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MICROMECHANICAL ANALYSIS OF FRP COMPOSITES

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ABSTRACT

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., Hexply Im7-8552, Kelvar and Carbon T300) embedded in epoxy resin has been analyzed under tensile loading using Finite element analysis software package Ansys 13.0. 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), In-plane shear modulus (G_{12}) 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.

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

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1. 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. et.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, 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. 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, υ_{12} and G_{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.

2. METHODOLOGY

The present research work deals with the evaluation of engineering properties by the elasticity theory based finite element analysis of representative volume elements of fiber-reinforced composites. 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.2 shows an isolated unit cell.

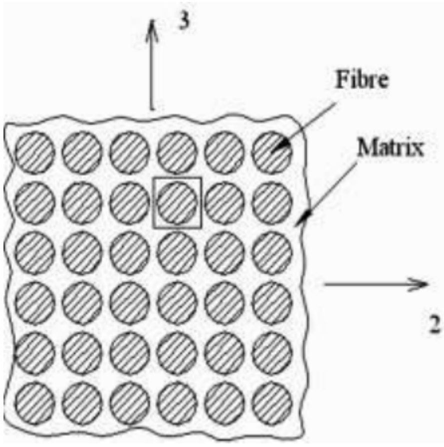

Fig.1: Concept of Unit Cells

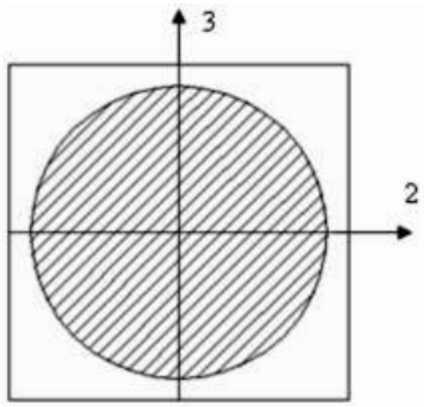

Fig.2: Isolated Unit Cells of Square packed array

2.1 Numerical solution

Finite element method is an approximate numerical method which has been successfully used for solutions of problems in various fields, including solid mechanics, fluid mechanics and heat transfer. In the present work, the computational numerical analysis is done using ANSYS version 13.0 running on an Intel i3 processor system.

Assumptions made for the present analysis were

- Fibers are uniformly distributed in the matrix;
- Fibers are perfectly aligned;
- There is perfect bonding between fibers and matrix;
- The composite lamina is free of voids and other irregularities; and
- The load is within the linear elastic limit.

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.

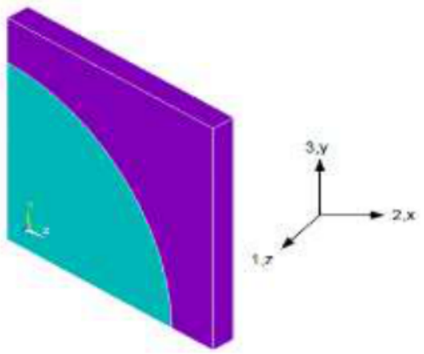

Fig.3: One-fourth portion of unit cell

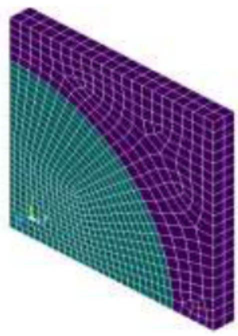

Fig.4: Finite Element mesh

2.2.1 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 is varied to the corresponding fiber volume.

$$V_f = \frac{\text{cross section area of fiber}}{\text{cross section area of unit cell}}$$

$$V_f = \frac{\frac{\pi}{4} r^2}{a^2} \qquad (1)$$

r radius of fibre
a edge length of square unit cell
V_f volume fraction of fibre

2.2.2 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.

2.2.3 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

2.3 Analytical solution

The mechanical properties of the lamina are calculated using the following expressions of Theory of elasticity approach and Halphin - Tsai's formulae.

Young's Modulus in the fiber direction and transverse direction

$$E_1 = \sigma_1/\varepsilon_1 \quad (2)$$

$$E_2 = \sigma_2/\varepsilon_2 \quad (3)$$

Major Poison's ratio

$$\nu_{12} = - \varepsilon_2/\varepsilon_1 \quad (4)$$

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

2.3.1 Rule of mixtures

Longitudinal young's Modulus: $E_1 = E_f V_f + E_m V_m$ (5)

Transverse young's Modulus: $E_2 = E_f V_f + E_m V_m$ (6)

Major Poisson's Ratio: $\nu_{12} = \nu_f V_f + \nu_m V_m$ (7)

In-Plane Shear Modulus: $G_{12} = G_f V_f + G_m V_m$ (8)

2.3.2 Semi-empirical model (Halphin- Tsai's)

The values obtained for transverse young's modulus and in-plane shear modulus through equations (6) and (8) do not agree with the experimental results. This establishes the need for better Modeling techniques, which include finite element method, finite difference method and boundary element methods. Unfortunately, these models are available for complicated equations. Due to this, semi-empirical models have been developed for the design purposes. The most useful of these semi-empirical models includes those of Halphin and Tsai, since they can be used over a wide range of elastic properties and fiber volume fractions.

Halphin and Tsai developed their models as simple equations by curve fitting to results that are based on elasticity. The equations are semi-empirical in nature since involved parameters in the curve fitting carry physical meaning.

Longitudinal Young's Modulus (E_1)

The Halphin-Tsai equation for the longitudinal Young's modulus is the same as that obtained through the strength of materials approach, that is,

$$E_1 = E_f V_f + E_m V_m \quad (9)$$

Transverse Young's Modulus (E_1)

The transverse Young's modulus, E_2, is given by

$$E_2/E_m = (1+\xi\eta V_f)/ (1-\eta V_f) \quad (10)$$

where $\eta = ((E_f/E_m)-1)/ ((E_f/E_m) +\xi)$ (11)

The term "ξ"is called the reinforcing factor and depends on the following;

- Fiber geometry
- Packing geometry
- Loading conditions

Major Poisson's Ratio (ν_{12})

The Halphin and Tsai equation for the Major Poisson's ratio is the same as that obtained using the strength of materials approach, that is,

$$\nu_{12} = \nu_f V_f + \nu_m V_m \quad (12)$$

In-Plane Shear Modulus (G_{12})

The Halphin and Tsai equation for the in-plane shear Modulus G_{12} is

$$G_{12}/G_m = (1+\xi\eta V_f)/(1-\eta V_f) \quad (13)$$

where

$$\eta = ((G_f/G_m)-1)/((G_f/G_m) + \xi \quad (14)$$

The value of reinforcing factor ξ depends on fibre geometry, packing geometry and loading conditions.

2.3.3 Materials

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

- Carbon T300/ Epoxy composite
- Hexply 8555 IM7/ Epoxy composite
- Kevlar/Epoxy composite

The typical properties of the three different composite materials are illustrated in table 1.

Table- 1: Typical properties of Fibers and Epoxy

Property	Symbol	Units	Carbon T300	Hexply 8555 IM7	Kelvar	Epoxy
Axial Modulus	E_1	Gpa	230	161	131	4.62
Transverse Modulus	E_2	Gpa	15	11.4	7	4.62
Axial Poisson's Ratio	ν_{12}	-	0.2	0.32	0.33	0.32
Transverse Poisson's Ratio	ν_{13}	-	0.2	0.32	0.33	0.32
Axial Shear Modulus	G_{12}	Gpa	27	5.17	21	1.308
Transverse Shear Modulus	G_{13}	Gpa	27	5.17	21	1.308

3. 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.
- τ^f_n = Shear stress intensity in the fiber at the fiber matrix interface.

3.1 Finite Element Analysis of Carbon T300/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.5~8 and the variation of normal stresses and also interfacial shear stresses with respect to the fiber volume fraction are shown in Fig. 9~10.

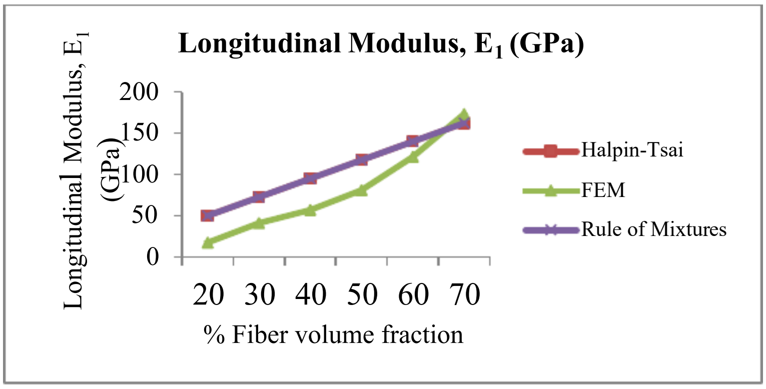

Fig.5: Variation of E_1 with fiber volume fraction.

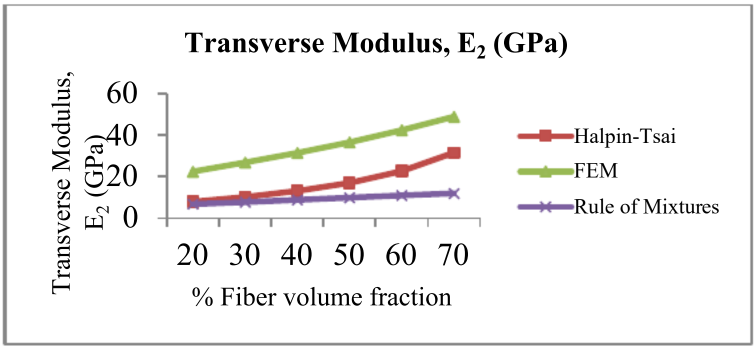

Fig.6: Variation of E_2 with fiber volume fraction.

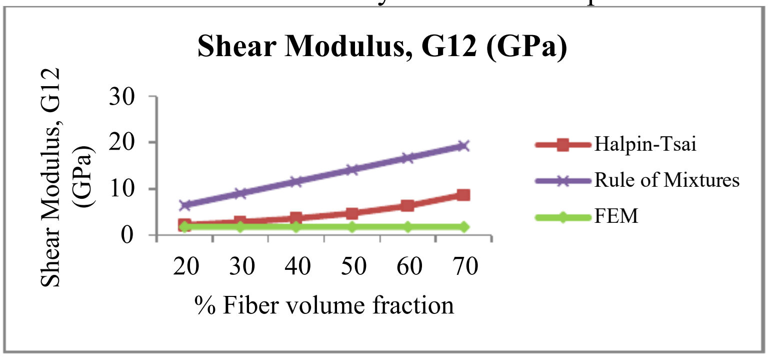

Fig.7: Variation of G_{12} with fiber volume fraction.

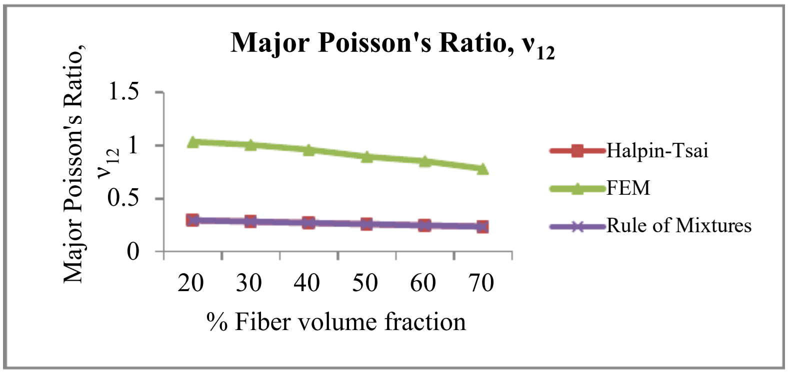

Fig.8: Variation of ν_{12} with fiber volume fraction.

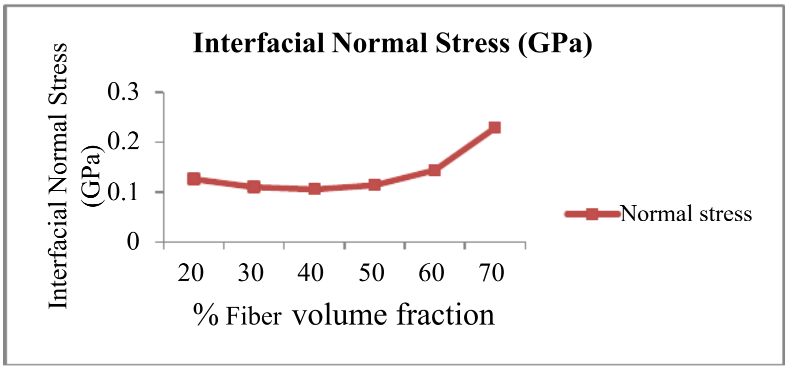

Fig.9: Variation of Interfacial Normal Stress with fiber volume fraction.

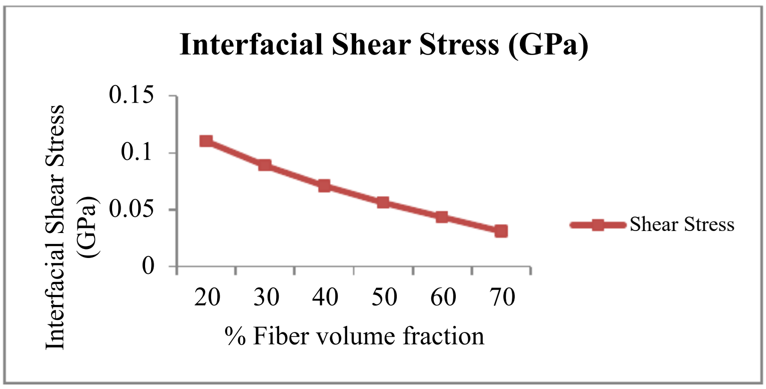

Fig.10: Variation of Interfacial Shear Stress with fiber volume fraction

3.2 Finite Element Analysis of Hexply 8555 IM7/Epoxy Composite

The variation of different engineering constants of a uni-directional Hexply 8555 IM7/Epoxy composite with respect to the different fiber volume fractions are shown from Fig.11~14 and the variation of normal stresses and also interfacial shear stresses with respect to the fiber volume fraction are shown in Fig.15~16.

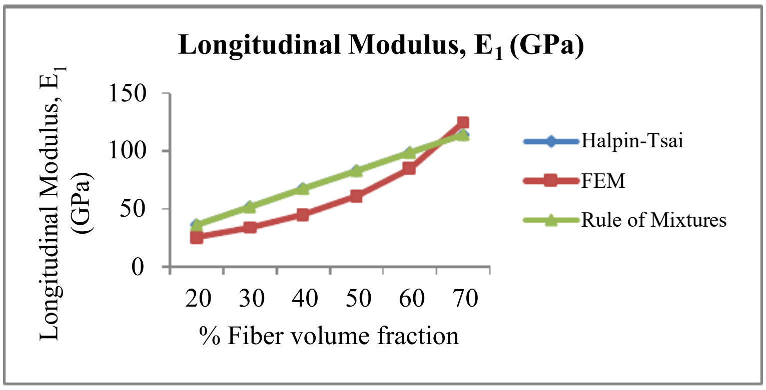

Fig.11: Variation of E_1 with fiber volume fraction

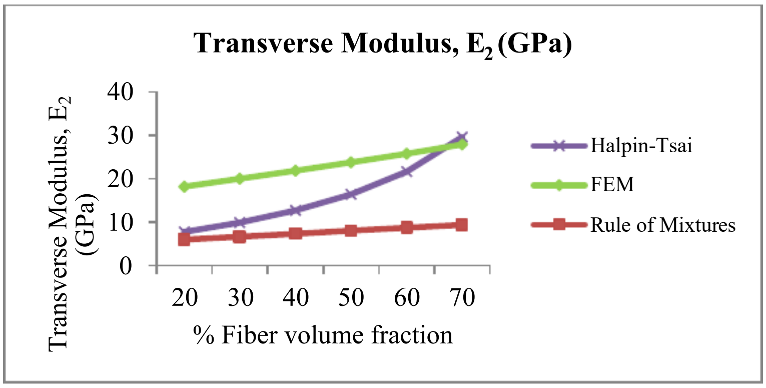

Fig.12: Variation of E_2 with fiber volume fraction

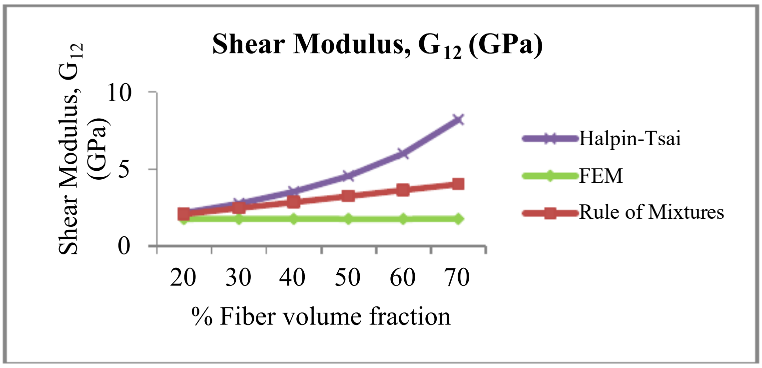

Fig.13: Variation of $G_{12}$with fiber volume fraction

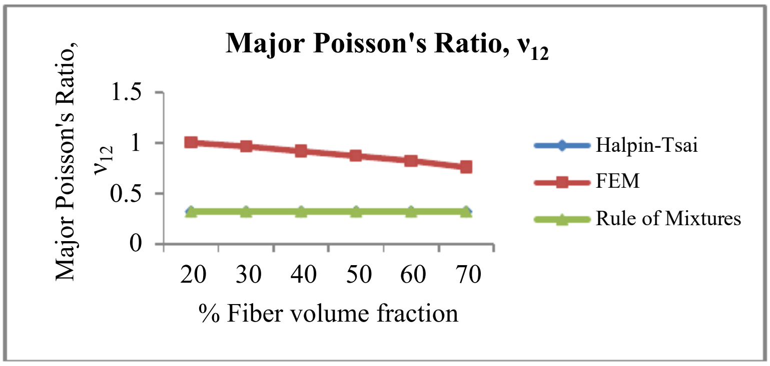

Fig.14: Variation of $\nu_{12}$with fiber volume fraction.

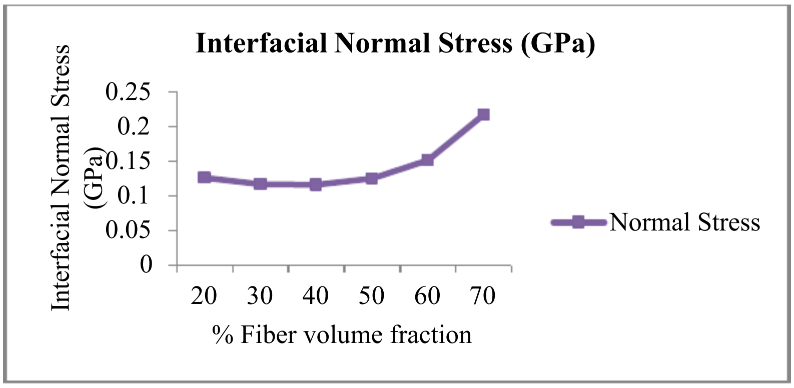

Fig.15: Variation of Interfacial Normal Stress with fiber volume fraction.

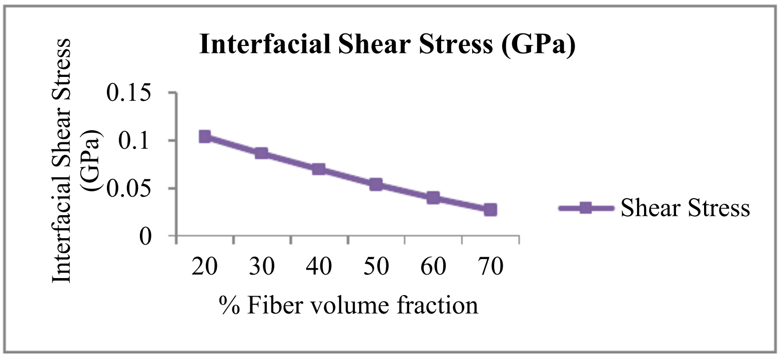

Fig.16: Variation of Interfacial Shear Stress with fiber volume fraction.

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.17~20 and the variation of normal stresses and also interfacial shear stresses with respect to the fiber volume fraction are shown in Fig.21~22.

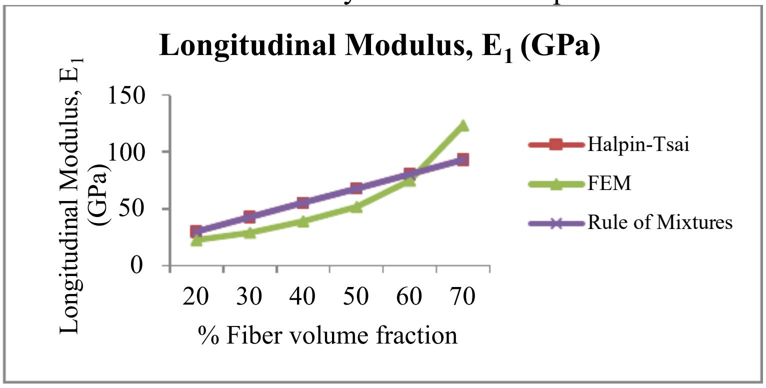

Fig.17: Variation of E_1 with fiber volume fraction.

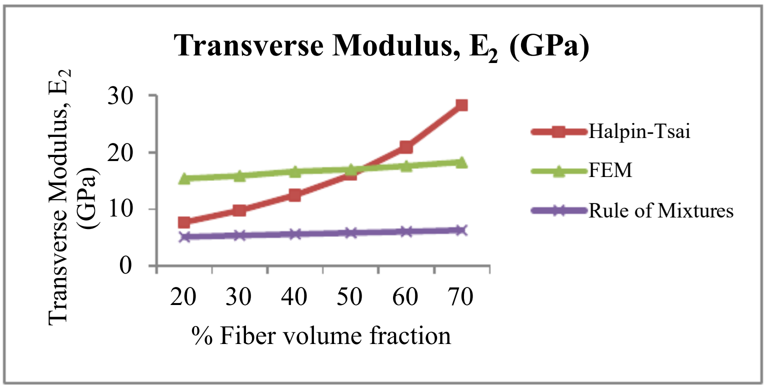

Fig.18: Variation of E_2 with fiber volume fraction.

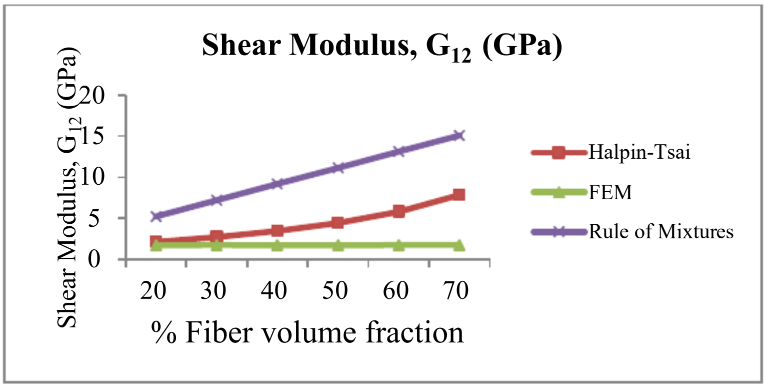

Fig.19: Variation of G_{12} with fiber volume fraction.

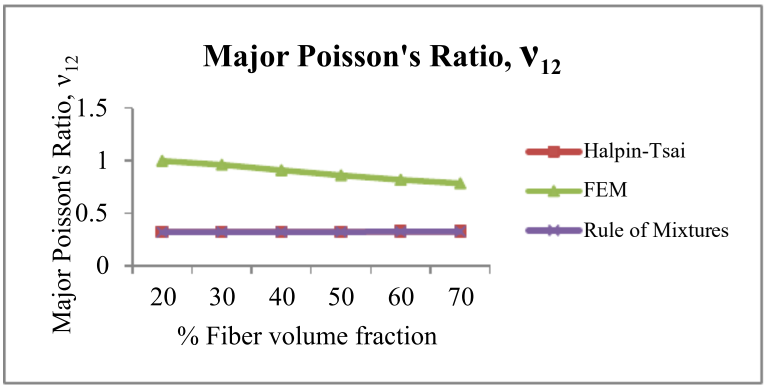

Fig.20: Variation of ν_{12} with fiber volume fraction.

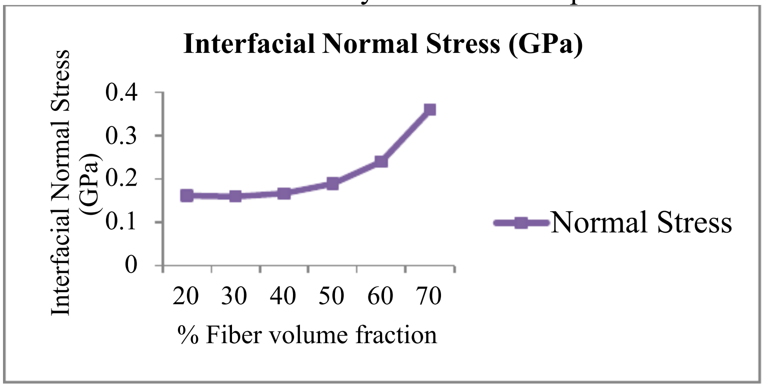

Fig.21: Variation of Interfacial normal stress with fiber volume fraction.

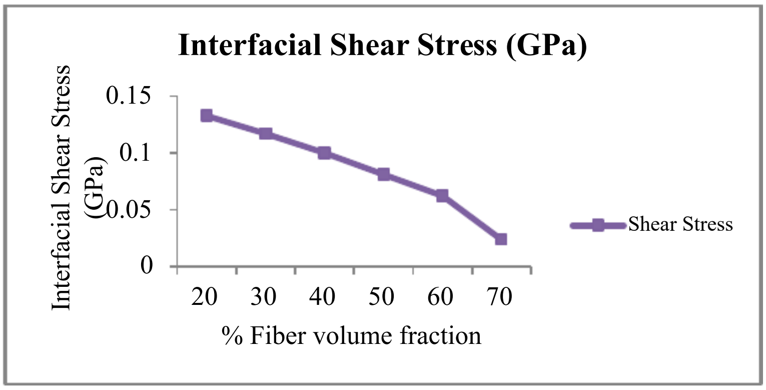

Fig.22: Variation of Interfacial Shear stress with fiber volume fraction.

3.3.1 ANALYSIS OF RESULTS

Figures 5-22 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 and E_l increases linearly with increase in fiber volume fraction up to 60 % thereafter it increases rapidly for all the three types of composites materials;
2. The transverse young's modulus E_2 increases linearly with increase in fiber volume fraction for all the three types of composites materials;
3. In plane Shear modulus G_{12} increases linearly with increase in fiber volume fraction for all the three types of composites materials;
4. Interfacial normal stress intensities are almost same with increase in fiber volume fraction up to 50% thereafter it increases rapidly for all the three types of composites materials;
5. Interfacial shear stress intensities decreases with increase in fiber volume fraction for all the three types of composites materials;

4. CONCLUSION

In this paper micromechanical analysis of three different types of composite (Viz., Carbon 300T/Epoxy, Hexply 8555 IM7/Epoxy and Kevlar/ Epoxy) materials has been carried out using FEA software, ANSYS 13 to evaluate several elastic constants. The results of elastic moduli E_1, E_2, G_{12} and ν_{12} are compared with the results obtained by using the Rule of Mixture and Semi-empirical Model (Halpin-Tsai's). It is seen that the results from the Finite Element simulation are little bit deviating with the analytical results. Interfacial normal stress and Interfacial shear stress intensities are also evaluated which are otherwise difficult to evaluate by using conventional methods. 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.

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