RESEARCH ARTICLE OPEN ACCESS

Micromechanical Analysis of FRP Composite with Orthotropic Fibers Subjected To Longitudinal and Transverse Loading

M. Gowtha Muneswara Rao[1] and Sk. Zareena[2]
Mechanical. Engg. Dept., CMR Technical Campus A.P., India.

ABSTRACT

The present research work deals with the micromechanical analysis of fiber reinforced composites with orthotropic fibers under fiber directional tensile loading and transverse 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 transverse Young's modulus corresponding Poisson's ratios are predicted. Fiber reinforced composite materials are now an important class of an engineering materials. They offer outstanding mechanical properties, unique flexibility in design capabilities, and ease of fabrication. Additional advantages include light weight and corrosion resistance, impact resistance, and excellent fatigue strength. Today fiber composites are routinely used in such diverse applications as automobiles, aircraft, space vehicles, offshore structures, containers and piping, sporting goods, electronics, and appliances. In the present work, micromechanical behavior of a square unit cell of uni-directional fiber reinforced composite with orthotropic fibers (viz., Carbon- T300 carbon- Im7 Kelvar-4Paramid and)embedded in epoxy resin has been analyzed under tensile loading using Finite element analysis software package Ansys 14.0. The 3-D Finite Element Model with governing boundary conditions has been developed from the unit cell of square pattern of the composite to evaluate the engineering constants like, Longitudinal modulus (E_1), Transverse modulus (E_2), and Major Poisson's ratio (ν_{12}) of the above FRP composites for various fiber volume fractions. Also, interfacial stresses induced at the fiber matrix interfaces due to longitudinal loading for various fiber volume fractions has been estimated. Finally the results obtained from finite element analysis (Numerical method) are validated with benchmark results. The present work will be useful to predict the engineering constants of uni-directional fiber reinforced composite materials subjected to longitudinal loading. And also present work will be useful to find the static behavior of FRP lamina subjected to longitudinal load.

Keywords: Epoxy, Finite Element Analysis, FRP, Interface, Lamina, Micromechanics.

I. INTRODUCTION

A Composite is a material system consisting of two or more phases on a macroscopic scale, whose mechanical performance and properties are designed to be superior to those of constituent materials acting independently. One of the phase is discontinuous, stiffer, and stronger and is called reinforcement. Where the less stiff and weaker phase is continuous and is called matrix. The low density, high strength, high stiffness to weight ratio, excellent durability and design flexibility of fiber-reinforced composite materials are the primary reasons for their extended use. The fiber reinforced composites can be a 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 fiber orientation, fiber volume fraction, fiber spacing, and fiber distribution in the matrix and layer sequence. 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 direction. Chen and Chang [1], Hussain S.A.t.al [2], have developed predictive models for micromechanical analysis of fiber reinforced composites with various types of constituents. 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 Interferometer with Electron Microscopy). The global mechanical response of metal-matrix composite and transverse tension is related with the micro mechanical behaviour 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, inter phase 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. N. Krishna Vihari [9] 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. In this paper the finite element method has been adopted for predicting various engineering constants uni-directional fiber reinforced composites and the results of E_x, E_y, ν_{12} are compared with the rule of mixtures and Halphin-Tsai criteria. Also, interfacial stresses induced at the interface of fiber and resign for various volume fractions have been estimated.

II. METHODOLOGY

A unidirectional continuous fiber reinforced composite lamina has been idealized as a large array of representative volume elements. Depending upon the arrangement of the fibers across the cross section of the lamina, different types of representative volume elements can be obtained such as square, hexagonal, staggered square patterns.etc. In any pattern repetition of a particular volume of the lamina can be observed, which is called the representative volume element (RVE).

For the present analysis, the lamina is considered as an array of square unit cells, one unit cell is adopted for the micromechanical analysis of the lamina. The cross sectional area of the fiber in the cell is governed by the fiber volume fraction, (V_f) which is the ratio of the volume of the fiber to the total volume of the unit cell.

Finite element method is implemented to study the response of the unit cell due to thermal and mechanical loads. The size of the problem is reduced to the possible extent by taking the advantage of symmetry in material arrangement, geometry, loading and boundary conditions. One-eighth (one fourth in cross section and half in length) portion of the unit cell is modeled for the analysis.

The volumes of the fiber and matrix in the portion of the unit cell modeled have been discretized into three dimensional elasticity based 20 node solid95 finite element of ANSYS software. The loading, boundary conditions and other multipoint constraints are applied in remain plane during and after deformation. The finite element software ANSYS is successfully executed for the analysis.

2.1: SQUARE ARRAY OF UNIT CELLS

A schematic diagram of the unidirectional fiber composite is shown in Fig.3.1.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).

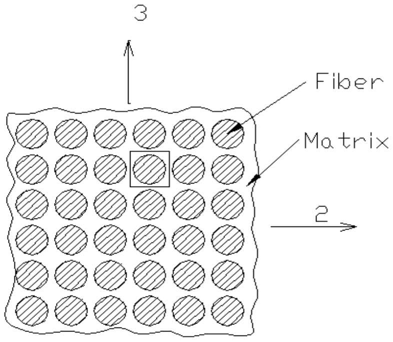

Fig .1 Concept of Unit cells

The 1-2-3 Coordinate system shown in Fig.3.2 is used to study the behaviour of unit cell. 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.

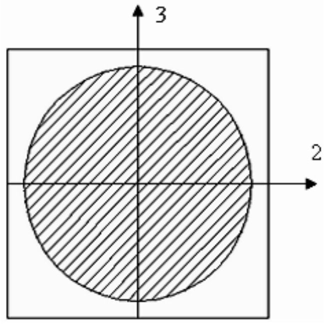

Fig.2 Isolated unit cell of Square packed array

It is assumed that the geometry, material and loading of unit cell are symmetric with respect to 1-2-3 coordinate system. Therefore, a one-eighth portion of the unit cell is modeled for the analysis.

2.2: 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.3 is used to study the behavior 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. The 3D Finite Element mesh on one fourth portion of the unit cell is shown in Fig.4.

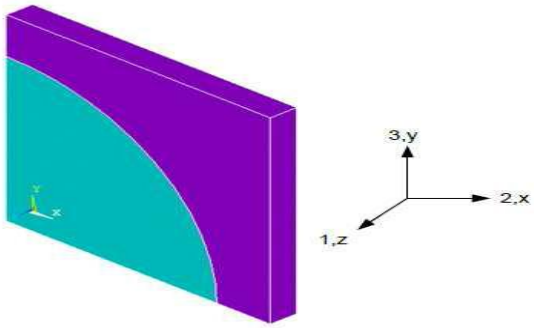

Fig.3 One-eighth portion of unit cell

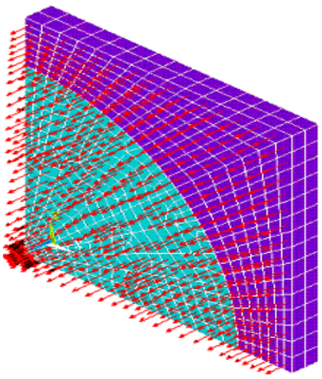

Fig.4 Finite Element mesh for E_1 model (Longitudinal load)

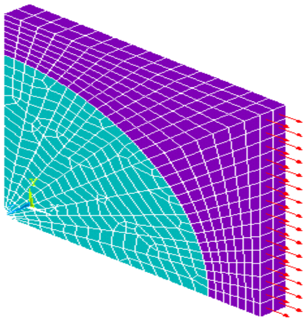

Fig.5 Finite Element mesh for E_2 model (Transverse load)

2.3: 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 is varied to the corresponding fiber volume.

2.4: Element type

The element SOLID186 of ANSYS V13.0 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. The element has 20 nodes having one degree of freedom i.e. temperature and with three degrees of freedom at each node: translation in the node x, y and z directions respectively.

2.3: Boundary conditions

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

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

In addition, the following multi point constraints are used.

The Ux of all the nodes on the Area at x =100 is same
The Uy of all the nodes on the Area at y =100 is same
The Uz of all the nodes on the Area at z = 10 is same

2.4 Analytical solution

$E_1= \sigma_1/\varepsilon_1$
$E_2 = \sigma_2/\varepsilon_2$
Major Poison's ratio $\nu_{12}= - \varepsilon_2 / \varepsilon_1$
where
σ_1= Stress in x-direction ε_1= Strain in x-direction
σ_2= Stress in y-direction ε_2 = Strain in y-direction

The mechanical properties of the lamina are calculated using the following expressions of Theory of elasticity.

2.5Rule of mixtures

Longitudinal young's Modulus: $E_1= E_fV_f+E_mV_m$
Transverse young's Modulus: $E_2 = E_fV_f+E_mV_m$
Major Poisson's Ratio: $\nu_{12}= \nu_fV_f + \nu_mV_m$

2.6 Materials

Three different types of fiber reinforced composite materials considered in this investigation, they are

- Carbon T300/ Epoxy composite
- Carbon IM7/ Epoxy composite

- Kevlar/Epoxy composite

The typical properties of the three different composite materials are illustrated in t

Table- 1: Typical properties of Fibers and Epoxy

property	symbol	carbonT 300	Carbon Im7	kevlar	Epoxy
Longitudinal Modulus	E_1 (Gpa)	230	290	131	4.62
Transeverse modulus	E_2 (Gpa)	15	21	7	4.62
Longitudinal poisson's ratio	ν_{12}	0.2	0.2	0.33	0.32
Transeverse poisson's ratio	ν_{13}	0.2	0.2	0.33	0.32
longitudinal Shear Modulus	G_{12} (Gpa)	27	14	21	1.6
Transeverse Shear Modulus	G_{13} (Gpa)	27	14	21	1.6

2.7: Loading

A pressure load of -1 MPa is applied in z-direction (longitudinal) for E_1 modal (Fig.4).
A pressure load of -1 MPa is applied in x-direction (transverse) for E_2 modal (Fig.5).

III. RESULTS

In the present work finite element analysis has been carried out to predict the engineering constants of three different types of uni-directional fiber reinforced composite materials viz., Hexply Im7-8552, Kelvar and Carbon T300 embedded in epoxy resin. The results obtained are validated with the results obtained by rule of mixtures and Halpin-Tsai. In addition to that the interfacial stresses which are induced at the interface of fiber and matrix for various fiber volume fractions are also determined.

σ^f_n = Normal stress intensity in the fiber at the fiber matrix interface.

3.1Finite Element Analysis ofCarbonT300/Epoxy Composite

The variation of different engineering constants of a uni-directional Carbon T300/Epoxy composite with respect to the different fiber volume fractions are shown from Fig.6~8.

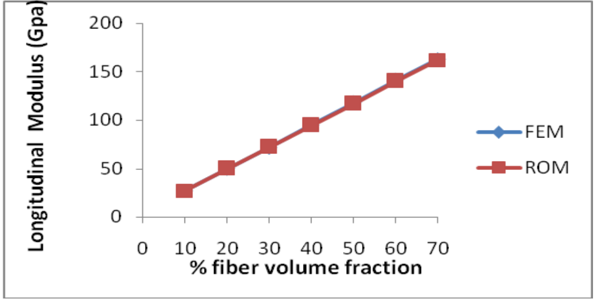

Fig.6: Variation of E_1 with fiber volume fraction

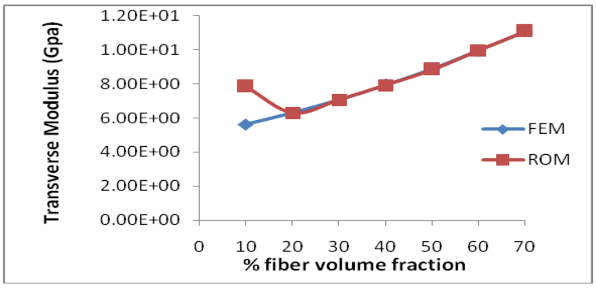

Fig.7: Variation of E_2 with fiber volume fraction.

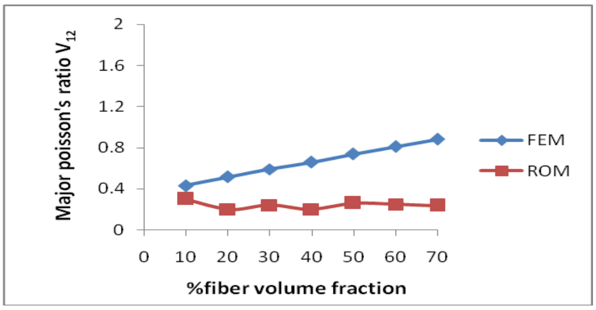

Fig.8: Variation of $\nu_{12}$with fiber volume fraction.

3.2Finite Element Analysis of CarbonIM7/Epoxy Composite

The variation of different engineering constants of a uni-directional IM7/Epoxy composite with respect to the different fiber volume fractions are shown from Fig.9-11.

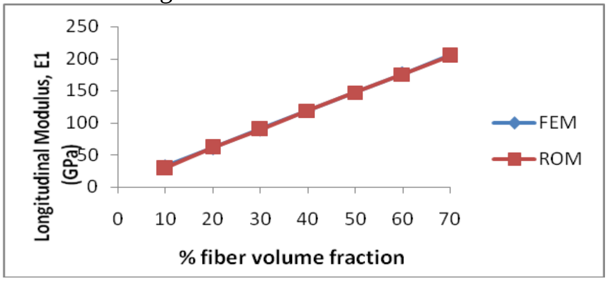

Fig.9: Variation of $E_1$with fiber volume fraction

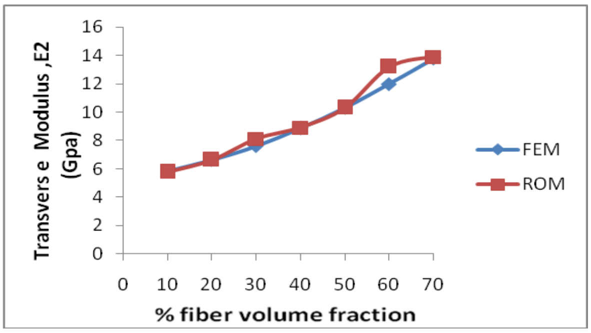

Fig.10: Variation of $E_2$with fiber volume fraction.

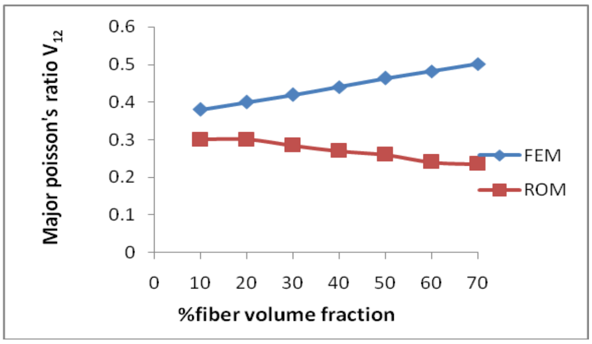

Fig.11: Variation of $\nu_{12}$with fiber volume fraction.

3.3 Finite Element Analysis of Kevlar/Epoxy Composite

The variation of different engineering constants of a uni-directional Kevlar/Epoxy composite with respect to the different fiber volume fractions are shown from Fig.12-14 .

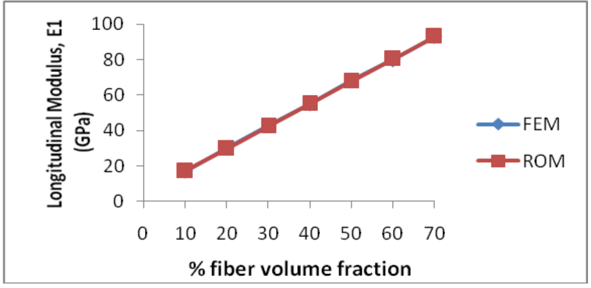

Fig.12: Variation of $E_1$with fiber volume fraction

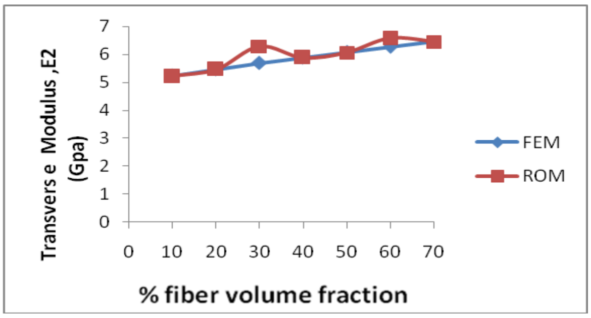

Fig.13: Variation of $E_2$with fiber volume fraction.

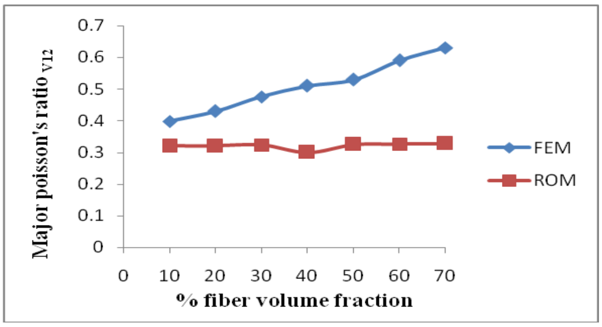

Fig.14: Variation of $\nu_{12}$with fiber volume fraction.

IV. ANALYSIS OF RESULTS

Figures 6-8 show the variation of various properties with the fiber volume fraction.

The observations are made from the plot are:

1. The longitudinal young's modulus E_1 increases linearly with increase in fiber volume fraction for all the three types of composites materials.
2. In longitudinal young's modulus the fiber volume fraction is high it will give more strength and high stiffness.
3. The transverse young's modulus E_2 increases linearly with increase in fiber volume fraction for all the three types of composites materials.
4. The major poisson's ratio ν_{12} increases with increase in fiber volume fraction for all three types of composites materials.
5. The observations are made from all the above graphs the % of fiber volume fraction is high it will give more strength and high stiffness.

V. CONCLUSION

In this paper micromechanical analysis of three different types of composite (Viz.,Carbon T300/Epoxy, IM7/Epoxy and Kevlar/ Epoxy) materials has been carried out using FEA software, ANSYS 14 to evaluate several elastic constants. The results of elastic moduli E_1, E_2, and ν_{12} are compared with the results obtained by using the Rule of Mixture .It is seen that the results from the Finite Element simulation are little bit deviating with the analytical results Also several properties for which simple and accurate analytical methods are not available are evaluated. Hence finite element method is a viable alternative to perform better analysis of fiber reinforced composite materials.

REFERENCES

[1] Salvatore Torquato, Christofer L. Y. Yeong, Mark D. Rintoul, David L. Milius and Ilhan A. Aksay, "Elastic Properties and Structure of Interpenetrating Boron Carbide/Aluminum Multiphase Composites", Journal of the American

Ceramic Society—Torquato et al., Vol. 82(5), May 1999, pp. 1263–68.

[2] Nimmer, R. P., Bankert, R. J., Russell, E. S., Smith, G. A., and Wright, P. K., "Micromechanical Modeling of Fiber/Matrix Interface Effects in Transversely Loaded SIC/Ti-6-4 Metal Matrix Composites", Journal of Composites Technology & Research, JCTRER, Vol. 13(1), Spring 1991, pp. 3-13.

[3] Nassehi, V., Dhillon, J., and Mascia, L., "Finite Element Simulation of the Micromechanics of Interlayered Polymer/Fibre Composite: A Study of the Interactions between the Reinforcing Phases", Composites Science and Technology, Vol. 47, 1993, pp. 349-358.

[4] Robertson, D. D. and Mall, S., "Fiber-Matrix Interphase Effects upon tranverse Behavior in Metal-Matrix Composites", Journal of Composites Technology & Research, JCTRER, Vol. 14(1), Spring 1992, pp. 3-11.

[5] Dong sheng Li & Michael R., "Journal of Composites Technology & Research", JCTRER, Vol. 42(4), Spring 1996, pp. 413-427.

[6] D. H. Allen, R. H. Jones and J.G. Boy, "Micromechanical analysis of a continuous fiber metal matrix composite including the effects of matrix viscoplasticity and evolving damage", Journal of the Mechanics and Physics of Solids Vol. 42(4), March 1994, pp. 505-529.

[7] Sun. C. T. and Vaidya. R. S., "Prediction of composite properties from a representative volume element", Composites Science and Technology, vol.56, 1996, pp. 171-179.

[8] S. L. Wire, R. A. Duckett, P. J. Hine and I. M. Ward, "Elastic property estimates of a unidirectional discontinuous fiber composite", Journal of composite science and technology Vol. 59,1999, pp. 419-427.

[9] D. F. O'Regan, M. Akay, B. Meenan, "A comparision of young's modulus predictions in fiber reinforced polyamide injection mouldings", Journal of composite science and technology Vol. 59, 1999, pp. 419-427.

[10] Zihui Xia, Yu Chen and Fernand Ellyin, "A meso/micro-mechanical model for damage progression in glass-fiber/epoxy cross-ply laminates by finite-element analysis", Journal of composite science and technology Vol. 50(8), 2000, pp. 1171-1179.

[11] Akser, E. O., and Choy K.L., "Finite Element Analysis of the stress distribution in a thermally and transversely loaded Ti-6Al-4V/SiC fibre composite", Composites: Part A, Vol. 32, 2001, pp. 243-251.

[12] Frank F. Shi**, "**The Mechanical Properties and Deformation of Shear-Induced Polymer Liquid Crystalline Fibers in an Engineering Thermoplastic", Journal of Composite Materials September Vol. 30(14), 1996, pp. 1613-1626.