Effect of Damage modes and Fiber volume fraction on the Effective properties of the Unidirectional composites

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Abstract

The aim of present work is to predict the effect of fiber volume fraction and different damage mechanisms such as fiber breakage, fiber-matrix debond and matrix cracks on the effective properties of the unidirectional fiber-reinforced composites based on a micromechanical analysis. The material properties are calculated using a Finite element method based numerical approach using a three-dimensional micromechanical representative volume element (RVE). The RVE is modeled by considering a square packing array of fibers with circular cross-section. The periodic boundary conditions are applied on the RVE to calculate elastic properties of composite.

1 Introduction

Composite materials refers to materials having strong fibers (continuous or noncontinuous) surrounded by a weaker matrix material. The matrix serves to distribute the fibers and also to transmit the load to the fibers. The bonding between fibers and matrix is created during the manufacturing phase of the composite material. This has fundamental influence on the mechanical properties of the composite material.

The evaluation of effective mechanical and thermal properties of composite materials is of paramount importance in engineering design and application. Generally, two approaches are considered in obtaining the global properties of composites: (a) macromechanical analysis and (b) micromechanical analysis. In macromechanical analysis the composite material is considered as a homogeneous orthotropic continuum. In micromechanical analysis the study of composite material is at the fiber and matrix level. Typically the unit cell technique combined with the known material properties of fiber and matrix is used to determine the overall behavior of the composite.

Murari and Upadhay [11][10] considered the effect of damage modes and fiber volume fraction on effective properties of the composites to model the damage based on the RVE analysis. E. J. Barbero et al. [8] gave the formulation for finding the effective properties of the composite materials with periodic microstructure model. M. Prabha et al. [14] used strain amplification factors and effective mechanical properties of the composite to find the stress amplification factors. L. Harish et al. [3] found the homogenised properties for unstrengthen masonry and also strengthened masonry using CFRP (inserted in bed joints) using modified rule of mixture. S. A. Bhalchandra et al. [1] Compared the properties of transversely isotropic lamina using method of cells and composite cylinder assemblage. V. D. Nguyen et al. [12] gave the expressions for imposing periodic boundary condition on arbitrary meshes by polynomial interpolation. Weidong Wu et al. [15] explained the method of applying periodic boundary conditions using Finite

Element Analysis. Patnaik et al.[13] studied the micromechanical characteristics of glass-fiber-reinforced polymer composites. The experimental results were in good agreement with finite element model based on representative area element approach. Siva I et al. [4] discussed the effect of fiber volume fraction on the mechanical properties of coconut sheat/usp composite. Mandar kulkarni [6] studied on the finite element analysis of 2-D representative volume element. Srihari kulkarni [7] worked on homogenization of damaged concrete meso-structures using representative volume elements. Erdogan Madenci and Ibrahim Guven [9] discussed about the Finite element method and its applications in engineering using ANSYS. Daniel Gay [2] and R. M. Jones [5] gave the constitutive equations for different types of materials.

2 Modeling and Analysis of Representative Volume Element

In this present investigation, unidirectional glass fiber as reinforcement phase and epoxy as matrix phase were considered for the composite material .The fiber and matrix materials are considered as isotropic and homogeneous. The properties of the constituent materials are as shown in Table 1.

Table 1: Mechanical properties of the constituent materials.

Properties	Glass fiber	Epoxy matrix
Young's modulus(GPa)	73	3.76
Poisson's ratio	0.2	0.38

2.1 Choice of damage mechanisms

Several micro damage mechanisms are possible in a lamina. In this study, it is assumed that the mechanisms present are: (a) Fiber break (due to σ_{11}), (b) Fiber-matrix debond (due to σ_{12} and σ_{13}) and (c) Matrix cracks (due to σ_{22} and σ_{33}).

In this study, Fiber break is represented by a centrally located crack in the fiber. The interface is assumed to be strong and fiber-matrix debond failure is modeled by a complete debond (to account for symmetry). Further, a linear elastic analysis is conducted for various lengths of the crack in the depth direction, with maximum length equal to the cell length 'l'. Note that contact conditions are not enforced in this analysis. It is assumed that the debond can grow either due to σ_{12} or σ_{13}, in the direction along the fiber. The matrix cracks are represented as the growth of radial cracks. The growth of the cracks is assumed to be along the fiber. All the assumed damage modes are shown in Figure 1.

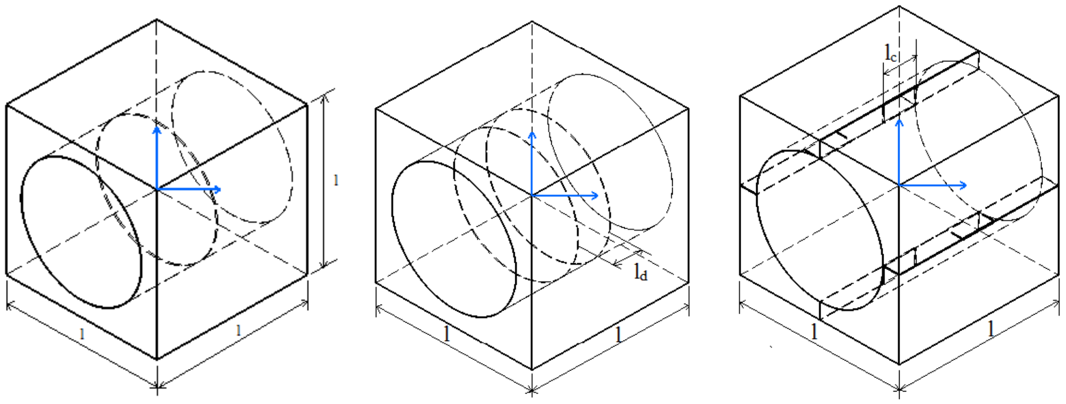
Definition of damage parameters

Fiber break: $d_1 = 0$ (when no fiber break); d_1=1(for complete fiber break).

Fiber-matrix debond: $d_2 = \frac{2\pi R_f l_d}{2\pi R_f l} = \frac{l_d}{l}$

Matrix cracks: $d_3 = \frac{2(l-D_f)l_c}{2(l-D_f)l} = \frac{l_c}{l}$

Where l_d and l_c are length of debond and length of matrix cracks respectively. The range of damage variables considered for the current study is 0.2 to 0.8.



(a) (b) (c)

Figure 1: (a) Fiber breakage (b) Fiber-matrix debond (c) Matrix cracks

2.2 Evaluation of Effective properties of the composites

In order to evaluate the effective properties of composite, 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. Three-dimensional structural solid element SOLID186 is used to determine elastic properties and is defined by 20 nodes having three translational degrees of freedom in 1, 2 and 3 directions at each node. In present work, transversely isotropic characteristics have been considered for the fiber-reinforced composite. A transversely isotropic material is to be a material whose effective properties are isotropic in one of its planes and the stiffness tensor is represented as

$$\begin{pmatrix} \overline{\sigma_1} \\ \overline{\sigma_2} \\ \overline{\sigma_3} \\ \overline{\sigma_4} \\ \overline{\sigma_5} \\ \overline{\sigma_6} \end{pmatrix} = \begin{pmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{12} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2}(C_{22}-C_{23}) & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{66} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{pmatrix} \begin{pmatrix} \overline{\varepsilon_1} \\ \overline{\varepsilon_2} \\ \overline{\varepsilon_3} \\ \overline{\varepsilon_4} \\ \overline{\varepsilon_5} \\ \overline{\varepsilon_6} \end{pmatrix}$$

Once the components of the transversely isotropic stiffness tensor are known, the elastic properties of homogenized material can be computed by

Longitudinal modulus

$$E_{11} = C_{11} - \frac{2C_{12}^2}{(C_{22}+C_{23})} \tag{1}$$

Transverse modulus

$$E_{22} = \frac{[C_{11}(C_{22}+C_{23}) - 2C_{12}^2](C_{22}-C_{23})}{(C_{11}C_{22}-C_{12}^2)} \tag{2}$$

Poisson's ratio

$$\nu_{12} = \frac{C_{12}}{(C_{22} + C_{23})} \tag{3}$$

$$\nu_{23} = \frac{C_{11}C_{23} - C_{12}^2}{C_{11}C_{22} - C_{12}^2} \tag{4}$$

Shear modulus

$$G_{12} = \frac{E_{11}}{2(1 + \nu_{12})} \tag{5}$$

$$G_{23} = \frac{E_{22}}{2(1 + \nu_{23})} \tag{6}$$

2.3 Boundary Conditions for Evaluation of Elastic Properties.

Composite materials can be represented as a periodic array of the RVEs. Therefore, the periodic boundary conditions must be applied to the RVE models. This implies that each RVE in the composite has the same deformation mode and there is no separation or overlap between the neighboring RVEs after deformation. The boundary conditions applied are given in Table 2. After applying boundary conditions, the corresponding engineering constants are calculated in terms of corresponding stresses as given below

$$\overline{\sigma}_{ij} = \frac{1}{V}\int_V \sigma_{ij} V^e \tag{7}$$

where $\overline{\sigma}_{ij}$ is the average stress, V is the volume of the RVE and V^e is the volume of each element.

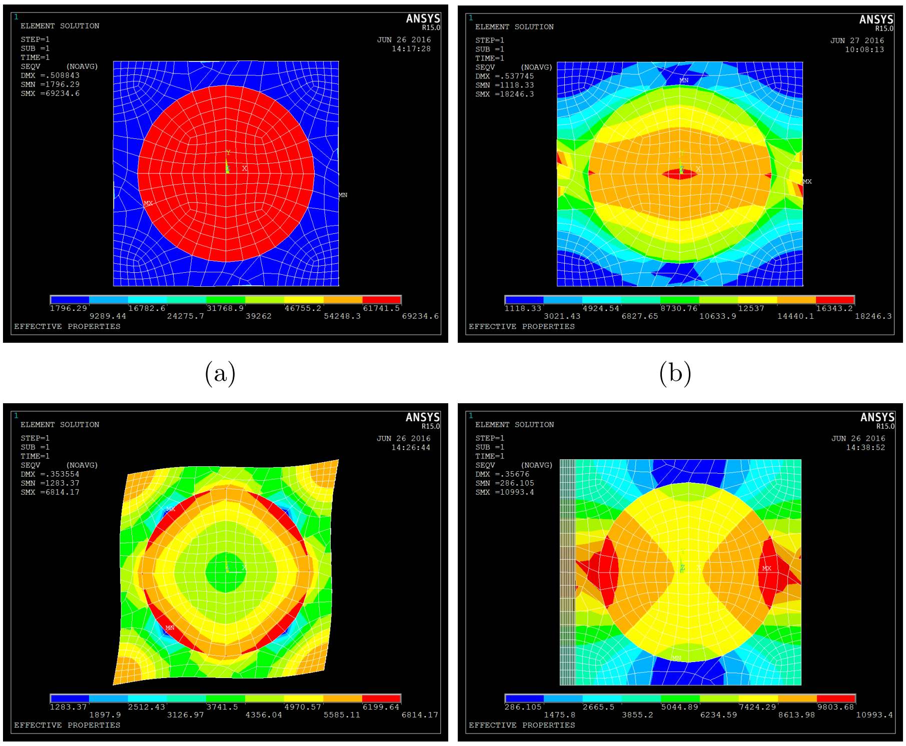
Table 2: Boundary conditions applied on RVE.

x, y, z = 0 node: UX, UY, UZ = 0			
$\overline{\varepsilon_{11}}$	z=l_1 nodes:UZ=l_1	z=-l_1 nodes:UZ=-l_1	All face nodes:UX,UY=0
$\overline{\varepsilon_{22}}$	x=l_2 nodes:UX=l_2	x=-l_2 nodes:UX=-l_2	All face nodes:UY,UZ=0
$\overline{\varepsilon_{33}}$	y=l_3 nodes:UY=l_3	y=-l_3 nodes:UY=-l_3	All face nodes:UX,UZ=0
$\overline{\varepsilon_{12}}$	z=$\pm l_1$ nodes:UX=$\pm\frac{l_1}{2}$	x=$\pm l_2$ nodes:UZ=$\pm\frac{l_2}{2}$	All face nodes:UY=0
$\overline{\varepsilon_{23}}$	x=$\pm l_2$ nodes:UY=$\pm\frac{l_2}{2}$	y=$\pm l_3$ nodes:UX=$\pm\frac{l_3}{2}$	All face nodes:UZ=0
$\overline{\varepsilon_{13}}$	z=$\pm l_1$ nodes:UY=$\pm\frac{l_1}{2}$	y=$\pm l_3$ nodes:UZ=$\pm\frac{l_3}{2}$	All face nodes:UX=0

where $2l_1$, $2l_2$ and $2l_3$ are the lengths of the RVE along the 1, 2 and 3 directions respectively.

3 Results and Discussion

The stress concentrations in the RVE for different loading conditions are shown in Figure 2. The damage is likely to occur in these areas of stress concentrations.



(a) (b)

(c) (d)

Figure 2: Stress concentration in the RVE when (a) $\varepsilon_{11} = 1$ (b) $\varepsilon_{22} = 1$ (c) $\varepsilon_{23} = 1$ (d) $\varepsilon_{12} = 1$

3.1 Effect of variation of fiber volume fraction on effective properties

To study the effect of perturbation of fiber volume fraction on the effective properties, a series of numerical experiments are conducted on undamaged unit-cell RVE with different fiber volume fractions. The results are compared with the effective properties obtained for the reference configuration and the plots, showing the percentage change in effective properties from the reference configuration with respect to the percentage change in volume fraction from the reference configuration, are shown in Figure 3.

3.2 Effect of damage on effective properties

To study the effect of damage on the effective properties, a series of numerical experiments are conducted on the unit-cell RVE with different damage modes and sizes, one at a time, at the reference volume fraction. To study the effect of different damages, percentage change in effective properties from the reference configuration is computed for each case. The effect of different types of damages on effective properties, at reference volume fraction, are shown in Figure 4.

3.3 Effect of damage on effective properties at other volume fractions

This study helps in understanding the coupling effect fiber volume fraction and damage. The plots of the variations of elastic properties with different damage modes at various volume fractions are shown in Figures 5 and 6.

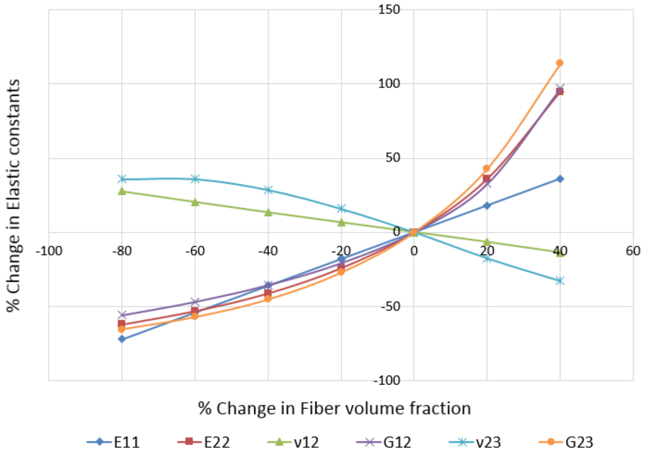
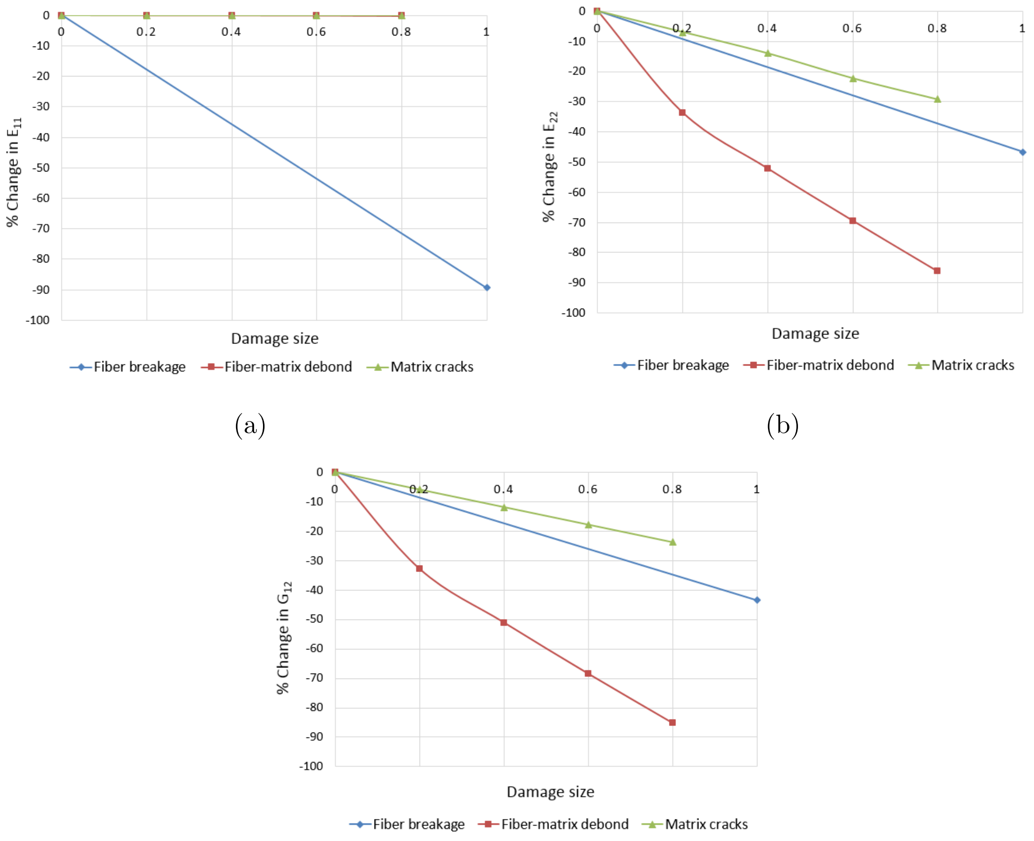


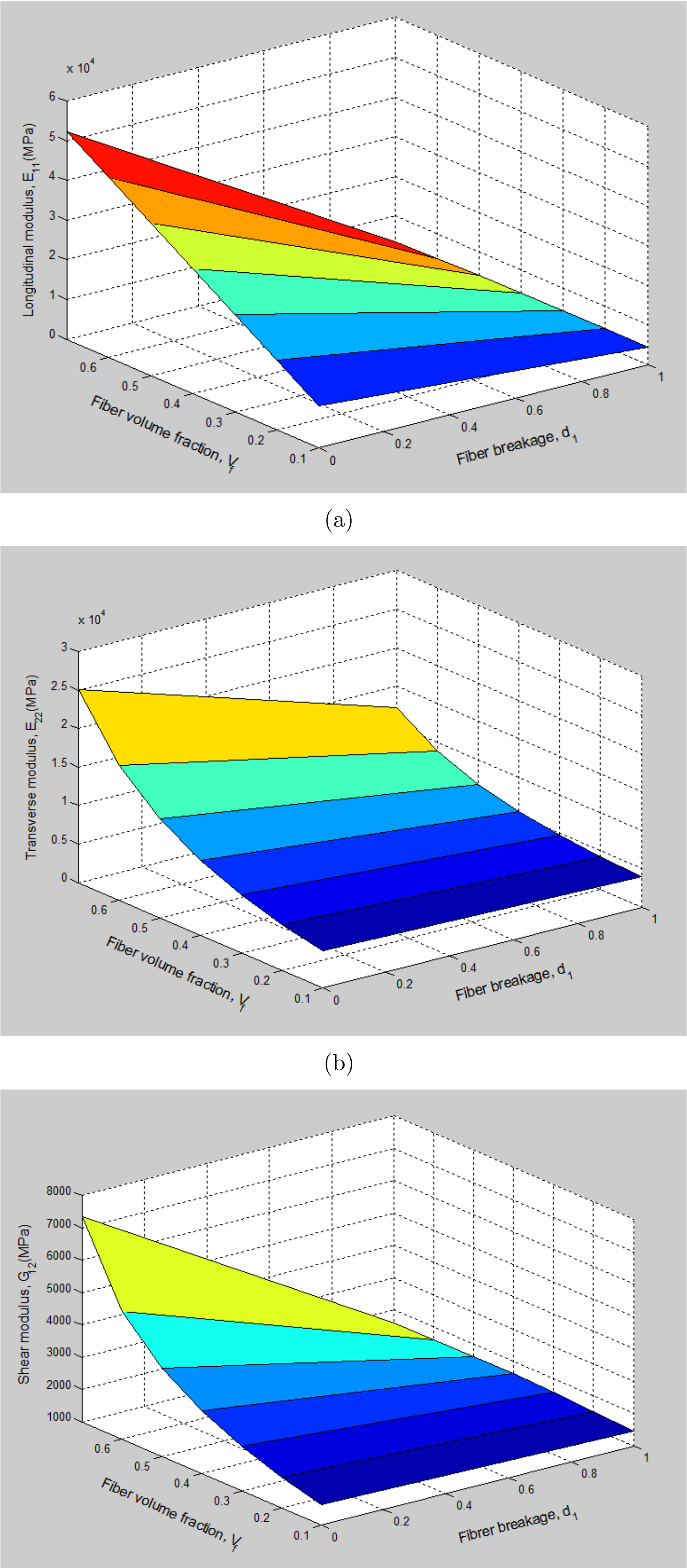
Figure 3: Effect of fiber volume fraction on the effective properties of glass/epoxy composite.



(a) (b)

(c)

Figure 4: Effect of damage modes on (a) E_{11} (b) E_{22} (c) G_{12}

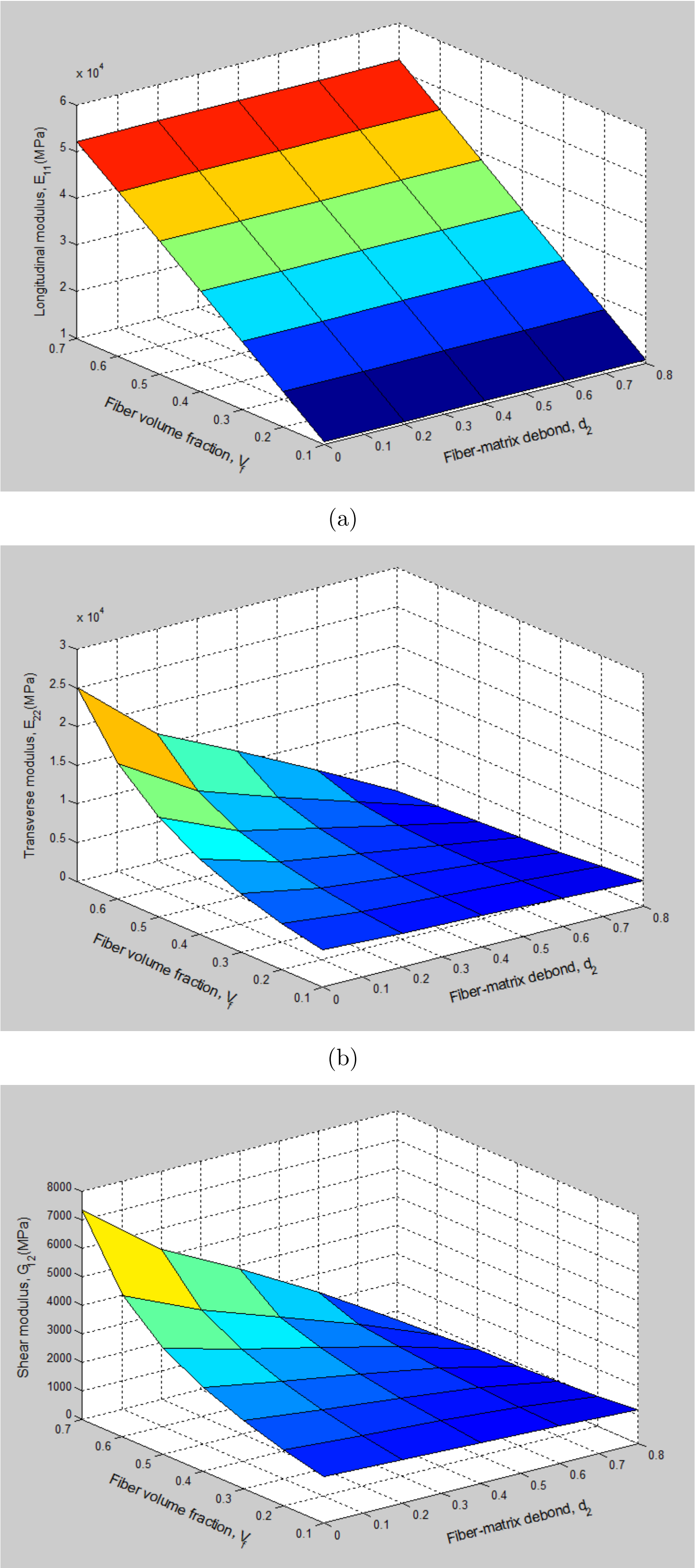


(a)

(b)

(c)

Figure 5: Effect of V_f and d_1 on (a) E_{11} (b) E_{22} (c) G_{12}



(a)

(b)

(c)

Figure 6: Effect of V_f and d_2 on (a) E_{11} (b) E_{22} (c) G_{12}

4 Conclusions

The following conclusions can be drawn.

(1) The Elastic moduli are increasing and Poisson's ratio is decreasing with increase in fiber volume fraction.

(2) Longitudinal modulus is severely affected by fiber breakage. It is reduced by 90%(approx.) at 0.5 Fiber volume fraction. In case of fiber–matrix debond all the effective properties are significantly affected except the longitudinal modulus. E_{22}, G_{12} and G_{23} are reduced by 80%(approx.) by fiber-matrix debond at 0.5 fiber volume fraction. The effect of matrix cracks is not significant on any of the properties.

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