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Prediction of Coefficients of Thermal Expansion of Hybrid FRP Composite with Fiber-Matrix Interface Debond

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Abstract

Prediction of coefficients of thermal expansion of graphite-boron-hybrid fiber and epoxy matrix composite lamina with fiber-matrix interface debond is carried out in the present analysis. Square unit cell is adopted for developing three dimensional finite element model. The finite element model is validated by comparing the numerical results with the existing literature and found close agreement. Later the finite element model is extended to predict the coefficients of thermal expansion of graphite-boron fiber-epoxy matrix hybrid composite with partial debond at the fiber-matrix interfaces for 60% fiber volume fraction (V_f). The finite element software ANSYS 11.0 has been successfully executed to evaluate the properties. The effect of debond on these properties is discussed.

Keywords: Debond, hybrid FRP, Micromechanics, Unit Cell.

Introduction

Micromechanics is intended to study the distribution of stresses and strains within the micro regions of the composite under loading. This study will be particularized to simple loading and geometry for evaluating the average or global stiffnesses and strengths of the composites [1, 2]. Micromechanics analysis can be carried theoretically using the principles of continuum mechanics, and experimentally using mechanical, photo elasticity, ultrasonic tests, etc. The results of micromechanics will help i) to understand load sharing among the constituents of the composites, microscopic structure (arrangement of fibers), etc., within composites, ii) to understand the influence of microstructure on the properties of composite, iii) to predict the average properties of the lamina, and iv) to design the materials, i.e., constituents volume fractions, their distribution and orientation, for a given situation.

The properties and behavior of a composite are influenced by the properties of fiber and matrix, interfacial bond and by its microstructure. Micro structural parameters that influence the composite behavior are fiber diameter, length, volume fraction, packing and orientation of fiber. A closed form micromechanical equation for predicting the transverse modulus, E_2, of continuous fiber reinforced polymers is presented [3]. Anifantis [4] predicted the micromechanical stress state developed within fibrous composites that contain a heterogeneous interphase region by applying finite element method to square and hexagonal arrays of fibers. Sun et al [5] established a vigorous mechanics foundation for using a representative volume element (RVE) to predict the mechanical properties of unidirectional fiber composites. Li [6] 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. Expressions for E_1 and G_{12} are derived using the theory of elasticity approach [1].

Takashi et al. [7] experimentally obtained all the independent elastic moduli of unidirectional carbon-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 [8] 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 [8] comprehensively reviewed the analysis of composite materials with respect to mechanical and materials point of view. Gorji [9] predicted thermoelastic properties in unidirectional composites.

Yiping Qiu and Peter Schwartz [10] investigated the fiber-matrix interface properties by using single fiber pull out test from a micro composite, which showed a significant difference between the interfacial shear strength of Kevlar fiber-epoxy in single fiber type and that in the hybrid at a constant fiber volume fraction. Mishra & Mohanthy [11] investigated the degree of mechanical reinforcement that could be obtained by the introduction of glass fibers in bio fiber (pineapple leaf fiber/ sisal fiber) reinforced polyester composite experimentally. Addition of relatively small amount of glass fiber to the pineapple leaf fiber and sisal fiber reinforced polyester matrix enhanced the mechanical properties of the resulting hybrid composites.

Takahashi and Chou [12] investigated the effect of interfacial debond on the transverse Young's moduli of fiber composites 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 debond by Hui-Z and Tsu-W [13]. Sambasiva Rao et al [14] developed three dimensional finite element models for the evaluation of the mechanical properties of T300-epoxy composite with fiber-matrix interface debond. Sivaji Babu et al [15] developed three dimensional finite element models for the evaluation of the mechanical properties of hybrid composite with fiber-matrix interface debond.

The present work is the extension of the work reported in reference [15] for the evaluation of coefficients of thermal expansion of a hybrid fiber reinforced composite with fiber-matrix interface debond.

Square Array of Unit Cells

A schematic diagram of the unidirectional fiber composite is shown in Fig. 1 where the fibers are arranged in the square array. It is assumed that the fiber and matrix materials are linearly elastic. A unit cell is adopted for the analysis. The cross sectional area of the fiber relative to the total cross sectional area of the unit cell 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).

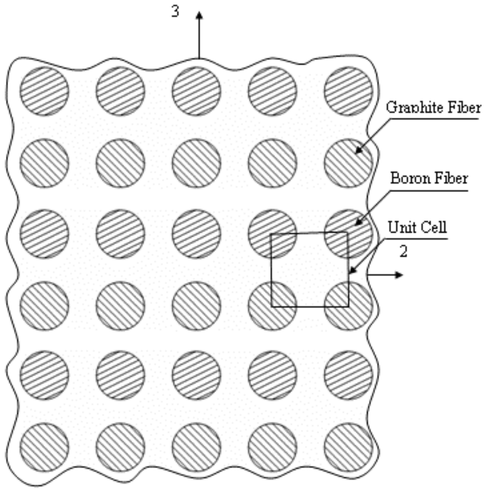

Figure 1: Concept of Unit Cells

Problem Statement

The present research work deals with the evaluation of coefficients of thermal expansion and shear moduli of graphite-boron-epoxy hybrid composite lamina by the elasticity theory based finite element analysis applied to square unit cell for imperfectly bonded fiber-matrix interface of the composites. Debond is given for entire length and extended in the circumferential direction.

Problem Modeling

Finite Element Model

The 1-2-3 Coordinate system shown in Fig. 2 is used to study the behaviour of unit cell where 1- is the fiber direction, perpendicular to the plane of the figure. The isolated unit cell behaves as a part of large array of unit cells by satisfying the conditions that the boundaries of the isolated unit cell remain plane.

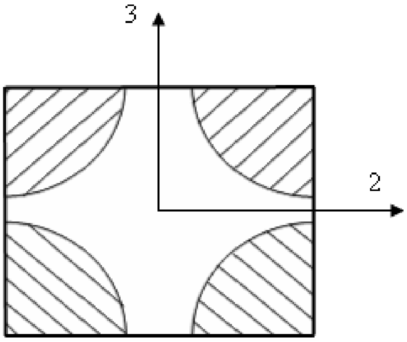

Figure 2: Isolated Unit Cell

It is assumed that the geometry, material and loading of unit cell are symmetric with respect to 1-3 plane of coordinate system. Therefore, a one-fourth portion (half in cross section and half along the length direction) of the unit cell is modeled for the analysis (Fig. 3).

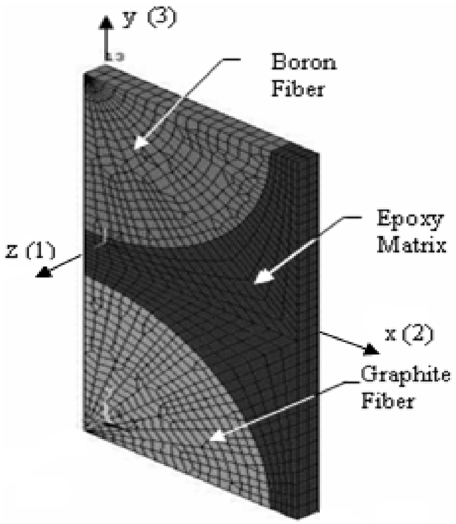

Figure 3: FE mesh.

Geometry of finite element model

The dimensions of the finite element model are taken as x = 100 units (2-in-plane transverse direction), y = 200 units (3-out-of-plane transverse direction) and z = 10 units (1-Fiber direction). The radius of fiber is taken corresponding to the volume fraction. For example, the radius of the fiber is calculated as 87.404 units, so that the fiber volume fraction becomes 0.60.

Element Type

The element used for the present analysis is SOLID 95 of ANSYS software [16], which is developed, based on three-dimensional elasticity theory and is defined by 20 nodes having three degrees of freedom at each node: translation in the x, y and z directions.

Loading

Uniform temperature load of 1 K is applied on the entire portion of the finite element model for the determination of coefficients of thermal expansion.

Materials

The top fiber in the unit cell is taken as boron and the bottom fiber as graphite. The properties of the constituent materials are given in Table 1.

Table 1: Properties of Constituents [1]

S. No.	Material	E (GPa)	ν	G (GPa)	α (/K)
1	Graphite Fiber	$E_1 = 233$ $E_2 = 23.1$ $E_3 = 23.1$	$\nu_{12} = 0.2$ $\nu_{13} = 0.2$ $\nu_{23} = 0.4$	$G_{12} = 8.96$ $G_{13} = 8.96$ $G_{23} = 8.27$	$\alpha_1 = -0.54\text{E-}06$ $\alpha_2 = 10.1\text{E-}06$
2	Boron Fiber	400	0.2	--	5.00E-06
3	Epoxy Matrix	4.62	0.36	--	41.4E-06

Boundary conditions

Due to the symmetry of the problem, the following symmetric boundary conditions are applied.

At x = 0, Ux = 0; At y = 0, Uy = 0; At z = 0, Uz = 0

In addition, the multipoint constraints are imposed on the boundaries of the unit cell to make them plane after loading.

Results and Discussion

The Coefficients of thermal expansion are determined using the equations

$$\alpha_1 = \varepsilon_1/\Delta t\,; \quad \alpha_2 = \varepsilon_2/\Delta t\,; \quad \alpha_3 = \varepsilon_3/\Delta t\,;$$

where the displacements for the calculation of strains are obtained from finite element solution.

Sufficient numbers of convergence tests are made and the finite element solutions for graphite-epoxy lamina are compared with the results of the alternate rule of mixtures [1] (Figs. 4&5) for perfectly bonding case and found close agreement. The above mentioned analysis is extended to study the behaviour of unit cell with debond along the length of the fiber and extended around the circumferential direction starting from bottom for the bottom fiber and top for the top fiber at the fiber-matrix interface.

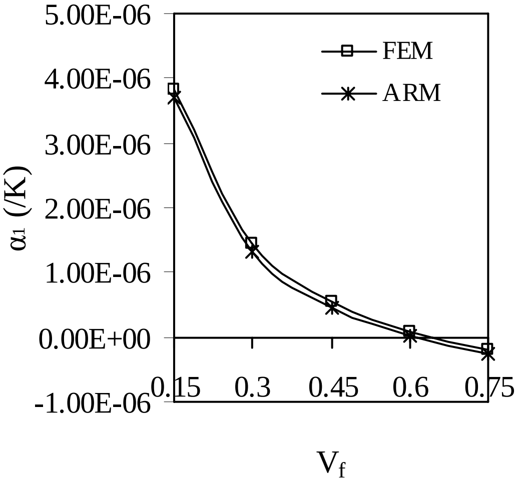

Figure 4: Validation for α1 with Alternate Rule of Mixtures

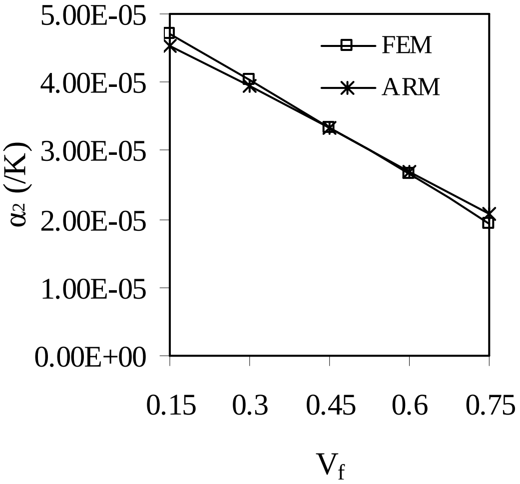

Figure 5: Validation for α2 with Alternate Rule of Mixtures

Fig. 6 shows that there is no significant variation in α_1 with respect to percentage debond. This is due to the reason that the thermal deformations of fiber and matrix materials in the longitudinal direction remains same irrespective of the connectivity between these materials at the interface (Fig. 7). Since the thermal expansion coefficient of Boron is more when compared with the longitudinal thermal expansion coefficient of

Graphite fiber, α_1 is more for boron-epoxy composite followed by hybrid-epoxy composite.

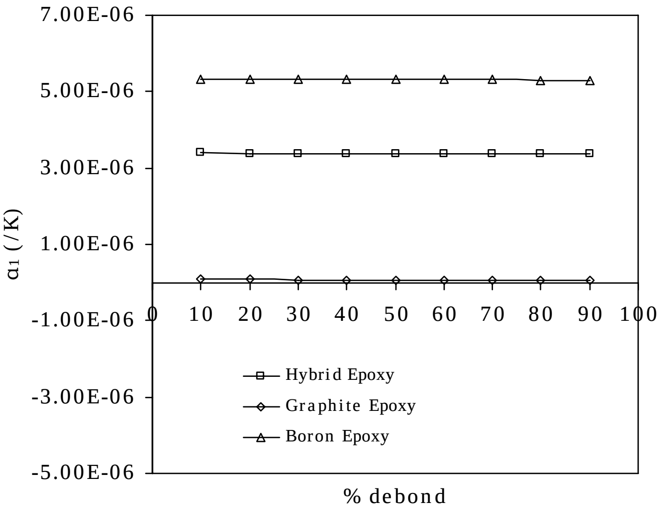

Figure 6*:* Variation of α_1

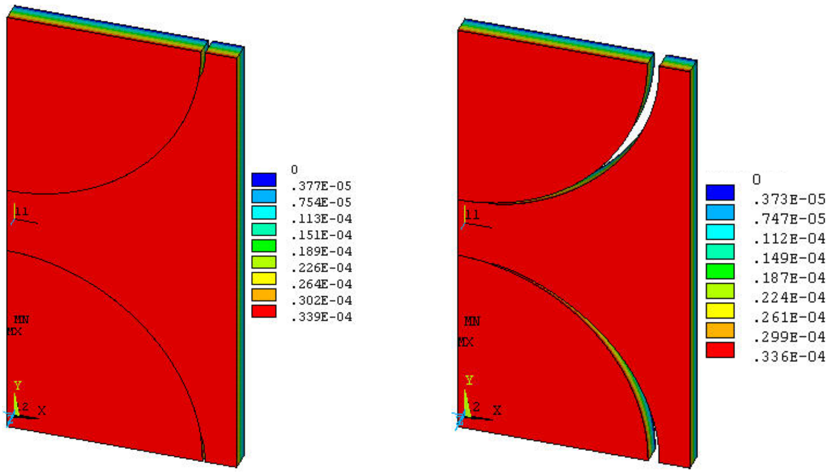

Figure 7: longitudinal displacement contours for 10% and 90% debond

A steep raise in α_2 can be found with respect to percentage debonding from Fig. 8. This is due to the reason that with increase in debonding, there is no control of fiber on matrix and the matrix expands freely in 2-direction resulting in the increase of strain in that direction as well as the property α_2 (Fig. 9). Unlike in the above case α_2 is found to be more for Graphite-epoxy because transverse thermal expansion coefficient of Graphite fiber is more than Boron fiber.

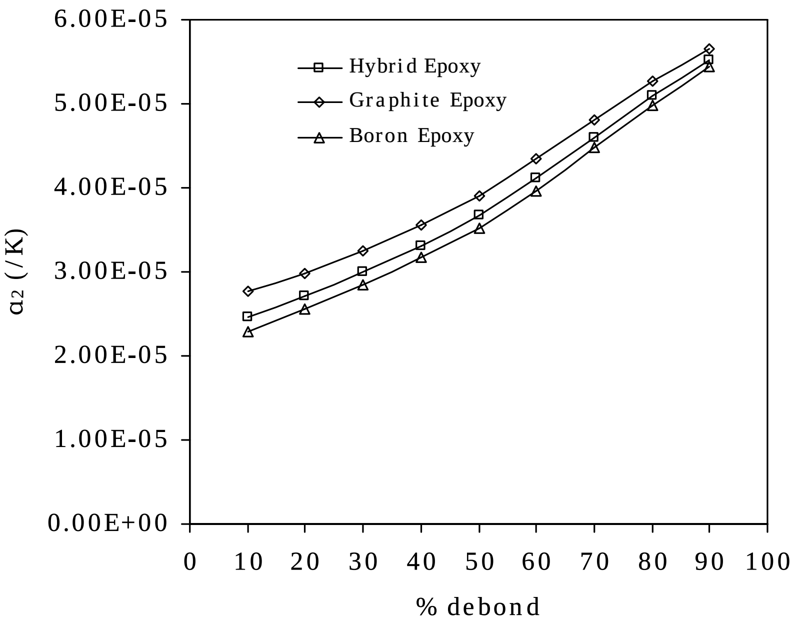

Figure 8: Variation of α_2

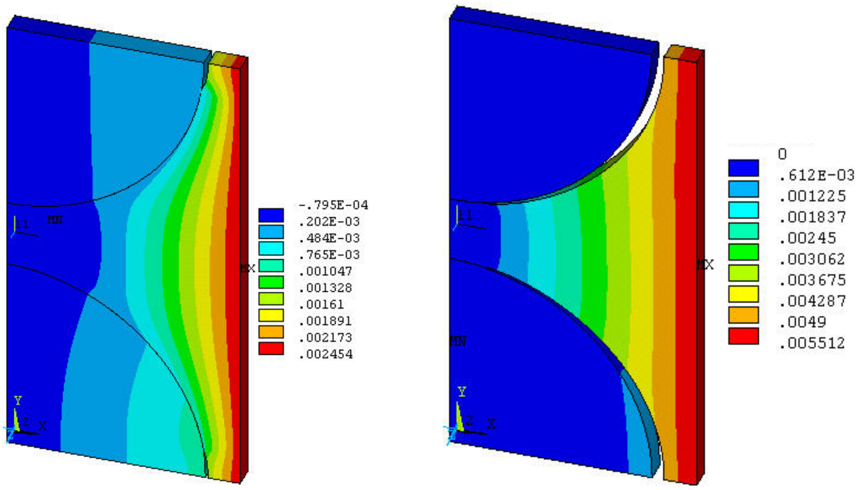

Figure 9: In-plane transverse displacement contours for 10% and 90% debond

A slight drop in α_3 up to 80% followed by a raise is seen in Fig. 10. This might be due to the low thermal expansion coefficients of fiber materials in transverse direction than matrix. Fibers try to restrict the free expansion of matrix up to 80% debonding. At higher values of debond, the load transfer between the fibers and matrix is very low due to less contact and therefore fibers may not influence the thermal expansion of composite in 3-direction (Fig. 11).

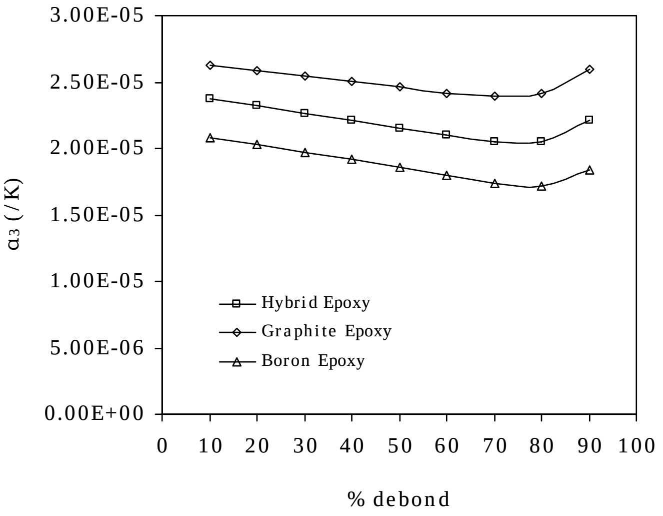

Figure 10: Variation of α_3

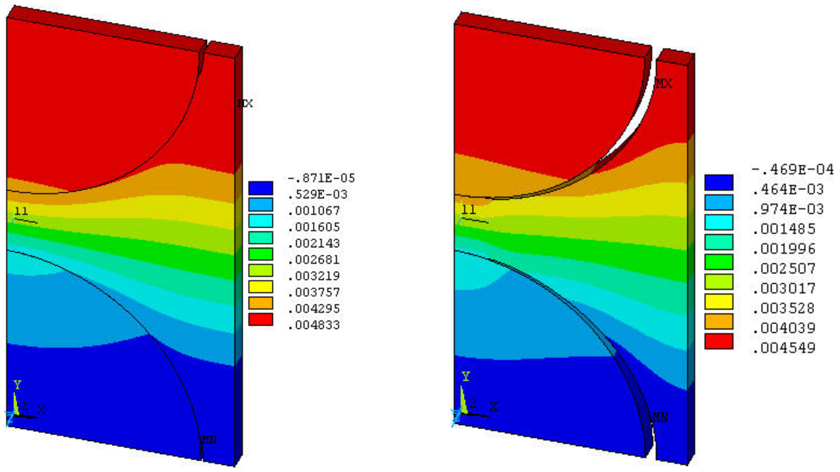

Figure 11: Out-of-plane transverse displacement contours for 10% and 90% debond.

Conclusions

Coefficients of thermal expansion of hybrid-epoxy fiber reinforced composite lamina with fiber-matrix interface debond have been predicted using theory of elasticity based finite element method applied to representative volume elements in the form of square unit cells. The following conclusions are drawn.

There is no considerable variation in α_1 with debond.

α_2 increases with increase in debond.

α_3 decreases with increase in debond up to 80% and later increases.

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