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PREDICTION OF MECHANICAL PROPERTIES OF UNIDIRECTIONAL FIBER REINFORCED COMPOSITE WITH FIBER-MATRIX INTERFACIAL DEBONDING USING SQUARE ARRAY

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ABSTRACT

The present investigation studies the influence of fiber-matrix interface debond on the micromechanical behaviour of fiber reinforced composite lamina. Three dimensional finite element models have been developed from the representative volume elements of the composite which are in the form of square unit cells. Mechanical properties are determined for three different values of fiber volume fraction (V_f). The finite element software NISA has been successfully executed to evaluate the properties. The results of the present analysis are in close agreement with solutions available in the literature for perfectly bonding as well as complete debond at fiber-matrix interface. The method is extended to analyse the cases where debond exists along the length of the fiber and extends around the circumference at the interface of the fiber and matrix. The debond effect on the mechanical properties is discussed.

Key Words: Debond, FRP, Micromechanics, Unit Cell.

1. INTRODUCTION

Fiber reinforced composites can be tailor made, as their properties can be controlled by the appropriate selection of the substrata parameters such as fiber orientation, volume fraction, fiber spacing, and layer sequence. The required directional properties can be achieved in the case of fiber reinforced composites by properly selecting various parameters enlisted above. As a result of this, the designer can have a tailor-made material with the desired properties. Such a material design reduces the weight and improves the performance of the composite. For example, the carbon-carbon composites are strong in the direction of the fiber reinforcement but weak in the other directions. Deteresa [1] observed that the mismatch in the thermoelastic properties between fiber and matrix (especially in kevlar-epoxy composites) results in significant thermal stresses with cool down from processing temperatures. This in turn severely limits the compressive and flexural fatigue strength of the composites.

Elastic constants of fiber reinforced composites with various types of constituents were determined by Chen and Chang [2], Hashin & Rosen [3], Hashin [4] and Whitney [5]. It is clear from the above comparison that four of the five independent composite moduli differ only in their expressions for the fifth elastic constant i.e., transverse shear modulus, which varies between two bounds that are reasonably close for the cases of practical interest. The values of elastic moduli presented by Hashin and Rosen [3] have very close bounds. Dean and Turner [6] demonstrated that most of the transversely isotropic graphite-fiber properties can be extrapolated by curve fitting of the ultrasonic test results. Kirz and Stinchcomb [7] modified the methodology adopted by Dean and Turner [6]. They calculated the complete set of elastic constants for graphite-epoxy composite lamina given by Hashin [4] by using the improved ultrasonic velocity measurements. These are in very good agreement with the equations derived by Hashin [8]. Kirz and Stinchcomb [7] observed that the modified equations of Hashin [8] can be used to evaluate the complete set of elastic properties for the transversely isotropic laminae.

Ishikawa et al. [9] experimentally obtained all the independent elastic moduli of unidirectional carbon-

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epoxy composites with the tensile and torsional tests of co-axis and off-axis specimens. They confirmed the transverse isotropy nature of the graphite-epoxy composites. Hashin [10] derived the expressions and bounds for the five effective elastic moduli of an unidirectional fiber composite consisting of transversely isotropic fibers and isotropic matrix on the basis of analogies between isotropic and transversely isotropic elasticity equations. He derived the effective moduli based on the rigorously tested composite cylinder assemblage (CCA) model. These results are important because most of the modern reinforcement fibers such as graphite, carbon, kevlar are highly anisotropic in nature. Hashin [10] comprehensively reviewed the analysis of composite materials with respect to mechanical and materials point of view. Gorji [11] predicted thermoelastic properties in unidirectional composites. Expressions for E_1 and G_{12} are derived using the theory of elasticity approach by Hyer [12].

The effect of interfacial debonding on the transverse Young's moduli of fiber composites was investigated by Takahashi and Chou [13] by use of a cavity formation model. An elastic contact model is developed to predict the transverse Young's moduli of unidirectional fiber composites with interfacial debonding by Hui-Z and Tsu-W [14]. A closed form micromechanical equation for predicting the transverse modulus, E_2, of continuous fiber reinforced polymers is presented by Morais [15].

Anifantis [16] predicted the micromechanical stress state developed with in fibrous composites that contain a heterogeneous inter-phase region by applying finite element method to square and hexagonal arrays of fibers. Sun et al [17] established a vigorous mechanics foundation for using a representative volume element (RVE) to predict the mechanical properties of unidirectional fiber composites. Li [18] has developed two typical idealized packing systems, which have been employed for unidirectional fiber reinforced composites, viz. square and hexagonal ones to accommodate fibers of irregular cross sections and imperfections asymmetrically distributed around fibers. He has determined the elastic properties of a composite with perfect bonding at fiber-matrix interface by applying two-dimensional finite element method to the square and hexagonal unit cells.

2. PROBLEM STATEMENT

The present research work deals with the evaluation of Mechanical properties by the elasticity theory based finite element analysis of representative volume elements of fiber-reinforced composites (square unit cell). This analysis has been done for perfectly and imperfectly bonded fiber-matrix interface of the composites.

3. METHODOLOGY

A schematic diagram of the unidirectional fiber composite is shown in Fig. 1, where the fibers are arranged in a square array.. It is assumed that the fiber and matrix materials are linearly elastic. A Representative Volume Element (R.V.E.) in the form of a square unit cell is adopted for the analysis. The cross-sectional area of fiber relative to the total cross-sectional area of the unit cell (Fig. 2) is a measure of the volume of fiber relative to the total volume of the composite. This fraction is an important parameter in composite materials and is called fiber volume fraction (V_f).

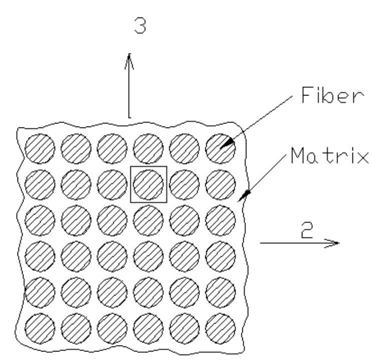

Fig. 1. Concept of unit cells

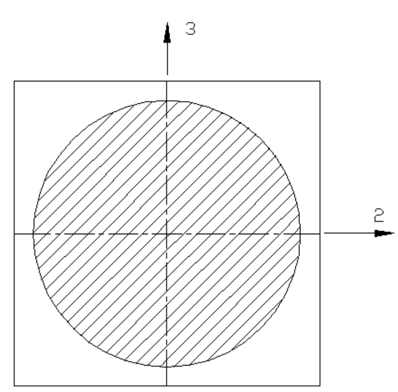

Fig. 2. Isolated unit cell. of Square packed array.

3-Dimentional Finite Element models are developed with governing boundary conditions to study the response of the unit cell due to the external loads. The Finite Element Software NISA 12 is successfully executed for the analysis.

The present finite element model is validated by comparing with the exact elasticity results given by Hyer

[12] for the case of perfect bonding, and with results of Takahashi and Chou [13] for totally debonding and found close agreement. The analysis is extended to predict the mechanical properties of the composite for different volume fractions with partial debonding at fiber-matrix interface.

4. RESULTS

The 1-2-3 coordinate system shown in Fig. 2 is used to study the behaviour of a unit cell (The direction 1 is along the fiber axis and normal to the plane of the 2D figure shown). The isolated unit cell behaves as a part of a larger array of unit cells.

It is assumed that the geometry, material and loading of the unit cell are symmetrical with respect to 1-2-3 coordinate system. Therefore, a one eighth portion of the unit cell is modeled (Fig. 3) for the prediction of mechanical properties. The 3D Finite Element mesh on one eighth portion of the unit cell is shown in Fig. 4.

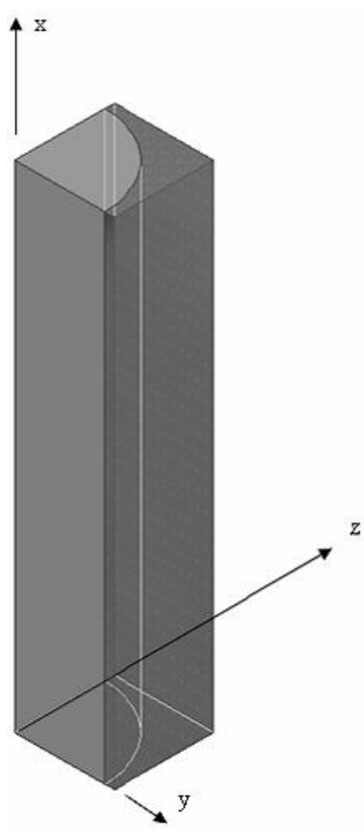

Fig. 3. One eighth portion of Square unit cell.

Element Type

The element NKTP4 of NISA [19] used for the present analysis is based on a general 3D state of stress and is suited for modeling 3D solid structure under 3D loading [18]. The element has 20 nodes with three degrees of freedom per node (U_X, U_Y and U_Z).

Materials

The graphite fiber and polymer matrix materials with following properties are used.

Graphite Fiber: E_1 = 233 GPa, E_2 (= E_3) = 23.1 GPa, ν_{12} (= ν_{13}) = 0.2, ν_{23} = 0.4, G_{12} (= G_{13}) = 8.96 GPa, G_{23} = 8.27 GPa.
Polymer Matrix: E = 4.62 GPa., ν = 0.36, G = 1.699 GPa.

Boundary Conditions: Due to the symmetry of the problem, the following symmetric boundary conditions are used.

- On the face at x = 0, $U_x = 0$
- On the face at y = 0, $U_y = 0$
- On the face at z = 0, $U_z = 0$

In addition, multipoint constraints are given so that the plane faces of the unit cell remain plane after deformation.

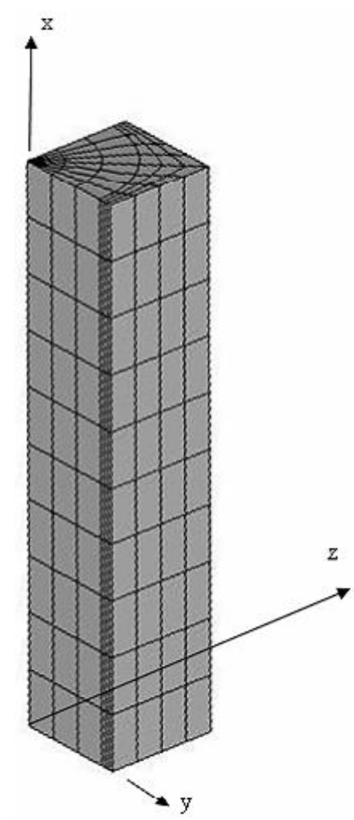

Fig. 4. 3D Finite element mesh.

The Young's modulus in 1-direction (E_1), is determined using the equation

$$E_1 = \sigma_1 / \varepsilon_1$$

The Poisson's ratio ν_{12} (= ν_{13}) is determined using the equation

$$\nu_{12} = - \varepsilon_2 / \varepsilon_1$$

The Young's modulus in transverse direction ($E_2 = E_3$), is determined using the equation

$$E_2 = \sigma_2 / \varepsilon_2$$

The Poisson's ratio ν_{21} (= ν_{31}) is determined using the equation

$$\nu_{21} = - \varepsilon_1 / \varepsilon_2$$

The Poisson's Ratio (ν_{23}) is calculated using the formula,

$$\nu_{23} = -\varepsilon_3 / \varepsilon_2$$

The finite element solutions are compared with the results of the elasticity theory [12] for perfectly bonding case(Table 1) and with the results of Takahashi and Chou [13] for totally debonding (Table 2) and found close agreement. The above mentioned analyses are extended to study the behaviour of unit cell with debond along the length of the fiber and extended around the circumferential direction at the fiber-matrix interface.

Table 1. Comparison of numerical results for perfect bonding

Property	**Elasticity Solution [12]** (GPa)	**Present work** (GPa)
E_1 (V_f = 0.6)	140.965	141.687
E_1 (V_f = 0.4)	96.035	95.996
E_1(V_f = 0.2)	50.347	50.3047

The Poisson's ratio ν_{12} is determined from the same model of E_1 and the finite element model used for the determination of other Poisson's ratios and E_2 is similar to E_1 model except in the direction of load. Hence the accuracy similar to E_1 can be expected for these cases also.

Table 2. Comparison of numerical results with complete debonding*

Property	**Takahashi [13]**	**Present work**
E_2 (V_f = 0.6)	16.536 GPa	16.817 GPa

* **Fiber –** FP Alumina E = 379 GPa, ν = 0.2
Matrix – Aluminum E = 68.9 GPa, ν = 0.345

5. DISCUSSION

The normalized values of E_1, E_2, ν_{12}, ν_{21} and ν_{23} are plotted in Figs. 5 to 9. The variation of the Young's modulus E_1 with respect to % debonding is negligible for all the values of V_f as the fiber action is predominant through out. Due to higher fiber stiffness of the composite, E_1 increases with increase in V_f (Fig.5). The transverse Young's modulus E_2 (=E_3) decreases with increase in debonding for all the values of V_f because of reduction in the action of the fiber with increase in debonding. This effect is observed to be more for higher volume fractions. Because of this effect, E_2 decreases with increase in V_f beyond 60% debonding (Fig.6). There is no significant variation of ν_{12} (=ν_{13}) with respect to debonding as in case of longitudinal modulus (Fig.7). ν_{21} and ν_{23} decrease with increase in debonding and V_f. The reasons discussed for transverse modulus may also holds good for these cases (Figs.8-9).

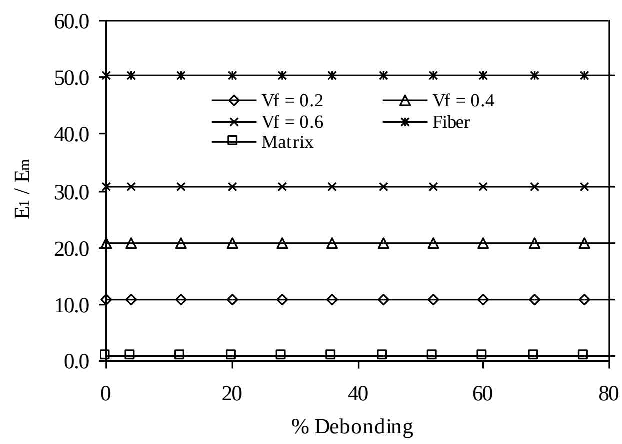

Fig. 5 Effect of debonding on E_1

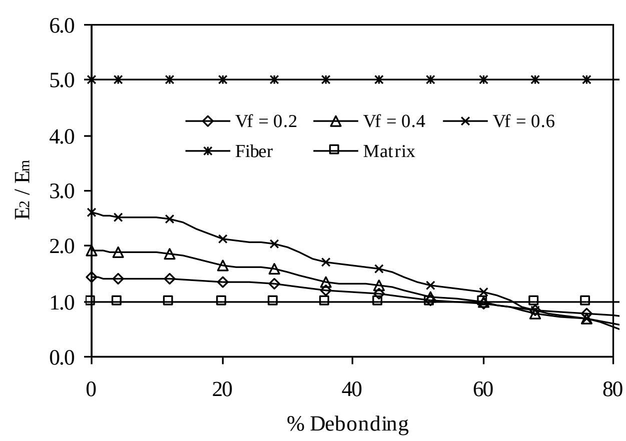

Fig. 6 Effect of debonding on E_2

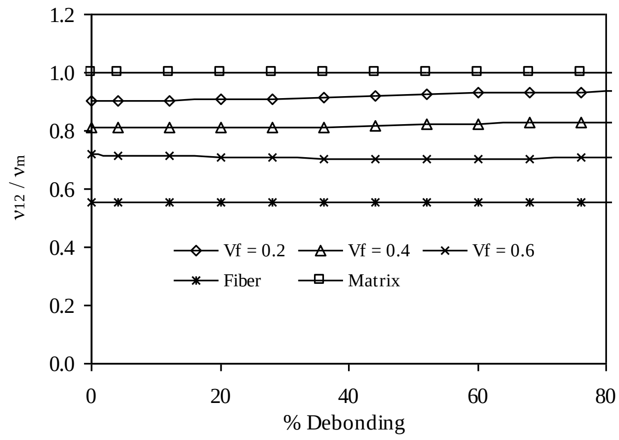

Fig.7 Effect of debonding on ν_{12}

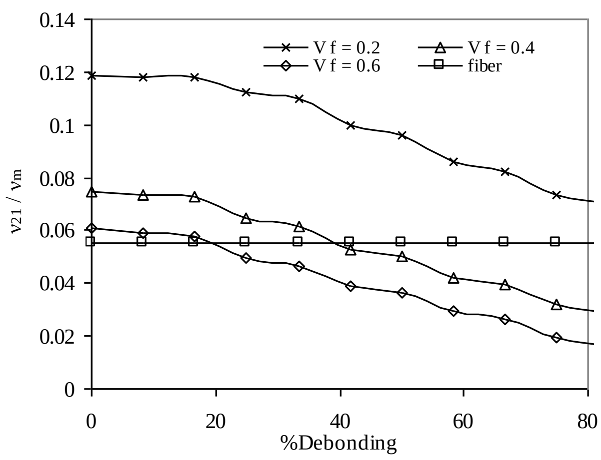

Fig. 8 Effect of debonding on ν_{21}

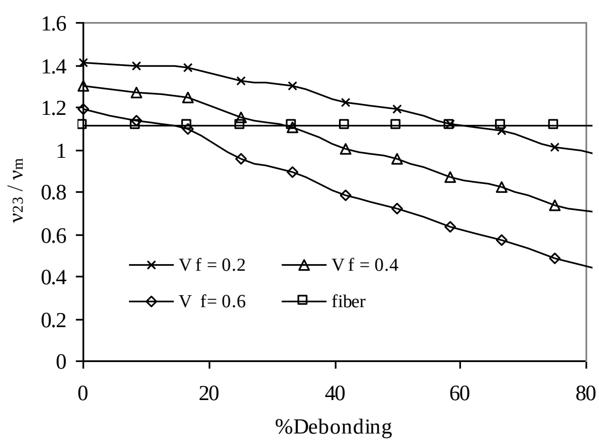

Fig.9 Effect of debonding on ν_{23}

6. CONCLUSIONS

Mechanical properties of unidirectional graphite fiber reinforced composite lamina have been predicted using theory of elasticity based finite element method applied to representative volume elements in the form of square unit cells with fiber-matrix interfacial debonding. The following conclusions are drawn.

- It has been observed that the composite behaves as a transversely isotropic material.
- There is no change in the value of longitudinal young's modules (E_1) due to debonding.
- E_2 is invariably affected by debonding and when the debonding is grater than 60%, the composite looses its utility as its value is much smaller than E of the matrix material.
- The major Poisson's ratio (ν_{12}) is not much affected by debonding.

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8. NOMENCLATURE

FRP Fiber Reinforced Plastic
E_1 Young's modulus in the longitudinal direction of the fiber
E_2 (= E_3) Young's modulus in the transverse direction of the fiber
ν_{ij} Poisson's Ratio (i, j = 1, 2, 3)
U_i Displacement (i = x, y, z)
σ_i Normal Stress (i = 1, 2, 3)
ε_i Normal Strain (i = 1, 2, 3)
τ_{ij} Shear Stress (i, j = 1, 2, 3)
γ_{ij} Shear Strain (i, j = 1, 2, 3)