International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 - 5161

Available at http://inpressco.com/category/ijcet

Research Article

Micromechanical Analysis of Effect of Interphase on Mechanical Properties of Kevlar Fiber Reinforced Epoxy Composites

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Accepted 13 January 2014, Available online 01 February 2014, **Special Issue-2, (February 2014)**

Abstract

The incorporation of a realistic interphasial region into the micromechanical analyses of composite systems is critical to the understanding of composite behaviour. The interphase in fiber reinforced composites depends on the fiber, matrix and surface treatment of fibers. The main objective of the present is investigating the effect of an interphase on elastic constants of unidirectional fiber reinforced composites. A finite element micromechanical model was used to predict effective elastic properties of Kevlar fiber reinforced epoxy composites with and without effect of interphase. A three-dimensional representative volume element (RVE) model with a hexagonal packing geometry is considered to predict the elastic properties of Kevlar fiber reinforced epoxy composites by finite element analysis. The finite element analysis is done by using ANSYS software with periodic boundary conditions. The analytical models like rule of mixtures, Halpin-Tsai and periodic microstructure methods are used to validate the finite element results. It has been observed that the interphasial region and fiber volume fraction significantly influencing the elastic properties of composites.

Keywords: *Fiber Composite, Interphase, Micromechanics, Representative Volume Element, Volume Fraction*

1. Introduction

There has been considerable interest in fiber reinforced composite materials for their application in various industries due to the specific properties like strength, stiffness, toughness, corrosion resistance and reduced cost. Fiber reinforced composites have generally assumed the existence of two phases, namely fiber and matrix. However, in reality an additional phase may exist between the fiber and matrix commonly known as the interphase. In any event, an interphase is the region through which material parameters, such as concentration of an element, crystal structure, atomic registry, elastic modulus, density, coefficient of thermal expansion, etc.; change from one side to another (Chawla, 1998). In composite materials a fiber-matrix interphase transfers loads between the matrix and the reinforcing fibers. One of the main engineering problems is the prediction of the elastic moduli of a composite from the moduli of its constituent phases. Several models for the prediction of elastic properties of fiber reinforced polymer composite materials with and without effect of interphase have already been proposed by researchers. (Wacker, *et al*, 1998) studied the influence of different types of glass fibre treatment on the transverse elastic properties of glass/epoxy composites experimentally and numerically. From this study the interphase influence on the properties of composites was predicted using a finite element method model. Mechanical properties of unidirectional fiber reinforced composite materials under transverse tensile loading at micromechanical level studied by (Wanga, *et al*, 2011). The interphase is represented by pre-inserted cohesive element layer between matrix and fiber with tension and shear softening constitutive laws in order to evaluate mechanical behaviours of composites. Experimental and numerical studies have showed that the interphase properties such as modulus, thickness, Poisson’s ratio and tensile strength do have a significant influence on both the transverse effective properties. (Aghdam and Falahatgar, 2004) developed A three-dimensional finite element micromechanical model to study effects of various parameters such as thermal residual stress, fiber coating and interphase bonding on the transverse behavior of a unidirectional SiC/Ti–6Al–4V metal matrix composite. The effect of an inhomogeneous interphase on elastic constants of unidirectional fiber reinforced composites investigated by (Jasiuk and Kouider, 1993). (Hwang and Gibson, 1993) predict the storage moduli and internal damping properties in unidirectional fiber reinforced composites having a fiber-matrix interphase region by using two dimensional finite element and strain energy method.

Although a great deal of work has already been done on elastic properties of fiber reinforced polymer composites, however determination of elastic properties of Kevlar fiber reinforced epoxy composites by finite element analysis is hardly been reported. To this end, the present study is undertaken to evaluate the effect of volume fraction on the elastic properties of Kevlar fiber

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reinforced epoxy composites by finite element analysis with and without effect of interphase. Finally, the results of finite element results are compared with the well existing analytical methods i.e. rule of mixture, periodic microstructure and Halpin-Tsai methods (Barbero, 1998).

2. Materials and methods

2.1 Materials

The presented model includes three phases, i.e. the fiber, matrix and interface. The materials are taken for the current study is Kevlar fiber as reinforcement and epoxy as matrix material, as well as the interphase is considered between the fiber and matrix. The properties of the constituent materials are as shown in Table 1. By varying the content of reinforcing fibers from 10 to 90% the overall composite material properties are determined with and without effect of interphase.

Table 1 Elastic property of fiber, matrix and interphase constituents (Aboudi, 1988)

Material/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
Interphase	10	0.35	1.5

2.2 Micromechanical modeling

Micromechanics are intended to study of composite material properties taking into account the interaction of the constituent materials in detail. The parameters which affect the composite properties are fiber diameter, length, volume fraction, packing and orientation of fiber. In a real unidirectional fiber reinforced composite the fibers are arranged randomly and it is difficult to model random fiber arrangement. In present work the arrangement of the fibers are considered cylindrical and infinite length embedded in an elastic matrix (Barbero, 1998). The schematic diagram of the unidirectional fiber composite where the fibers are arranged in the hexagonal array is shown in Fig. 1.

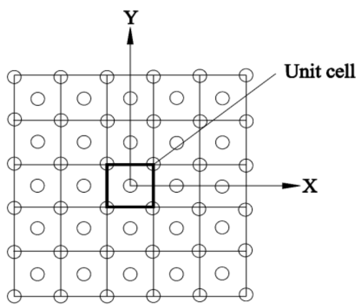

Fig. 1 Arrangement of fibers in hexagonal array

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.

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

Where $[C_{ij}]$ is Stiffness matrix,σ is stress and ε is strain.

According to their behavior, composites may be characterized as generally anisotropic, monoclinic, orthotropic, and transversely isotropic. In this paper, transversely isotropic characteristics have been considered for the fiber reinforced composite. The transversely isotropic stiffness tensor is represented in Eq. 2 (Barbero, 2011).

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

Once the components of the transversely isotropic stiffness tensor C are known, the elastic properties of homogenized material can be computed by Eq. 3 (Barbero, 2011).

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

Where E_1, E2, E_3, ν_{12}, ν_{23}, G_{12} and G_{23} are the longitudinal modulus, transverse modulus, in-plane Poisson's ratio, interlaminar Poisson's ratio, in-plane shear modulus and interlaminar shear modulus of composite.

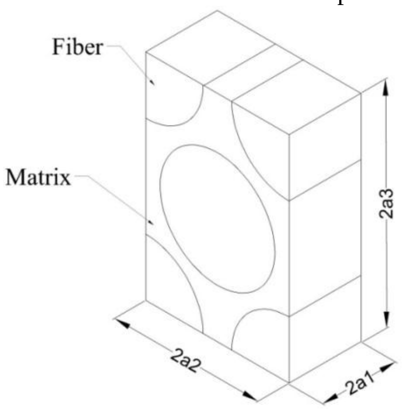

Fig.2 Representative volume element of Kevlar/epoxy composite without interphase

Depending upon the arrangement of the fibers, hexagonal representative volume element with different volume fraction of fiber is considered for the present analysis. RVE is considered as a three-phase composite, which includes the fiber and matrix, as well as the interphase between them. The interphase region serves as a buffer between the bulk matrix and fiber, and its properties are critical to the overall composite performance. Fig. 2 and 3 shows the representative volume element of hexagonal unit cell with and without effect of interphase.

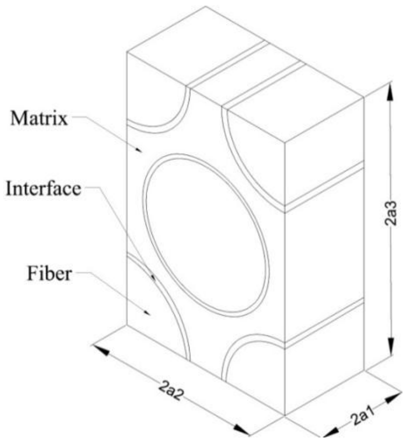

Fig.3 Representative volume element of Kevlar/epoxy composite with interphase

3. Finite Element Analysis

In order to evaluate the effective coefficients the finite element software package ANSYS is used. The program is written in APDL (ANSYS Programming Design Language), which is delivered by the software and it makes the handling much more comfortable. The model assumed that the fiber is a perfect cylinder in a cube. By varying the cylinder diameter with different volume fractions range from 10-90% the model is developed. The ANSYS model of representative volume element of hexagonal unit cell with interphase as shown in Fig. 4. 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 following assumptions are considered for the present analysis.

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

The dimensions of finite element model are taken as 4, 6.928 and 1 units in x- y- and z- directions respectively. The dimensions of cylinder are obtained according to the fiber volume fraction. 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. The meshed model of representative volume element with and without effect of interphase at 50% of fiber volume fraction is shown in Fig.5 and 6.

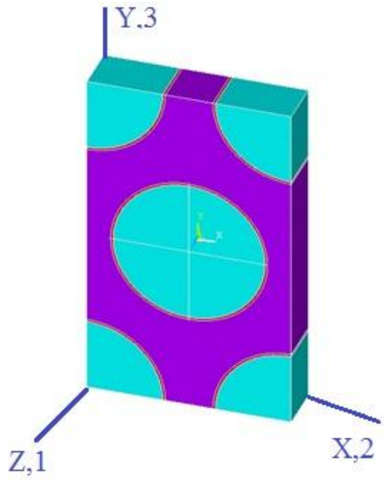

Fig.4 Representative volume element of ANSYS model at 50% fiber volume fraction

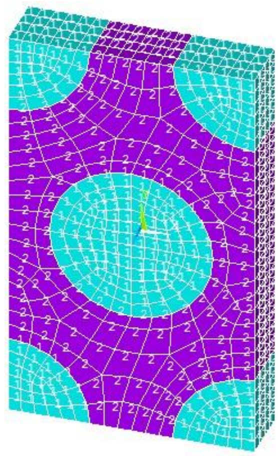

Fig.5 Meshed model of representative volume element without interphase

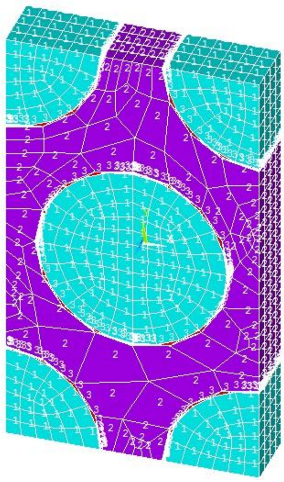

Fig.6 Meshed model of representative volume element with interphase

3.1 Periodic boundary conditions

Three-dimensional fiber composite materials can be represented as a periodic array of representative volume element. Therefore, the periodic boundary conditions must be applied to the representative volume element models. This implies that each representative volume element in the composite has the same deformation mode and there is no separation or overlap between the neighboring representative volume elements after deformation (Kari et al., 2007). The average stresses and strains are obtained by using Eq. 4. Fig. 7 shows the counter of stress and strain in representative volume element at 50% of volume fraction.

$$\overline{\sigma_{ij}} = \frac{1}{V}\int_V \sigma_{ij}\,dV,$$
$$\overline{\varepsilon_{ij}} = \frac{1}{V}\int_V \varepsilon_{ij}\,dV. \qquad (4)$$

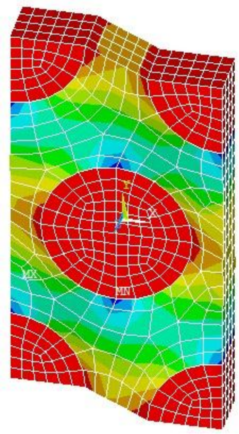

Fig.7 Counter of stress in representative volume element

$\overline{\sigma_{ij}}$ and $\overline{\varepsilon_{ij}}$ are the average stresses and average strains and *V* is the volume of the representative volume element. 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.

4. Results and Discussion

4.1 Effect of volume fraction on longitudinal modulus (E_1)

The longitudinal Young modulus of composite is in which the load is applied parallel to the direction of the fibres. It can be defined the ratio of longitudinal stress to the longitudinal strain. Fig. 8 shows the effect of fiber content on the longitudinal modulus of composites using rule of mixture, Halpin-Tsai, periodic microstructure and finite element method with and without effect of interface.

It can be observed from the figure 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. This is because the stiffness of the composite increases with increase in volume fraction of fiber.

Table 1 Analytical and numerical results of longitudinal modulus at different of volume fraction of fiber

Volume fraction	ROM, Halpin-Tsai and Periodic microstructure	FEM without interphase	FEM with interphase
0.1	15.51	14.12	16.21
0.2	27.58	26.28	28.93
0.3	39.64	38.39	41.02
0.4	51.71	50.1	52.52
0.5	63.77	61.29	65.13
0.6	75.84	73.27	77.49
0.7	87.9	85.43	89.95
0.8	99.3	97.21	101.92
0.9	113.1	110.12	116.12

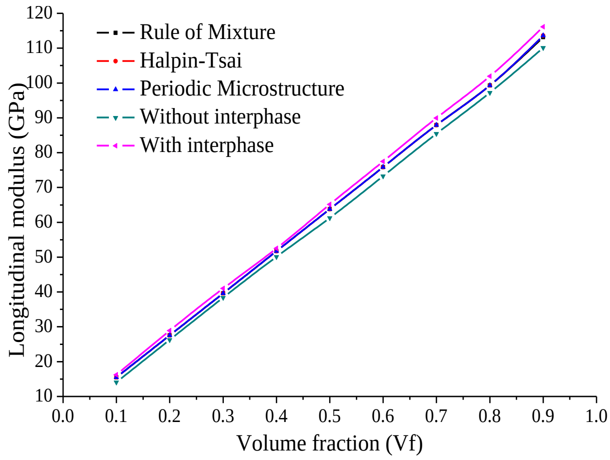

Fig.8 Longitudinal modulus validation with different volume fraction of fiber

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

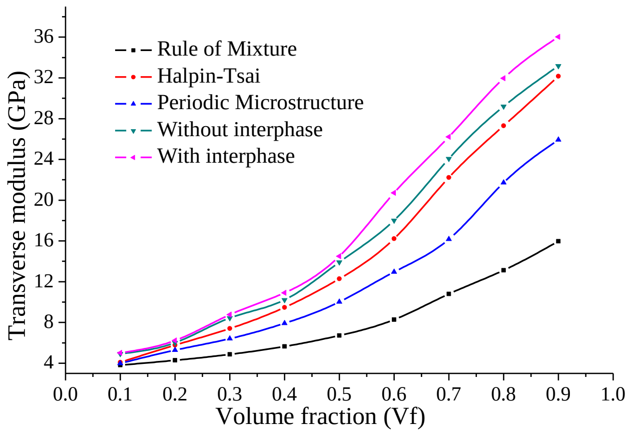

Fig.9 Transverse modulus validation with different volume fraction of fiber

The transverse Young modulus of composite is in which the load is applied perpendicular to the direction of the fibres. It can be defined the ratio of transverse stress to the transverse strain. Fig. 9 shows the effect of fiber volume fraction on transverse modulus of composites using finite element analysis with and without effect of interface and three analytical methods. As expected, it is clear from the figure that the transverse modulus increases with increase in fiber volume fraction and a good agreement of finite element analysis results with Halpin-Tsai methods compare to the rule of mixture and periodic microstructure.

4.3 Effect of volume fraction on in plane Poisson's ratio (v_{12})

Fig. 10 shows the effect of fiber volume fraction on the in plane Poisson's ratio of composite.

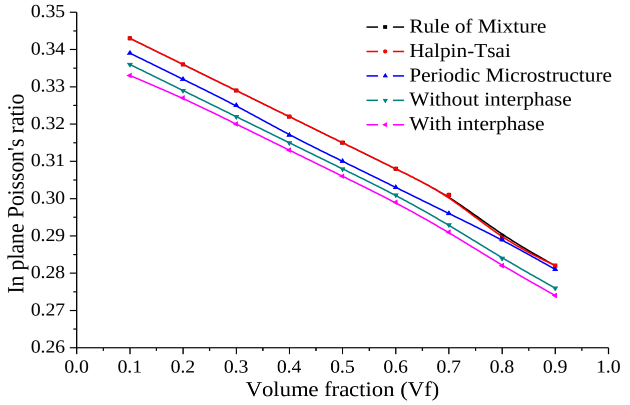

Fig.10 In plane Poisson's ratio validation with different volume fraction of fiber

It is evident from the figure that the in plane Poisson's ratio decreases because of increase in volume fraction of fiber increases resistant of the material as a result the Poisson's ratio is decreasing with respective V_f. The finite element results are good agreement with analytical methods. However as far as comparison finite element results are good agreement with periodic microstructure.

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

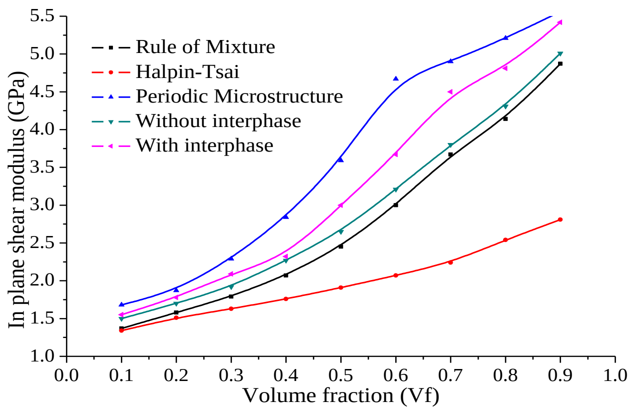

Fig.11 In plane shear modulus validation with different volume fraction of fiber

In plane shear modulus of composite is the ratio of shear stress to the shear strain in longitudinal direction. Fig. 11 shows the effect of fiber volume fraction on the in plane shear modulus of Kevlar fiber reinforced epoxy composites with and without effect of interface at different volume fractions. It is clear from the figure that the shear modulus increases with increases in fiber volume fraction. Also, it can be observed that there is a good agreement of results obtained from finite element method with Halpin-Tsai method as compared to rule of mixture.

Table 2 shows the analytical and numerical results of Kevlar fiber reinforced epoxy composites with and without effect of interface at 50% of volume fraction of fiber.

Table 2 Analytical and numerical results of representative volume element at 50% of volume fraction

Model/Property	E_1 (GPa)	$E_2 = E_3$ (GPa)	v_{12}	G_{12} (GPa)
Rule of Mixtures	63.77	6.71	0.315	2.45
Halpin-Tsai	63.77	12.28	0.315	1.91
Periodic micro structure	63.77	10.02	0.310	3.59
FEM with interphase	61.29	13.92	0.308	2.65
FEM without interphase	65.13	14.50	0.306	3.01

In present work, the elastic properties of Kevlar fiber reinforced epoxy composites with and without effect of interphase has been evaluated using analytical and finite element method the following conclusions can be drawn:

1) Representative volume element model of hexagonal unit cell has successfully applied for the finite element analysis using ANSYS software to determine the elastic behavior of Kevlar fiber reinforced epoxy composites with and without effect of interphase at different volume fractions.
2) Various analytical methods like rule of mixture, Halpin-Tsai and periodic microstructure methods are discussed to determine the elastic behavior of hybrid composite material.
3) It has been observed that the fiber volume fraction significantly influencing the elastic properties of composites. The properties like longitudinal modulus, transverse modulus and in plane shear modulus of composites are increasing and in plane Poisson's ratio is decreasing with increasing in fiber volume fraction as expected.
4) It has been observed that elastic properties predicted by the finite element analysis agree well with the existing analytical predictions. The interphase influence on the elastic properties of composites was predicted using a finite element method.

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