum of these nodal forces, F, the longitudinal modulus is calculated as:

$$E_{\ell 11} = \frac{F.L}{A.u} \tag{1}$$

where L is the length in X direction, and A is the cross-sectional area.

Such a method of analysis corresponds directly to the derivation of the micromechanics equations for the ply longitudinal modulus used in the ICAN computer code and coupon testing to measure it. The longitudinal (along the fiber) strain in all constituents are equal. The longitudinal modulus and the Poisson's ratios ($\upsilon_{\ell 12}$ and $\upsilon_{\ell 13}$) computed from the displacements applied in 1 direction and as predicted by the FEA, are consistent with the assumptions made in the derivation of the micromechanics equations.

The prediction of room temperature elastic moduli, $E_{\ell 11}$ and $E_{\ell 22}$, Poisson's ratios, $\upsilon_{\ell 12}$, $\upsilon_{\ell 13}$ and shear modulus $G_{\ell 12}$ by both ICAN and FEA are shown in figures 4 to 7 for comparison purposes. It should be noted that the ICAN computer code simulates a commingled tow fiber reinforced composite, while finite element in this case is simulating commingled fiber reinforced composite. The agreement between the predictions of ICAN and FEA is excellent with the exception of transverse modulus. The possible reasons for the discrepancy in the transverse modulus will be discussed later. There is a 37 percent reduction in longitudinal modulus when 44 percent of fibers are S-glass hybridizing fibers. There is a 25 percent increase in transverse modulus for the same amount of hybridizing fibers. There is not much change in the Poisson's ratios or the shear modulus in the 1–2 direction for different amount of hybridizing fibers.

The analysis for the longitudinal and transverse thermal expansion coefficients (TEC) is performed by applying a uniform temperature to the composite. Center planes are fixed in X, Y, and Z directions in such a way so that the composite is forced to deform symmetrically in all directions. Resuling nodal displacements are obtained from the finite-element analysis due to the applied thermal loading. The thermal expansion coefficients are then computed by applying their basic definition. Longitudinal thermal expansion coefficients for different amounts of S-glass hybridizing fibers are shown in figure 8. There is considerable difference between the finite elements and the ICAN predictions. It is believed that the model is not long enough, so that the conditions of uniform displacements could not be reached at the plane where displacement were obtained for computing longitudinal thermal expansion coefficients. Displacement at X/L = 0.3125 are plotted in figure 9. There is considerable nonuniformity in the displacement particularly along B–B. Since, micromechanics equations assume a uniform displacement field, a much longer model in the finite-element simulation is needed to achieve such a condition in this particular case. Transverse thermal expansion coefficient is plotted for different amounts of hybridizing fibers in figure 10(a). It seems rather insensitive to the amount of hybridizing fibers, yet ICAN and finite-element predictions are quite different. Again looking at the displacements in the 2–2 directions, there is some nonuniformity present. The reason for this discrepancy lies in the high degree of heterogeneity not only in fiber longitudinal and transverse modulus, but also between the fiber and matrix modulus and thermal expansion coefficients. The micromechanics equations assume that a uniform displacement field has been achieved away from the boundary. To achieve this, one has to either use specialty finite elements or a larger model with more fibers, depending upon the degree of heterogeneity. Although, the results are not shown here, for a different hybrid composite system, where the degree of heterogeneity is much less, the ICAN and finite-element results are much closer. In other words, one has to view the finite-elements results with caution. For the same reason, one has to view the experimental results with caution too. When experiments are performed on small coupons, and the results are used for the design of large components, they could be erroneous.

It shows that the properties obtained via micromechanics equations, where the effort required is considerably less as compared to a detailed finite-element analysis, can be used with confidence in the analysis/design of hybrid composite structures, and the finite-element results should be interpreted with caution. Again, the discrepancy in the results wherever present is due to the fact that there is high degree of heterogeneity between the moduli and the thermal expansion coefficients of the fiber and matrix material used in the present work.

4.2 Microstresses

Microstresses in the fiber and matrix were also computed for both longitudinal and transverse loading. However, the microstresses were computed for only one hybrid composite, i.e., case (c) where two out of nine fibers are S-glass hybridizing fibers. In the case of longitudinal (along the fiber) loading, a uniform displacement is applied on the front face ($X/L = 1$), while the back face ($X/L = 0$) is restrained in x direction. Resulting nodal forces, and thus, the equivalent stress on that face is computed by finite-element analysis. The same stress in the 1 direction is applied for the ICAN analysis. The finite-element stresses are evaluated in the center cell at the middle plane ($X/L = 0.5$). The longitudinal stress in graphite and S-glass fibers and the longitudinal stress in matrix at the middle plane are shown in figure 11. There is excellent agreement between the FEA and ICAN microstress results for this loading case.

In the case of transverse loading, the same stress is applied on the composite for both ICAN and FEA analyses. The 2–2 microstresses for the top ply constituents are shown in figure 12, while 2–2 microstresses for the middle ply constituents are shown in figure 13. Most of the microstress results are in good agreement with the finite-element analysis results, except for the 2–2 stress in glass fiber which shows about 50 percent difference. This discrepancy was believed to be due to the high degree of heterogeneity in the fiber material of graphite (E_1/E_2) and also the ratio of moduli of the fiber and matrix materials. The micromechanics equations used in the ICAN computer code assume a uniform displacement field (i.e., the stress evaluation point is far away from the boundary/load application points), and the applied load is resisted in the ratio of the stiffnesses of the constituents. Although the results are not shown here, for a different composite system where the degree of heterogeneity in the properties of the constituent materials is much less, the finite element and the ICAN predictions for microstresses are much closer. A further investigation in this aspect is continuing. In order to achieve these uniform displacement conditions in the finite-element model, either specialty finite elements or a larger model with more numbers of fibers, depending upon the degree of heterogeneity, has to be used as mentioned before. In other words, one has to be careful in analyzing results obtained from finite elements analyses.

5. CONCLUSIONS

Three-dimensional finite-element analysis and a micromechanics based computer code ICAN were used for the prediction of composite properties and microstresses for a unidirectional graphite/epoxy composite with varying percentages of S-glass fibers used as hybridizing fibers. The mechanical properties, i.e., normal and shear moduli and the Poisson's ratios, predicted by both methods are in good agreement with the exception of transverse modulus. However, there is difference in the prediction of thermal expansion coefficients. The constituent microstresses due a longitudinal and transverse load are also generally in good agreement. The finite-element model, depending upon the degree of heterogeneity has to be large enough to be able to simulate conditions assumed in the micromechanics equations, e.g., condition of uniform displacement, etc. Both the finite-element analysis and the composite micromechanics equations can be used with confidence to obtain the properties of hybrid composites needed for analysis/ design of hybrid composite structures. However, caution should be used in interpreting finite-element results to ensure that the computational simulation model geometry simulate the conditions assumed in the micromechanics equations.

6. REFERENCES

1. Agarwal, B.D.; and Broutman, L.J.: Analysis and Performance of Fiber Composites. Second ed. Wiley, 1990.

2. Murthy, P.L.N.; and Chamis, C.C.: Integrated Composite Analyzer (ICAN). Users and Programmers Manual. NASA TP-2515, 1986.

3. Caruso, J.J.: Application of Finite Element Substructuring to Composite Micromechanics. NASA TM-83729, 1984.

4. MSC/NASTRAN, User's Manual, Version 64, Vol. I and II. The MacNeal-Schwendler Corp., Los Angeles, CA, 1984.

TABLE I.—PROPERTIES OF CONSTITUENT MATERIALS

	P–75 fiber	R–930 matrix	S-glass fiber
Modulus, E_{11}, GPa	517	2.1	85.5
Modulus, E_{22}, GPa	6.2	2.1	85.5
Poisson's ratio, ν_{12}	.2	.45	.2
Poisson's ratio, ν_{23}	.25	.45	.2
Shear modulus, G_{12}, GPa	7.6	.7	35.7
Shear modulus, G_{23}, GPa	.7	.7	35.7
Coefficient of thermal expansion			
α_{11} ppm/°C	−1.3	65	5.0
α_{22} ppm/°C	10.1	65	5.0

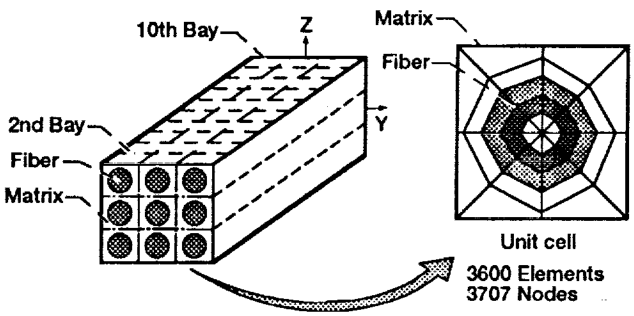


Figure 1.—Schematic of the model used in finite element analysis.

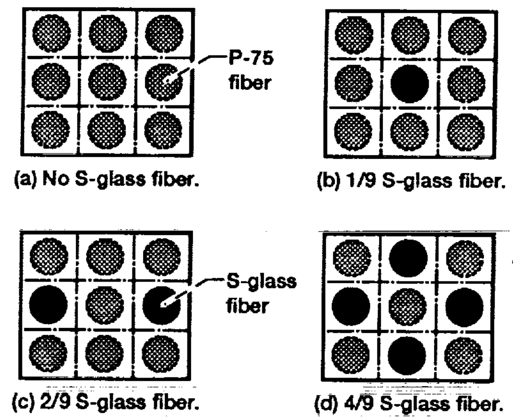


Figure 2.—Cases of hybrid composites evaluated.

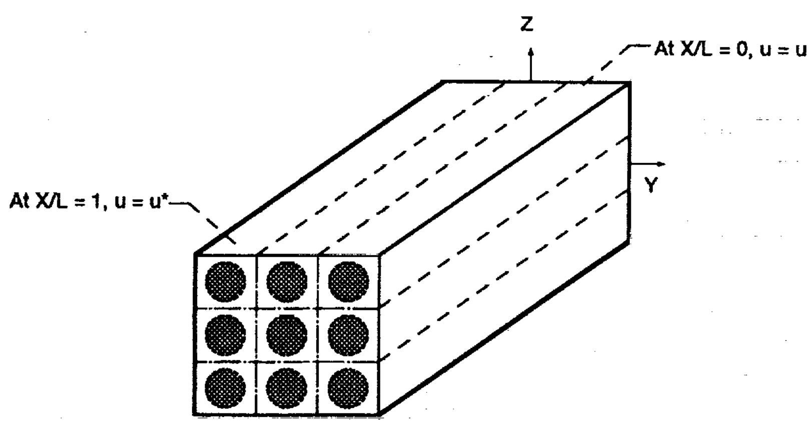


Figure 3.—General boundary conditions for the longitudinal load.

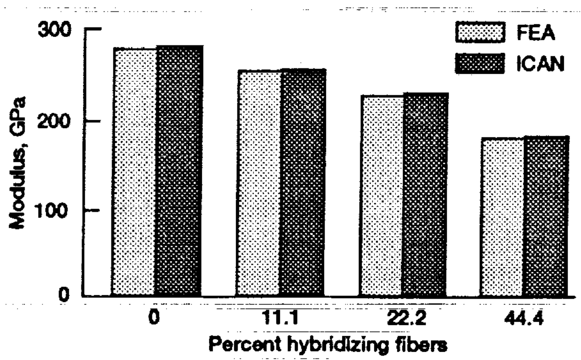


Figure 4.—Longitudinal modulus, $E_{\ell 11}$.

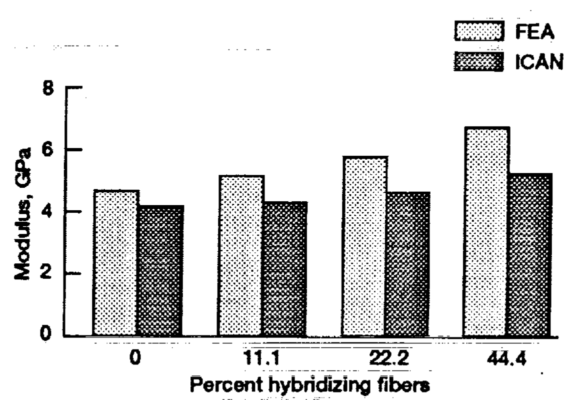


Figure 5.—Transverse modulus, $E_{\ell 22}$.

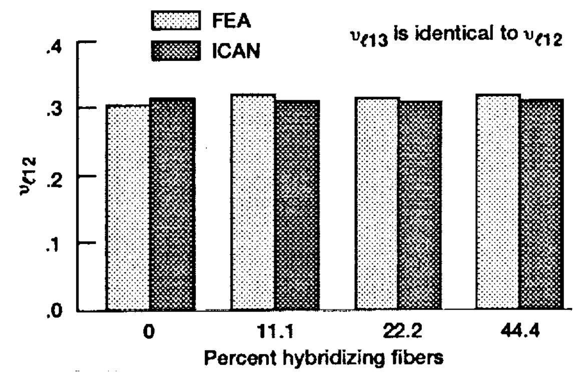


Figure 6.—Poisson's ratio, $\nu_{\ell 12}$.

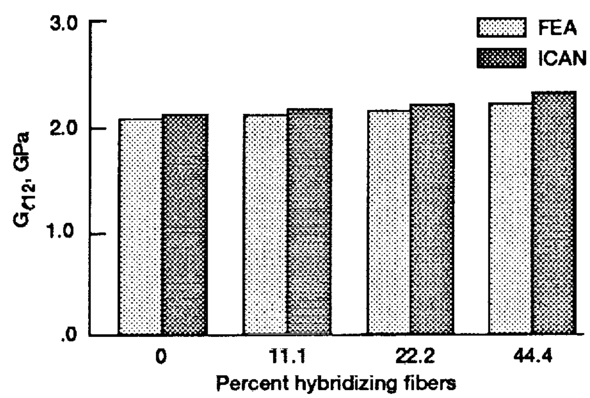


Figure 7.—Shear modulus, $G_{\ell 12}$.

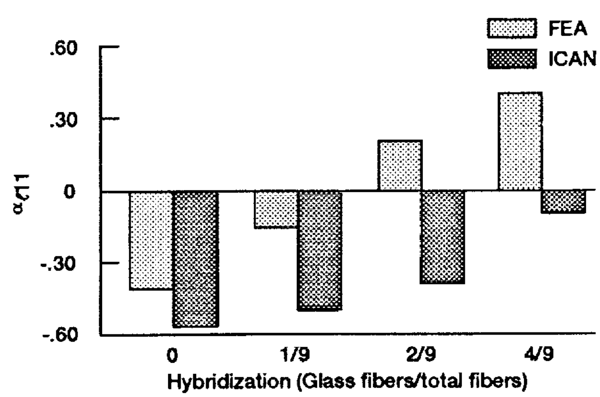


Figure 8.—Longitudinal thermal expansion coefficient P-75/R930//SGLA/R930 composite (fvr .54).

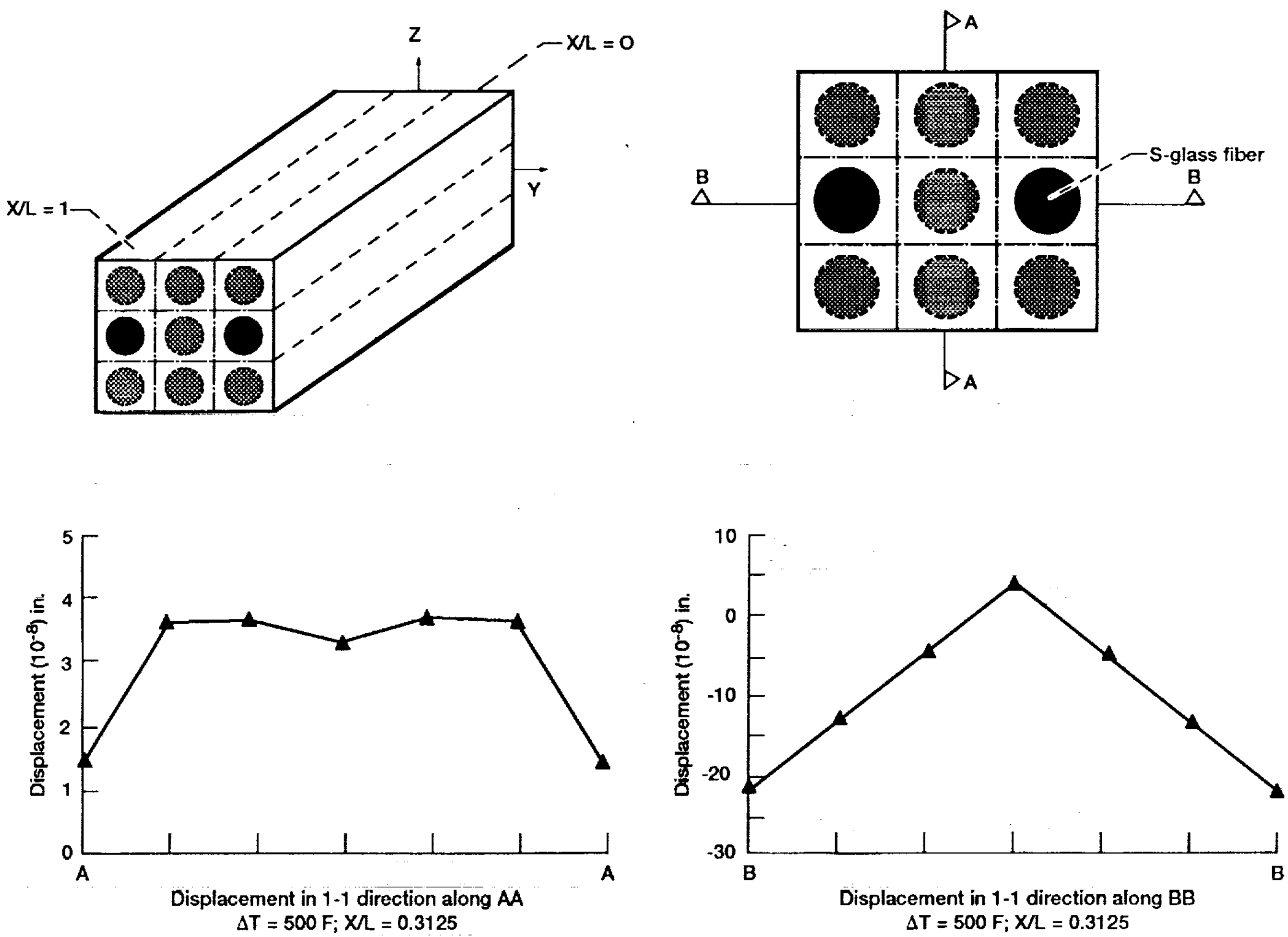
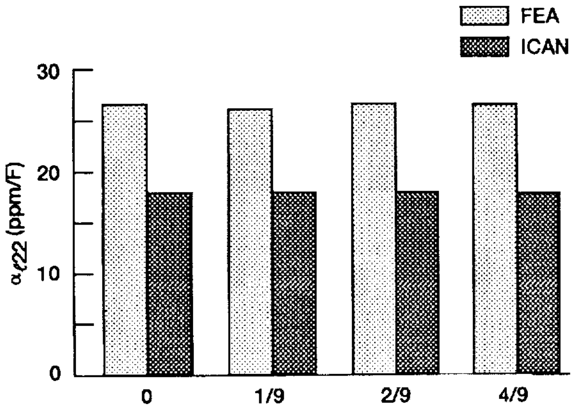
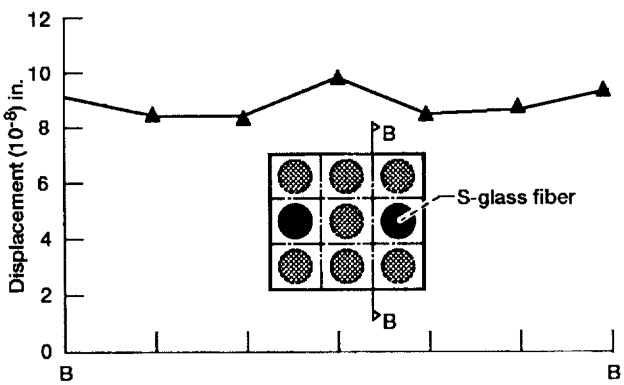


Figure 9.—Displacements in 1-1 direction (X/L = 0.3125).



(a) Transverse thermal expansion coefficient P-75/R930//SGLA/R930 composite (fvr .54).



(b) Displacement in 2-2 direction along BB due to ΔT = 500 F; X/L = 0.5.

Figure 10.—Transverse thermal expansion coefficient and displacement in 2-2 direction along BB. ΔT = 500 F (x/L = 0.5).

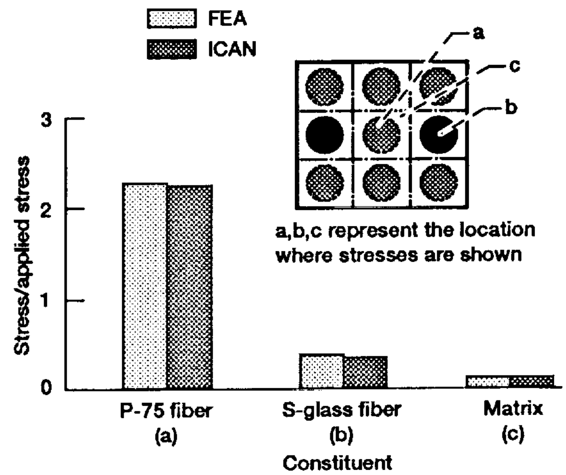


Figure 11.—Longitudinal stress due to the loading in 1-1 direction.

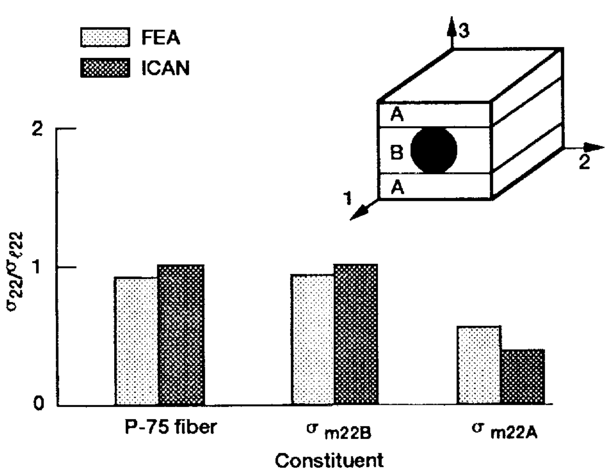


Figure 12.—Transverse stress due to the loading in 2-2 direction (top ply).

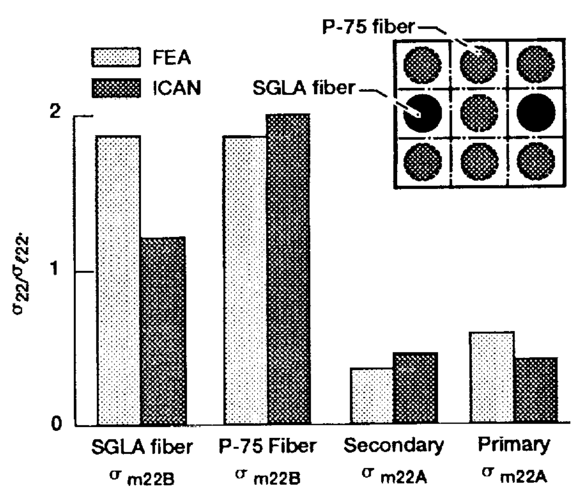


Figure 13.—Transverse stress due to the loading in 2-2 direction (middle ply).

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13. ABSTRACT ***(Maximum 200 words)***

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14. SUBJECT TERMS
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