PREDICTION OF ELACTIC PROPERTIES OF FRP COMPOSITE LAMINA FOR LONGITUDINAL LOADING

Syed Altaf Hussain, B. Sidda Reddy and V. Nageswara Reddy
Department of Mechanical Engineering, Rajeev Gandhi Memorial College of Engineering and Technology, Nandyal, India
E-Mail: s_a_hussain1@rediffmail.com

ABSTRACT

A structural 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. FRP composites are slowly emerging from the realm of advanced materials and are replacing conventional materials in a variety of applications. However, the mechanics of fiber-reinforced composites is complex owing to their anisotropic and heterogeneous characteristics. The mechanical properties E_1,E_2,$\upsilon_{12,}$ and G_{12} are determined for three different types of FRP (Glass/Epoxy composite, Graphite/Epoxy composite and Kevlar/Epoxy composite) unidirectional continuous fiber lamina at different fiber volume fractions using the finite element method. A finite element model incorporating the necessary boundary conditions is developed and is solved using commercially available FEA package. The results are compared with analytical solution possible.

Keywords: model, FRP, micro-mechanics, finite element method.

Notations

E_1	Longitudinal Young's Modulus along
E_2	Transverse Young's Modulus along
G_{12}	Shear Modulus along
υ_{12}	Major Poisons ratio along
υ_{21}	Minor Poisons ratio along
V_f	Volume fraction of fiber
V_m	Volume fraction of matrix
E_f	Young's Modulus of fiber
E_m	Young's Modulus of matrix
η	packing factor
ξ	Reinforcing factor
r	Radius of fiber
a	Edge length of square unit cell
G_f	Shear Modulus of fiber
G_m	Shear Modulus of matrix

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 properties of a fiber reinforced plastics 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. A great number of micromechanical models have been proposed in the literature [1-4] for predicting various mechanical properties of composite materials. Several other models have been proposed such as numerical homogenization [5], FEM [6, 7] among others.

In this paper the finite element method is adopted for predicting various engineering properties of a FRP lamina and the results of Ex, Ey, υ_{12} and G_{12} are compared with the rule of mixtures and Halphin-Tsai criteria.

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 (square unit cell)

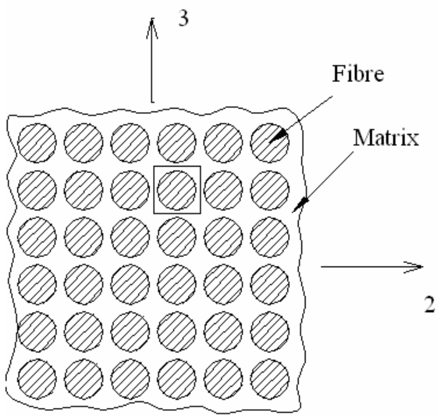


Figure-1. Concept of unit cells.

 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

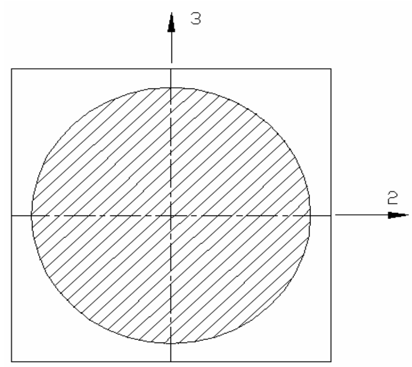


Figure-2. Isolated unit cell.

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 7.1 running on a Pentium IV 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

The 1-2-3 coordinate system shown in Figure-2 is used to study the behavior of a unit cell (The direction 1 is along the fiber axis and normal to the plane of the 2D plane given in (Figures 1 and 2). 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 fourth portion of the unit cell is modeled Figure-3 for the prediction of mechanical properties. The 3D Finite Element mesh on one fourth portion of the unit cell is shown in Figure-4.

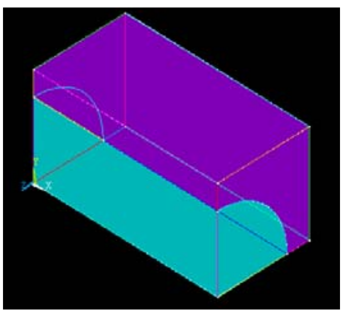


Figure-3. One-fourth portion of unit cell.

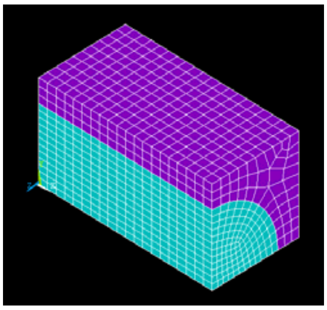


Figure-4. Finite element mesh.

2.2.1 Element type

The element SOLID95 of ANSYS V10.0 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 with three degrees of freedom per node (UX, UY and UZ).

2.2.2 Geometry

The dimensions of the finite element model are taken as X = 200 units Y = 100 units Z = 100 units.
The radius of the fibre is varied corresponding to the volume fraction.

$$V_f = \frac{\text{C/S Area of fibre}}{\text{C/S Area of unit cell}}$$

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

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

ε_2 = Strain in y-direction

2.2.3 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

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: $E2 = E_f V_f + E_m V_m$ (6)

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

In-Plane Shear Modulus: $G_{12} = G_f V_F + G_m V$ (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
The Halphin-Tsai equation for the longitudinal Young's modulus is the same as that obtained through the strength of materials approach, that is,

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

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

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

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

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

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

where

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

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

2.3.3. Materials

Three different types of composite materials are taken for the analysis.

Glass/ Epoxy composite
Graphite/ Epoxy composite
Kevlar/Epoxy composite

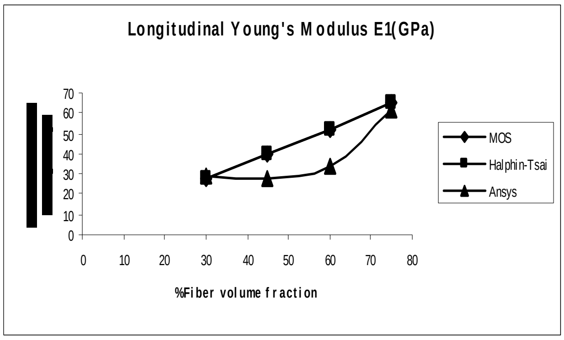
Table-1. Typical properties of fibers (SI system of units).

Property	Units	Graphite	Glass	Aramid(or)Kevlar
Axial modulus	Gpa	230	85	124
Transverse modulus	Gpa	22	85	8
Axial Poisson's ratio	-	0.30	0.2	0.36
Transverse Poisson' s ratio	-	0.35	0.2	0.37
Axial shear modulus	Gpa	22	35.42	3
Axial coefficient of thermal expansion	µm/m/oc	-1.3	5	-5
Transverse coefficient of thermal expansion	µm/m/oc	0.70	5	4.1
Axial tensile strength	Mpa	2067	1550	1379
Axial compressive strength	MPa	1999	1550	276
Transverse tensile strength	MPa	77	1550	7
Transverse compressive	MPa	42	1550	7
Shear strength	MPa	36	35	21
Specific gravity	-	1.8	2.5	1.4

Table-2. Typical properties of matrices (SI system of units).

Property	Units	Epoxy	Aluminium	Polyamide
Axial modulus	Gpa	3.4	71	3.5
Transverse modulus	Gpa	3.4	71	3.5
Axial Poisson's ratio	_	.3	.3	.35
Transverse Poisson' s ratio	_	.3	.3	.35
Axial shear modulus	Gpa	1.308	27	1.3
Axial coefficient of thermal expansion	µm/m/^{o}c	63	23	90
Transverse coefficient of thermal expansion	µm/m/^{o}c	0.33	0	0.33
Axial tensile strength	Mpa	72	276	54
Axial compressive strength	MPa	102	276	108
Transverse tensile strength	MPa	72	276	54
Transverse compressive	MPa	102	276	108
Shear strength	MPa	34	138	54
Specific gravity	_	1.2	2.7	1.2

Glass/Epoxy composite



Figur-5. Variation of E1with fiber volume fraction.

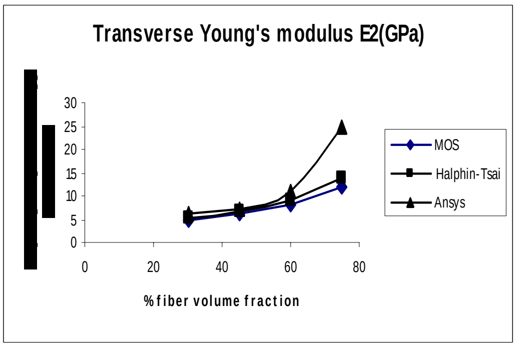


Figure-6. Variation of E2with fiber volume fraction.

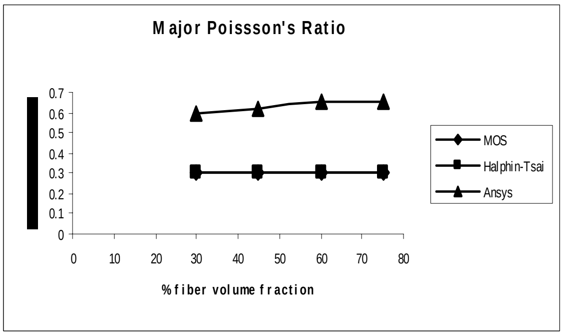


Figure-7. Variation of ν_{12} with fiber volume fraction.

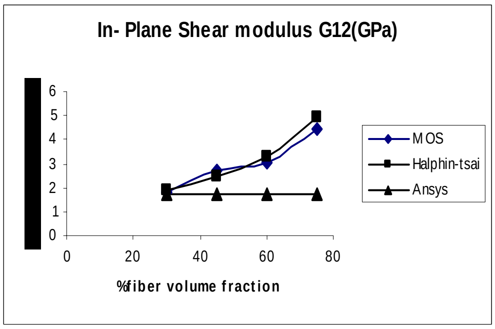


Figure-8. Variation of G_{12} with fiber volume fraction Graphite/Epoxy composite.

ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

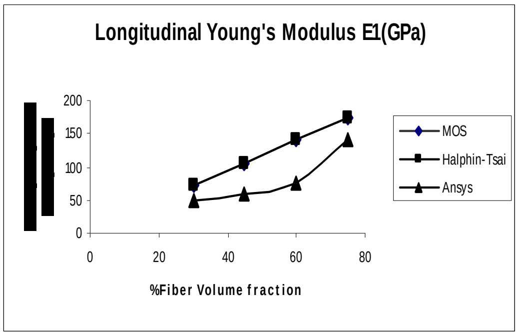


Figure-9. Variation of E1with fiber volume fraction.

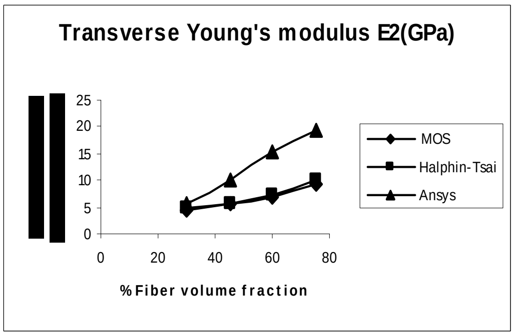


Figure-10. Variation of E1with fiber volume fraction.

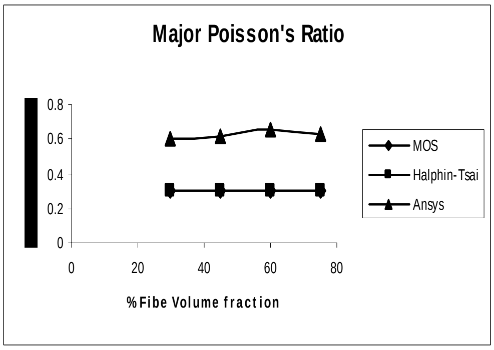


Figure-11. Variation of ν12 with fiber volume fraction.

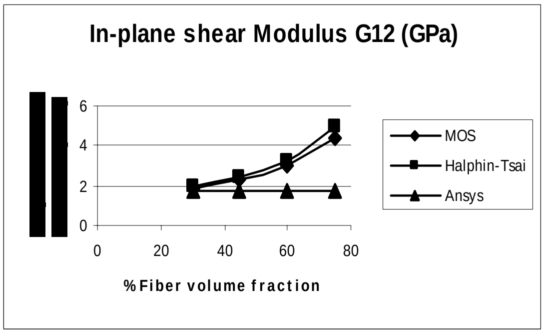


Figure-12. Variation of G12 with fiber volume fraction after Kevlar/Epoxy composite.

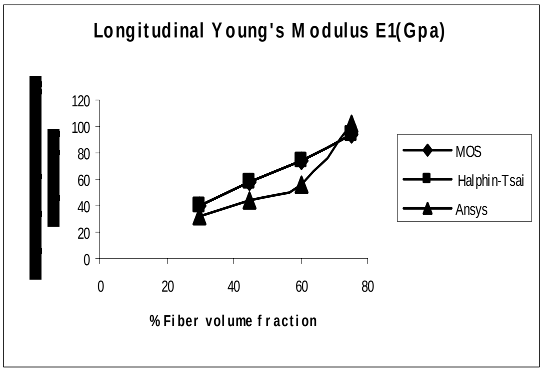


Figure-13. variation of E1with fiber volume fraction.

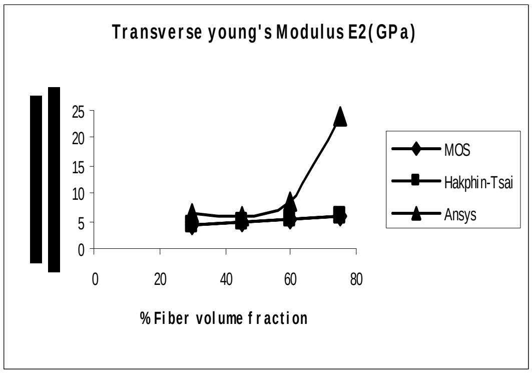


Figure-14. variation of E2with fiber volume fraction.

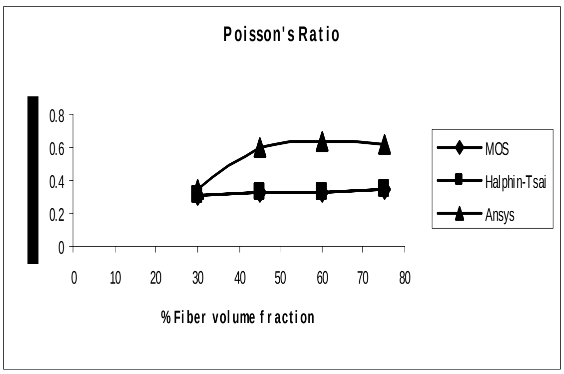


Figure-15. Variation of ν_{12} with fiber volume fraction.

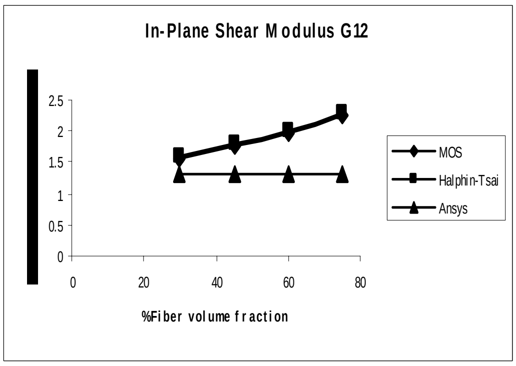


Figure-16. Variation of G_{12} with fiber volume fraction.

4. ANALYSIS OF RESULTS

Figures 5-16 show the variation of various properties with the fiber volume fraction. The observations made from the plots are:

1. The longitudinal young's modulus E_1 and transverse young's modulus E_2 increases linearly with increase in fiber volume fraction for all the three types of composite materials;
2. The Poisson's ratio ν_{12} increase linearly with increase in fiber volume fraction up to 50% followed by Rapid decrease for higher fiber volume fraction;
3. In-plane shear modulus G_{12} gradually increases with increase in fiber Volume fraction up 60% thereafter it increases rapidly for higher fiber volume fraction for all three types of composite materials; and
4. Comparison of elastic properties of three different composite materials reveals that Kevlar/Epoxy composite are stronger than the other two composites.

5. CONSLUSIONS

Several elastic properties of three different FRP composite lamina have been evaluated for various fiber volume fractions with the help of FEA software, ANSYS. 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 (Halphin- Tsai's). 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 provides with a large property set to perform better analysis for fiber reinforced composite materials

REFERENCES

[1] Issac M. Daniel and Ori Ishai. 1994. Engineering Mechanics of Composite Materials. Oxford university press.

[2] R L McCullough. 1990. Micromodels for Composite Materials ¾ Continuous Fibre Composites. In: Delaware Composite Design Encyclopedia. Vol. 2, Technomic Publishing Company.

[3] J C Halpin. 1992. Primer on Composites Materials Analysis. 2nd Edition. Lancaster: Technomic. pp.153-192.

[4] M H Zheng. 2001. Simulation of the Mechanical Properties of Fibrous Composites by the Bridging Micromechanical Model. Composite-Part A, Vol. 32, pp. 143-172.

[5] C T Sun and R S Vaidya. 1996. Prediction of Composite Properties from a Representative Volume Element. Composites Science and Technology. 56: 171-179.

[6] S T Pericles, G E Stavroulakis and P D Pnagiotopoulos. 1997. Calculation of Effective Transverse Elastic Moduli of Fiber-reinforced Composites by Numerical Homogenization. Composites Science and Technology. 57: 573-586.

[7] A Sreeramamurthy. 1991. Finite Element Modeling of Stress-Strain Behaviour of Composite Materials ¾ an Overview. Advances in Composite Materials. Oxford and IBH Publishing Company Pvt. Ltd. pp. 513-524.

[8] A Balaco De Morais. 1996. Modeling Lamina Longitudinal Compression Strength of Carbon Fibre Composite Laminates. Journal of Composite Materials. 30: 1115-1131.

[9] M W Hyer. 1998. Stress Analysis of Composite Materials. WCB McGraw-Hill.

[10] R M Jones. 1975. Mechanics of Composite Materials. Scripta Book Company.