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Effect of Unit Cell on Elastic Properties of Fiber Reinforced Polymer Composite Materials

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ABSTRACT

The mechanics of fiber reinforced composites are complex due to their anisotropic and heterogeneous characteristics. The present work is to evaluate the material properties of fiber reinforced composites for different volume fractions up to 60%. A numerical homogenization technique based on the finite element analysis (FEA) with unit cell was used to evaluate the material properties of unidirectional Kevlar fiber reinforced Epoxy composite. A three-dimensional single and multiple unit cell micromechanical models have been developed by using ANSYS software. The material properties obtained using the numerical homogenization techniques were compared with different analytical methods like rule of mixture, Halpin-Tsai, and periodic microstructure methods. The effect of volume fraction of fiber on predicted material properties of composite is also studied.

Keywords : Fiber composite, finite element analysis, Micromechanics, Unit cell, Volume fraction.

I. INTRODUCTION

The development and characterization of fiber composite materials are becoming an essential part of present engineered materials because they offer advantages such as strength, stiffness, toughness, high corrosion resistance, high wear resistance, high chemical resistance, reduced cost. Except for the experimental studies, either micro or macro mechanical methods are used to obtain the overall properties of composites [1]. Two different analyses are employed to determine the elastic properties of Kevlar fiber reinforced epoxy composites. One is analytical method and another is numerical techniques. Several models for the prediction of elastic properties of fiber reinforced polymer composites have already been proposed by researchers. Srivastava et al. [2] evaluated the effective material properties of the short fiber composites consist of different shape, size and distribution using numerical homogenization technique. The investigations are carried out to study the influence of various parameters like volume fraction, aspect ratio and particle distribution. Multiple cell modeling of fiber reinforced composites with the presence of interphases is studied by Chin and Liu [3]. Numerical simulations of damage evolution in composites reinforced with single and multi-fibers were presented by Wang et al. [4]. The present study is to evaluate the effect of volume fraction on the elastic properties of unidirectional Kevlar fiber reinforced epoxy composites using single and multiple unit cells by finite element analysis. The numerical results are compared with the well existing analytical methods i.e. rule of mixture, periodic microstructure and Halpin-Tsai methods [5].

II. METHODS AND MATERIAL

A. Material

The materials are taken for the current study is Kevlar fiber as reinforcement and Epoxy as matrix material. The properties of the constituent materials are as shown in Table 1.By varying the content of reinforcing fibers from 0 to 70% the overall composite material properties are determined.

Table 1: Material properties of Kevlar fiber/ Epoxy composite [6]

Property	Young's modulus (GPa)	Poisson's ratio	Shear modulus (GPa)
Kevlar fiber	124.1	0.28	2.9
Epoxy	3.45	0.35	1.3

B. Micromechanical Modelling

The unidirectional continuous fiber reinforced composite has been considered as a large array of unit cell. Depending upon the arrangement of the fibers, square unit cell with single and multi fibers with different volume fraction of fiber is considered for the present analysis. Fig.1 shows the arrangement of fibers in 1×1, 2×2 and 3×3 square unit cell.

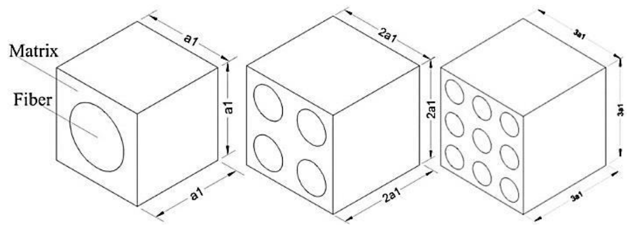

Figure1. Arrangement of fibers in 1×1, 2×2 and 3×3 square unit cell

The generalized Hooke's law can be formulated to correlate the stiffness matrix C_{ij}, average stress σ_{ij} and strain ε_{ij}; for homogenized composites as show in Eq. (1)

$$\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \sigma_4\\ \sigma_5\\ \sigma_6\end{Bmatrix}=\begin{bmatrix}C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16}\\ & C_{22} & C_{23} & C_{24} & C_{25} & C_{26}\\ & & C_{33} & C_{34} & C_{35} & C_{36}\\ & & & C_{44} & C_{45} & C_{46}\\ & & & & C_{55} & C_{56}\\ & & & & & C_{66}\end{bmatrix}\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\\ \varepsilon_4\\ \varepsilon_5\\ \varepsilon_6\end{Bmatrix} \quad (1)$$

In this paper, transversely isotropic characteristics have been considered for the fiber reinforced composite. The transversely isotropic stiffness tensor is represented in Eq. (2) [7].

$$\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \sigma_4\\ \sigma_5\\ \sigma_6\end{Bmatrix}=\begin{bmatrix}C_{11} & C_{12} & C_{12} & 0 & 0 & 0\\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0\\ C_{12} & C_{23} & C_{22} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1}{2}(C_{22}-C_{23}) & 0 & 0\\ 0 & 0 & 0 & 0 & C_{66} & 0\\ 0 & 0 & 0 & 0 & 0 & C_{66}\end{bmatrix}\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\\ \varepsilon_4\\ \varepsilon_5\\ \varepsilon_6\end{Bmatrix} \quad (2)$$

Once the components of the transversely isotropic tensor C are known, the elastic properties of homogenized material can be computed by Eq. (3) [7].

$$\begin{aligned}
E_1 &= C_{11} - 2C_{12}^2/(C_{22}+C_{23})\\
E_2 &= \left[C_{11}(C_{22}+C_{23}) - 2C_{12}^2\right](C_{22}-C_{23})/(C_{11}C_{22}-C_{12}^2)\\
\nu_{12} &= C_{12}/(C_{22}+C_{23})\\
\nu_{23} &= [C_{11}C_{23}-C_{12}^2]/(C_{11}C_{22}-C_{12}^2)\\
G_{12} &= C_{66}\\
G_{23} &= C_{44} = 1/2(C_{22}-C_{23})
\end{aligned} \quad (3)$$

III. FINITE ELEMENT ANALYSIS

The model assumed that the fiber was a perfect cylinder in a cube. By varying the cylinder diameter with different volume fractions range from 20-60% the model is developed. The ANSYS parametric design language (APDL) was used to calculate the average strains, stresses and material properties. For modelling of unit cells an orthogonal coordinate system is used that has one axis aligned with the fiber direction. The axis 1 is aligned with the fiber direction; the axis 2 is in the plane of the unit cell and perpendicular to the fibers and the axis 3 is perpendicular to the plane of the unit cell and is also perpendicular to the fibers. The fibers are assumed perfectly aligned, homogeneous and uniformly distributed in the matrix. Three dimensional elements SOLID 186 is used for the present analysis and is defined by 20 nodes having three degrees of freedom at each node. Meshed model of 1×1, 2×2 and 3×3 square unit cell is shown in Fig.2.

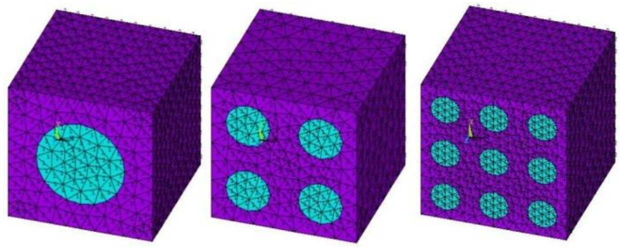

Figure. 2. Meshed model of 1×1, 2×2 and 3×3 square unit cell

A. Periodic boundary conditions

Three-dimensional fiber composite materials can be represented as a periodic array of unit cells. Therefore, the periodic boundary conditions must be applied to the unit cell models. This implies that each unit cell in the composite has the same deformation mode and there is no separation or overlap between the neighbouring unit cells after deformation [8].

$$\overline{\sigma_{ij}} = \frac{1}{V}\int_V \sigma_{ij} dV,$$

$$\overline{\varepsilon_{ij}} = \frac{1}{V}\int_V \varepsilon_{ij} dV.$$

$\overline{\sigma_{ij}}$ and $\overline{\varepsilon_{ij}}$ are the average stresses and average strains and V is the volume of unit cell. The elastic properties can be calculated by using the constitutive equations of the material properties as the ratio of corresponding average stresses and average strains by applying appropriate boundary conditions along with these periodic boundary conditions.

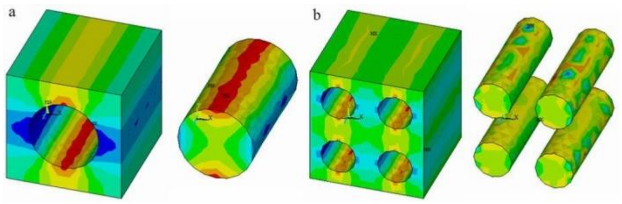

Figure. 3. (a) Counter of stress in 1×1 unit cell (b) Counter of stress in 2×2 unit cell

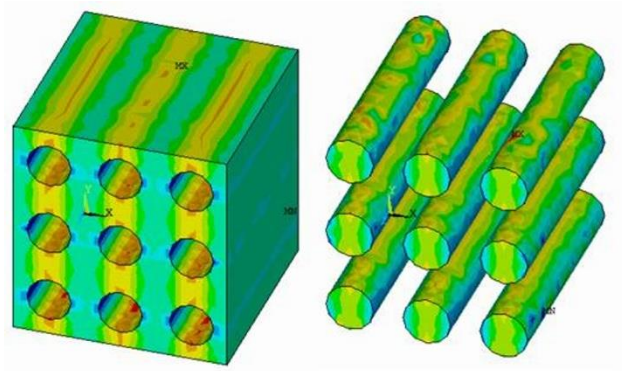

Figure. 4. Counter of stress in 3×3 unit cell of fiber composite

III. RESULTS AND DISCUSSION

To predict the overall elastic properties of Kevlar fiber reinforced Epoxy composite a finite element analysis procedure was developed.

A. Effect of volume fraction on longitudinal modulus (E_1)

Longitudinal modulus of composite is the ratio of longitudinal stress to the longitudinal strain. Fig.5 (a) shows the effect of fiber content on the longitudinal modulus of composites using FEA, rule of mixtures, Halpin-Tsai and periodic microstructure techniques.

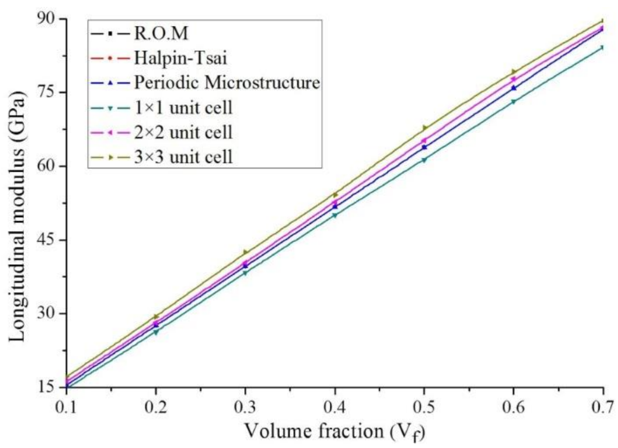

Figure.5. Longitudinal modulus validation with different volume fraction.

It can be observed from the fig that the longitudinal modulus increasing with increase in volume fraction of fiber and there is a good agreement of finite element model with other analytical methods.

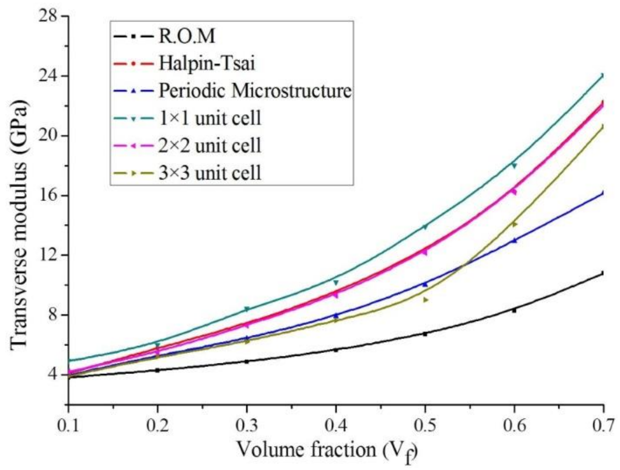

Figure.6. Transverse modulus validation with different volume fraction

B. Effect of volume fraction on transverse modulus (E_2=E_3)

Transverse modulus of composite is the ratio of transverse stress to the transverse strain. Fig.6 shows the effect of fiber volume fraction on transverse modulus of composites using finite element analysis and three analytical methods. It is clear from the Fig that the transverse modulus increases with increase in fiber volume fraction. In analytical method the Halpin-Tsai and periodic microstructure results are closely agreed with the finite element results compare to the rule of mixture method.

C. Effect of volume fraction on in plane Poisson's ratio (ν_{12})

Fig. 7 shows the effect of fiber volume fraction on the in plane Poisson's ratio of composite. It is evident from the fig that the major Poisson's ratio decreases with increase in fiber volume fraction as expected. However as far as comparison of the methods, finite element results with 1×1 unit cell are closely agreed with the analytical methods compared to the 2×2 and 3×3 unit cell.

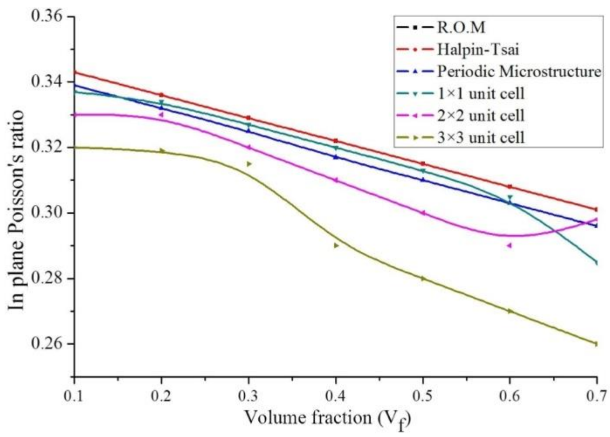

Figure.7. In plane Poisson's ratio validation with different volume fraction

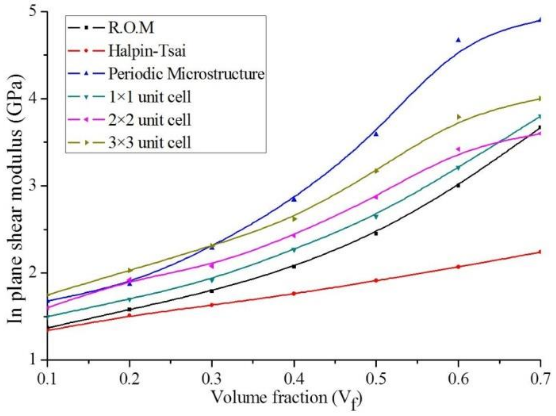

Figure.8. In plane shear modulus validation with different volume fraction

D. Effect of volume fraction on in plane shear modulus (G_{12})

In plane shear modulus of composite is the ratio of shear stress to the shear strain in longitudinal direction. Fig.8 shows the effect of fiber volume fraction on the in plane shear modulus of Kevlar fiber reinforced Epoxy based composites. It is clear from the fig that the shear modulus increases withy increases in fiber volume fraction. Table 2 shows the analytical and numerical results of Kevlar fiber/ Epoxy composite at 40% of volume fraction.

Table 2 : Analytical and numerical results of Kevlar fiber/ Epoxy composite at 40% of volume fraction

Model/Property	Rule of Mixtures	Halpin-Tsai	periodic microstructure	1×1 unit cell	2×2 unit cell	3×3 unit cell
Longitudinal modulus(Gpa)	51.71	51.71	51.71	50.10	52.46	53.94
Transverse modulus(Gpa)	5.64	9.48	7.92	10.21	9.30	7.64
In plane Poisson's ratio	0.322	0.322	0.317	0.31	0.32	0.29
In-plane shear modulus(Gpa)	2.07	1.76	2.84	2.27	2.43	2.62

IV. CONCLUSION

The elastic properties of single and multiple fiber unit cell model of Kevlar fiber reinforced Epoxy composite evaluated by using finite element analysis and the following conclusions have been drawn from the current study.

1. Different types square unit cells like 1×1, 2×2 and 3×3 models has successfully applied for the finite element analysis using ANSYS software. The numerical results agreed with the existing analytical predictions.

2. Various analytical methods like rule of mixture, periodic microstructure and Halpin-Tsai methods are discussed to determine the elastic behaviour of composite materials.

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