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Finite Element Micromechanical Modeling of FRP Composite with Orthotropic Fibers Subjected To Longitudinal Loading

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ABSTRACT

The present research work deals with the micromechanical analysis of fiber reinforced composites reinforced with orthotropic fibers under fiber directional tensile loading using three-dimensional finite element method. The problem is modeled in ANSYS software and the FE model is validated with bench mark results. Longitudinal Young's modulus and corresponding Poisson's ratios are predicted. The distribution of interfacial stresses around the circumference of the fiber is also determined for three different fiber-matrix combinations. The present work will be useful to find the static behavior of FRP lamina subjected to longitudinal load.

1 Introduction

Mechanics of materials deals with stresses, strains, and deformations in engineering structures subjected to mechanical and thermal loads. A common assumption in the mechanics of conventional materials, such as steel and aluminum, is that they are homogeneous and isotropic continua. For a homogeneous materials, properties do not depends on the location, and for an isotropic materials, properties do not depend on the orientation. Fiber-Reinforced composites, on the other hand, are microscopically inhomogeneous and nonisotropic. As a result, the mechanics of fiber reinforced composites are far more complex than that of conventional materials.

One of the approaches is used in the mechanics of fiber- Reinforced composites materials are Micromechanics approach, in which the interaction of the constituent materials is examined on a microscopic scale. Equations describing the elastic and thermal characteristics of a lamina are, in general, based on micromechanics formulations. An understanding of the interaction between various constituents is also useful in delineating the failure modes in fiber-reinforced composites materials. Good number of publications are available on this area. Zheng-Ming Huang [1] has implemented a micromechanical model to simulate the overall thermal and mechanical properties of a fibrous composite out of an elastic deformation range. This micromechanics model is called the Bridging model. Application of the model to predict various properties of unidirectional lamina and multidimensional laminates, including thermoelastic behaviour, elasto-plastic response, and ultimate failure strength, strength at elevated temperature and fatigue strength and S-N curve is demonstrated. Anifantis [2] studied that, variations in topology, material properties and adhesion characteristics, the micro mechanical stress states developed within fibrous composites that contain a heterogeneous interface region has been predicted numerically. Tandon [3] has evaluated the interfacial normal strength in unidirectional SCS-0/ epoxy composites by using single fiber specimens. These model specimens are incrementally loaded in tension to failure with a specifically built loading device mounted on the straining stage of the microscope. Qing Wang et al [4] has presented in situ strain measurement is performed at a submicron scale using a newly developed micromechanics technique SIEM (Speckle Interferometry with Electron Microscopy). The global mechanical response of metal-matrix composite and transverse tension is related with the micro mechanical behavior of the interface. Nimmer [5] investigated that, analytical models are presented and are used to explore the mechanics of transversely loaded, high temperature composites with a thermally induced residual stress field and a vanishingly weak fiber-matrix interface strength. Robertson et al [6] has presented the formulation of a new 3-dimensional micromechanical model for fiber reinforced material. It is based on the relaxation of the coupling effect between the normal and shear stress. Asp, L.E, Berglund, L.A., [7] developed failure initiation in polymer-matrix composites loaded transverse to the fibers is investigated by a numerical parametric study where the effects of constituent properties, interphase properties and thickness are examined. Dragan, [8] stresses in the models from unidirectional carbon/epoxy composite material are studied using Finite Element Method (FEM), can be used in order to predict stress distribution on the examinated model. Hussain et.al [9] studied on unidirectional continuous fiber lamina at different fiber volume fractions using the finite element method. Salvatore et.al [10] studied the elastic moduli and structure of boron carbide/ aluminum (B4C/Al) multiphase composites using rigorous bounding and experimental characterization techniques. V. Nassehi, J. Dhillon & L. Mascia [11] adopted finite element analysis has been applied to study the mechanical behavior of composites with ductile thermoplastic and rubbery interlayer between fibers and matrix. N. Krishna Vihari[12] adopted micromechanical approach to predict the stresses at the fiber-matrix interface of Boron/S-G/E-G fiber and Epoxy matrix composites due to temperature gradient across the lamina.

The aim of the current work is to predict elastic modulus three different fibers reinforced plastic laminas subjected to longitudinal loading and the interfacial stresses for a fixed volume fraction of 50%.

2. SQUARE ARRAY OF UNIT CELLS

The fibers are arranged in the square array which is known as the unidirectional fiber composite. And this unidirectional fiber composite is shown in Fig. 1. It is assumed that the fiber and matrix materials are linearly elastic. A unit cell is adopted for the analysis. The measure of the volume of fiber relative to the total volume of the composite is taken from the cross sectional areas of the fiber relative to the total cross sectional area of the unit cell. This fraction is considered as an important parameter in composite materials and is called fiber volume fraction (V_f).

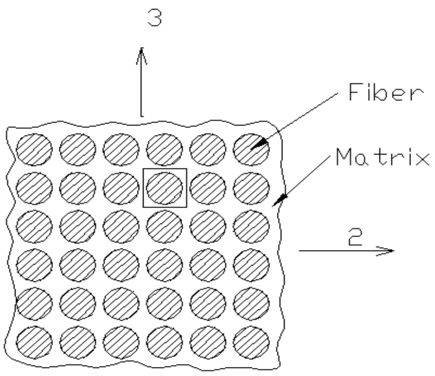

Fig.1 Concept of Unit Cells

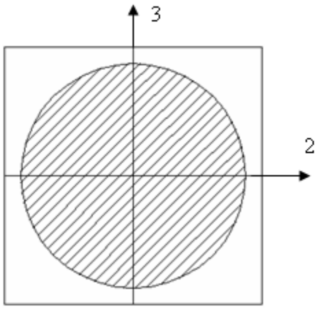

Fig.2 Isolated Unit Cell of Square packed array

3. PROBLEM STATEMNT

The analysis deals with the evaluation of the stresses at the fiber-matrix interface for a fiber volume fraction of 50% with various material combinations using 3D finite element method.

4. FINITE ELEMENT MODEL

In the study of the Micromechanics of fiber reinforced materials, it is convenient to use an orthogonal coordinate system that has one axis aligned with the fiber direction. The 1-2-3 Coordinate system shown in Fig.2 is used to study the behaviour of unit cell. The 1 axis is aligned with the fiber direction, the 2 axis is in the plane of the unit cell and perpendicular to the fibers and the 3 axis is perpendicular to the plane of the unit cell and is also perpendicular to the fibers. 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.

Due to symmetry in the geometry, material and loading of unit cell with respect to 1-2-3 coordinate system it is assumed that one fourth of the unit cell is sufficient to carry out the present analysis.

4.1 Geometry

The dimensions of the finite element model are taken as

- X=100 units,
- Y=100 units,
- Z=10units.

The radius of fiber is calculated as 79.788 units, so that the fiber volume fraction becomes 0.5. (Fig. 3). Z denoted the fiber direction, x,y represents inplane and out of plane directions.

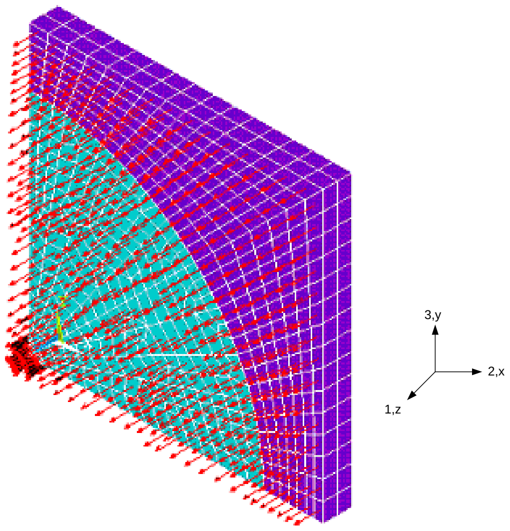

Fig.3. Finite element mesh on one-eighth portion of the unit cell

4.2 Element type

The element used for the present analysis are SOLID 95 of ANSYS defined by 20 nodes having one degree of freedom i.e. temperature and three degrees of freedom at each node: translation in the node x, y and z directions respectively.

4.3 Materials

The properties of the constituent materials used for the present analysis are given in (Table 1.)

4.4 Loading

A pressure load of -1 MPa is applied in the Z-direction.

Table1. Properties of Constituent

S.NO	Material	E	E	V	**v**	G (Gpa)	G (Gpa)
1	Carbon Fiber(T300)	E_1	230	ν_{12}	0.2	G_{12}	27
		E_2	15	ν_{13}	0.2	G_{13}	27
		E_3	15	ν_{23}	0.07	G_{23}	7
2	Carbon Fiber(IM7)	E_1	290	ν_{12}	0.2	G_{12}	14
		E_2	21	ν_{13}	0.2	G_{13}	14
		E_3	21	ν_{23}	0.04	G_{23}	8.75
3	Kevlar Fiber	E_1	131	ν_{12}	0.33	G_{12}	21
		E_2	7	ν_{13}	0.33	G_{13}	21
		E_3	7	ν_{23}	0.04	G_{23}	2.63
4	Epoxy (Matrix)	E	4.62	ν	0.32	---	----

E=Young’s Modulus

V=Poissons Ratio

4.5 Boundary conditions

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

- At x = 0, $U_x = 0$
- At y = 0, $U_y = 0$
- At z = 0, $U_z = 0$

In addition, the following multi point constraints are used.

- The U_x of all the nodes on the Area at x =100 is same
- The U_y of all the nodes on the Area at y =100 is same
- The U_z of all the nodes on the Area at z = 10 is same

5. RESULTS

Sufficient number of convergence tests is made and the present finite element model is validated by comparing the Young’s modulus that is computed from the results obtained to the values from rule of mixtures and found in close agreement. This comparision is shown in (Table 2).

Table 2 Young’s Modulus E (GPa) for 50% V_f

Materials	E	E from FEM GPa	E from Rule of Mixtures GPa	% Error	ν (FEM)
T-300-Epoxy	E_1	118.0637	117.310	0.638	0.737
Carbon (IM7)-Epoxy	E_1	147.41	147.31	0.0673	0.463
Kevlar-Epoxy	E_1	68.017	67.81	0.3043	0.553

The following stresses are computed at the fiber-matrix interface.

- σ^f_n = Normal stress in the fiber at the interface
- σ^f_c = Circumferential stress in the matrix at the interface
- σ^f_1 = Directional stress in the fiber at the interface.

- τ^f_{nc} = Shear stress in the fiber at the interface.
- σ^m_c = Circumferential stress in the matrix at the interface
- σ^m_1 = Directional stress in the matrix at the interface

6. ANALYSIS OF RESULTS

Fig. 4 shows the normal stress in fiber at the interface for three different reinforced composite materials. The normal stress is maximum at 0^0 and is minimum at 90^0 positions. Curve of the carbon lm7 reinforced composite material shows the minimum stress values because its longitudinal directional properties are superior then those of other two materials and same matrix is used in three combinations. The same stresses in T-300 reinforced and Kevlar reinforced composites are approximately equal from $\theta=45^0$ to 90^0 positions of the fiber. From Fig. 5, we can observe that the values of σ^f_c obtained for carbon (lm7) material are minimum and these stress is maximum at 90^0 position and minimum at 0^0. Similar type of response is observed in other two reinforced composites.

The variation of fiber directional stress in fiber for all the three composites is nearly same and almost constant with angular position as shown in Fig. 6. The shear stresses are zero at the starting and ending positions of the fibers, maximum at the center of the fiber matric interface. This phenomenon is same for all the three reinforced composites and magnitude is ultimate for T300-epoxy followed by Kevlar-epoxy and lm-7-epoxy lamina as shown in Fig.7.

Variation of circumferential stress in the matrix is shown in Fig. 8, from which we can observe that the carbon lm7 had minimum stress values also that the carbon T300 and Kevlar materials had approximately equal stresses. Negative stresses developed from 0 to 63^0 positions and later positive directional stresses are observed.

The variation in fiber directional stress of matrix is shown in Fig. 9. All the three materials have different stress values. Maximum fiber directional stresses are developed in Kevlar reinforced matrix followed by carbon T300, Carbon lm7.

The circumferential stresses in matrix had given the tensile stress from63^0 to 90^0 positions whereas the same stresses in fiber had shown compression nature.

The variation in stresses with angle is due to the geometrical arrangement of fiber and matrix in unit cell and the constraints imposed on boundaries.

The variation of stresses with material is due to the variation of mismatch in fiber to matrix Young's modulus.

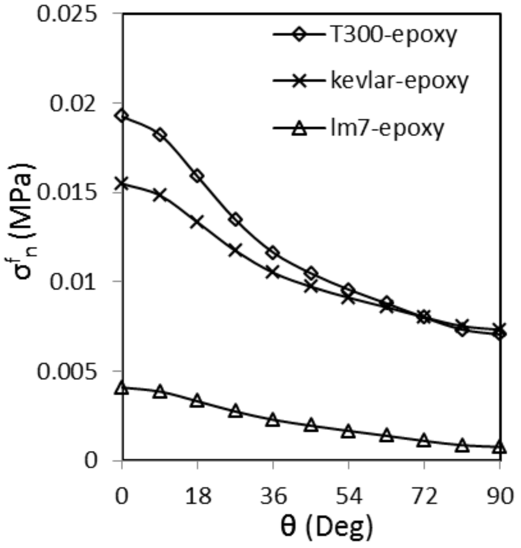

Fig. 2 Variation of σ^f_n with respect to θ

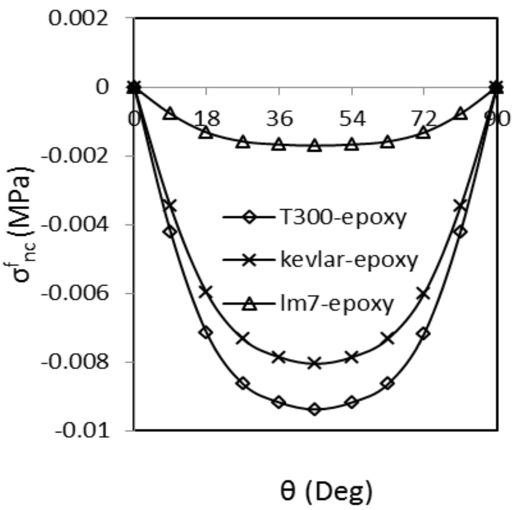

Fig. 3 Variation of τ^{f}_{nc} with respect to θ

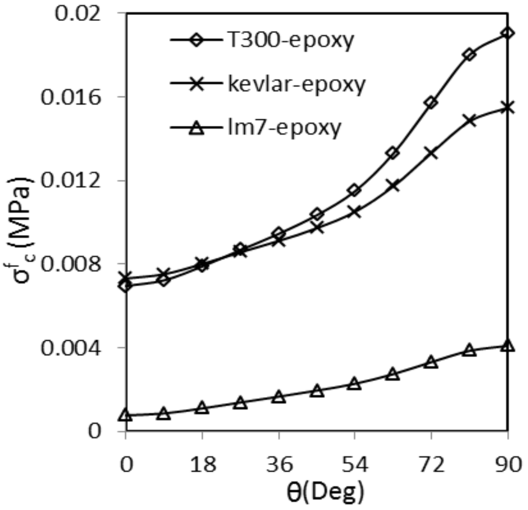

Fig. 4 Variation of σ^{f}_{c} with respect to θ

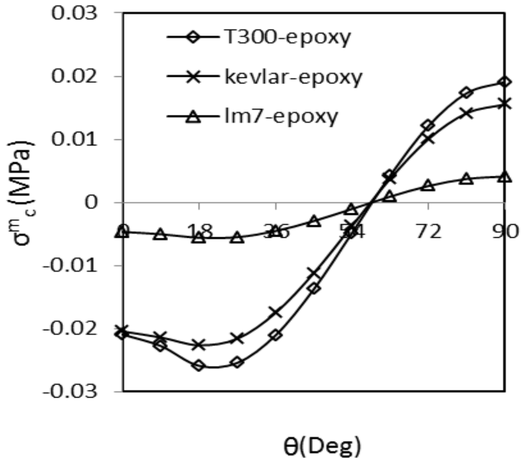

Fig. 5 Variation of σ^{m}_{c} with respect to θ

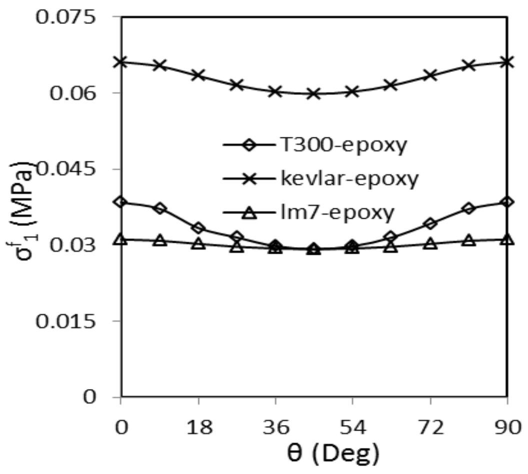

Fig.6 Variation of σ^{f}_{1} with respect to θ

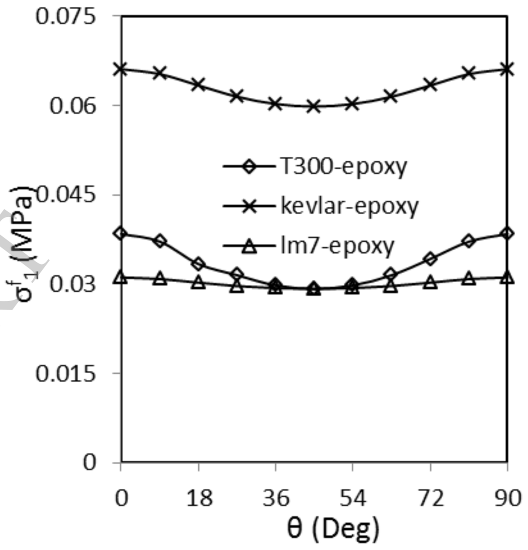

Fig. 7 Variation of σ^{m}_{1} with respect to θ

7. CONCLUSIONS

Micromechanical analysis of continuous fiber reinforced composite is performed using three-dimensional FEM. The following conclusions are drawn:

- The normal stress is maximum at 0^0 and minimum at 90^0 for all three materials.
- A reverse trend to normal stress is observed in circumferential stress in fiber is maximum at 90^0 and minimum at 0^0 for all three materials.

- The fiber directional stresses are almost same at all locations of interface.
- The fiber directional stress in matrix is minimum for carbon (lm7) composite.
- The normal and shear stresses are same for both fiber and matrix at the fiber-matrix interface for all the three composites and hence only normal and shear stress of fiber are shown.

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