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ORIGINAL ARTICLE

Parametric Study on Volume Fraction of Representative Volume Element (RVE) CFRP and GFRP towards Tensile Properties

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Abstract

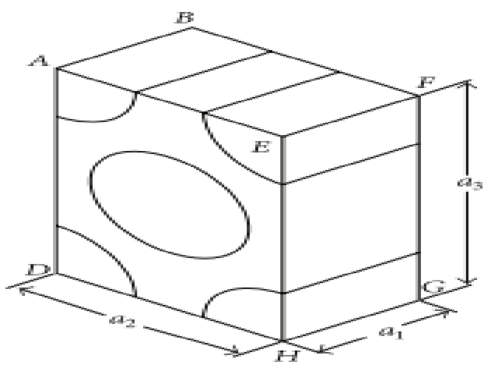
The study of Representative Volume Element (RVE) on Composite Material has been performed in the aim to obtain the relation and effect of fiber volume fraction on its tensile properties which is one of the important mechanical properties for composite designers in automotive and aerospace community.The properties such as fibre content, orientation, dimension of constituent fibres (diameter), level of intermixing of fibres, interface bonding between fibre and matrix, and arrangement of fibres between different types of fibres, influences the mechanical properties of hybrid composite.Representative Volume Element (RVE) for each constituent Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) assumed isotropic behavior for carbon fibre, glass fibre and epoxy resin matrix and assumed to be perfectly bonded interface between fibre and matrix region i.e. strain compatibility at the interface. The scope of study on the micro mechanical modelling via representative volume element (RVE) is limited only to unidirectional composites.The result of parametric study performed deduces that incremental volume fraction of carbon and glass respectively will increase the E_{11} (Modulus of Elasticity in Tensile Direction) and enhance the tensile properties of both CFRP and GFRP.

Keywords: Representative Volume Element, Micro mechanical, RVE, Carbon Fiber Reinforced Polymer, Glass Fiber Reinforced Polymer

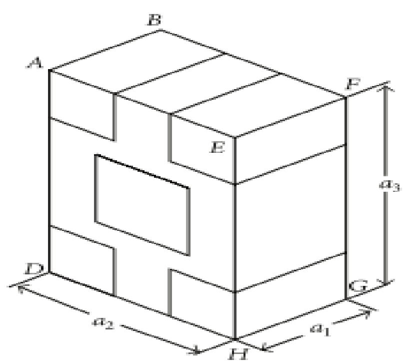
Introduction

The major contribution of FRP composite can be seen in the designs of high performance and lightweight solutions in the automotive and aerospace industries. high strength to weight ratio of the FRP materials may be customized in order to design optimal structures compared to traditional structures which made using metal alloys (z. li et al, 2016). The use of reliable design and prediction methods will ensure superior performance of composite. the tensile properties such as tensile modulus in longitudinal/transverse direction, tensile strength in longitudinal/transverse direction, failure strain in longitudinal/transverse direction are more important to take into account together with cost saving. the modulus of elasticity and improved tensile strength of composite could bring the greater impact on the application in industry such as aerospace, automotive, marine etc. Tensile properties are of critical parameters differentiating stiff and strong materials from tensile perspective either static or dynamic loading and uniaxial loading or multi axial loading (zhiye et al., 2016).

Micromechanical is the analysis on the level of individual constituents that represent the whole material of composite material or might as well defined as heterogeneous materials which composed of diverse parts that occupy the same volume (chen et al., 2019). lacks of experimental techniques and finite element modeling (fem) at micro and macro level have limits the findings and explanation on mechanics and material science of composite under static loading (ameri et al., 2016). in the generation of rve for composite, it is necessary for the rve or unit cell to be isolated with a simplicity purpose. the rve model generated should possess an equally value of elastic constant and fiber volume fraction as the composite as shown in figure 1 (bhaskara et al., 2014).



(a)



(b)

Figure 1:(a) hexagonal RVE with circular fiber, (b) hexagonal RVE with square fiber. (Bhaskara et al., 2014)

The result of virtual and experimental approach of micromechanics can help to understand the sharing of load among the constituents of the composites, microscopic structure (arrangement of fibers) within the composites (Drathi and Ghosh, 2015). Besides that, micromechanics can also provide understanding regarding the influence of microstructure on the properties of composite and as well as predicting the average properties of the lamina in terms of extracting the modulus of elasticity in tensile direction by dividing stress implied with strain experienced by the RVE under tensile mode. Micromechanical modelling can also be beneficial in providing the understanding of the physics of deformation and damage at more fundamental scale. Furthermore, micromechanics can perform simulation and optimization of macroscale/real scale scenarios in designing of composite materials. The composite material design and optimization can be performed by varying the parameters such as the constituent's volume fractions, constituent distributions and also the orientation. Influencing the properties and behaviour of the composite are the properties of fiber and matrix, interfacial bond and by its microstructure (Qingping et al,2018). Microstructural parameters that influence the composite behaviour are fiber diameter, length, volume fraction, packing and orientation of fiber (Vu Bac et al, 2015).

The RVE finite element modelling will provide answer on fiber/matrix deformation and homogenous study of composite at micro scale level (Swolf et al, 2016) .Representative Volume Element (RVE) for each constituent CFRP and GFRP assumed isotropic behavior for carbon fiber, glass fiber and epoxy resin matrix. Representative Volume Element (RVE) for each constituent CFRP and GFRP are assumed perfectly bonded interface between fiber and matrix region i.e. strain compatibility at the interface.The micromechanical modelling of representative volume element (RVE) will just represent the unidirectional composite material as referred to Figure 2.

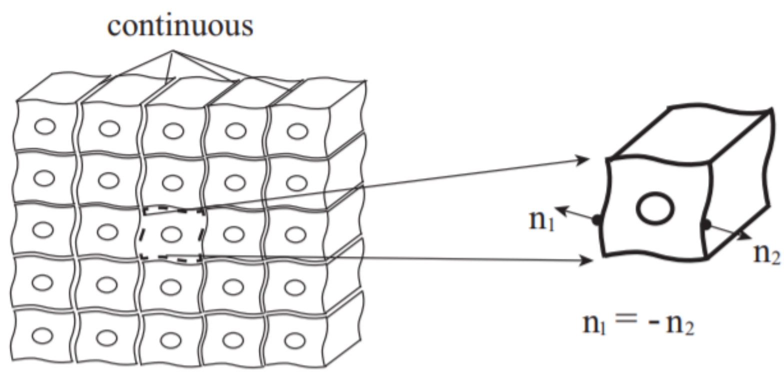


Figure 2: Representation of a unidirectional composite domain and the RVE simulation mode (Z. Li et al., 2016)

Materials and Methods

Microstructural Study under Tensile Loading

For purpose of volume fraction calculation at cross sectional position, parameters used are 20kv voltages and 1500x magnification in order to zoom in upto 3μm. The microstructure view of composite CFRP and GFRP is important to identify the condition of interface between two composites on post failure. Scanning electron microscopy (SEM) [JEOL 6010 Plus] was utilized to investigate the morphology of composites as shown in Figure 3. Coating of composites samples using gold layer is required before being assessed via SEM and as shown in Figure 4. The microscopic view using SEM has been conducted at Material Lab, Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka (UTeM).

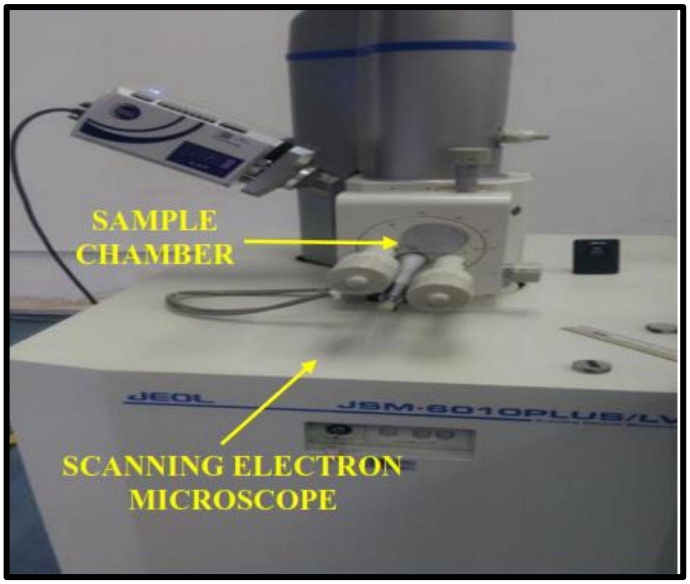


Figure 3: Scanning Electron Microscope (SEM) Used to Assess Morphological of Failure after Mechanical Test

Figure 4: Coating of Samples with Gold Material to Create a Conductive Layer

Boundary Conditions

The boundary conditions for the RVE models are based on tensile test experiments where there is a side that is in fixed condition and the opposing side subjected with loading i.e. displacement control. The displacement and rotational displacement for fixed boundary condition were all constrained in x (1), y (2) and z (3)-direction. There are six surfaces for three dimensional model as shown in Figure 5. The boundary conditions are set as accordance to the aims of the computation from RVE which are longitudinal, transverse and shear modulus of elasticity. The boundary conditions are tabulated in Table 1. Figure 5 illustrates boundary conditions of 3D RVE modelled showing region where displacement load is applied and fixed region is located at the back.

Table 1: Boundary Conditions for 3D Model RVE for Each Loading Type

Analysis for Modulus of Elasticity	**Boundary Conditions**	**Descriptions/Surface**
Longitudinal	Fixed	(U1=U2=U3=UR1=UR2=UR3 =0) BACK
	Displacement control	U3 ≠ 0
Transverse	Fixed	(U1=U2=U3=UR1=UR2=UR3 =0) WEST
	Displacement control	U1 = 1 µm EAST
Shear	Fixed	(U1=U2=U3=UR1=UR2=UR3 =0) BACK
	Displacement control	U1 = 1 µm FRONT

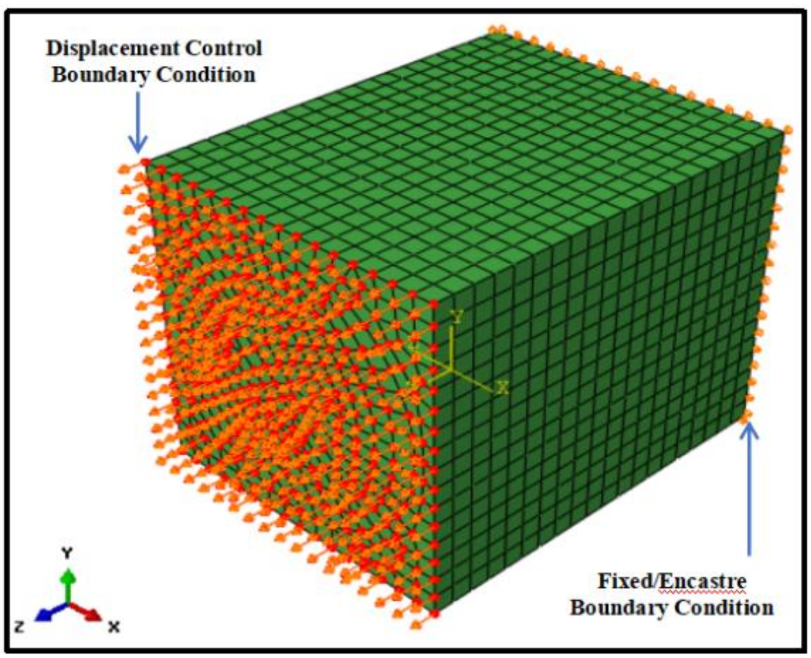


Figure 5: Boundary Conditions Applied on Tensile Test Simulation of RVE Front Showing Displacement Load and Fixed/Encastre at the Back

RVE with Multiple Fibres

In forming composite which consists of several fibres at different sizes, attempt has been made in modelling RVE with 9 fibres of CFRP in order to validate the model before attempting fof hybrid composites C/GFRP RVE. The size of cross section of RVE with 9 fibres could be determined as 22.74×22.74 according to its volume fraction (dimension is in μm). Figure 6 shows the geometry and finite element meshing of RVE with 9 fibres of CFRP.

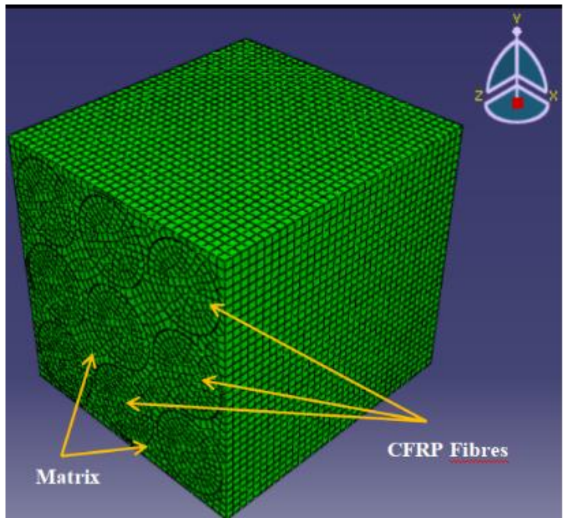


Figure 6: Finite Element Meshing for CFRP RVE with 9 Fibres of CFRP

Figure 7 and Figure 8 demonstrate the geometry and boundary conditions of RVE for purpose of computing modulus of elasticity in longitudinal direction, E_1. and transverse direction, E_2 respectively.

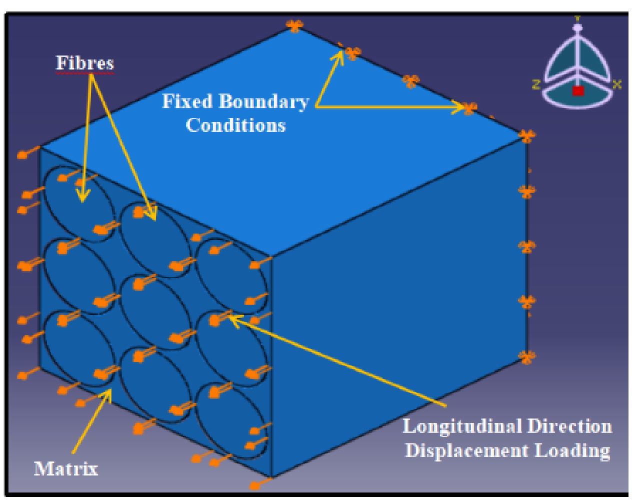


Figure 7: RVE with Longitudinal Direction Tension Loading

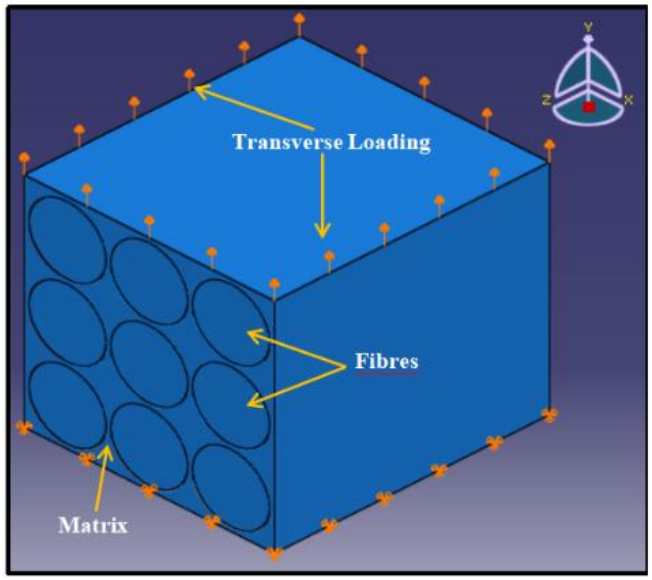


Figure 8: RVE Subjected to Transverse Tension

Modulus of elasticity in longitudinal direction, E_1

The result of total reaction force, F1 is required in order to calculate the total stress, σ1 of the composite. It is also important to determine longitudinal total strain, ε1 to obtain the stiffness property which in this study is the longitudinal Young's modulus, E1 of the composite. Below shows Eq. (1) (Babu et al, 2018) used in order to determine the E1 for each composite used in analysis.

$$E_1 = \frac{\sigma}{\varepsilon} = \frac{F/A}{\varepsilon} \tag{1}$$

Results and Discussion

Microstructural Study on CFRP and GFRP

The profile of Energy Dispersive X-ray Spectroscopy (EDS) of elemental analysis or chemical characterization of a Carbon Fibre Reinforced Polymer (CFRP) and Glass Fibre Reinforced Polymer (GFRP) are shown as in Figure 9. High percentage of Carbon Element was observed in the sample of CFRP as in Figure 10 followed by Zirconium Element which originated from Epoxy Resin embedded in the prepreg. On the other hand, Silicone Element is detected at substantial level for Glass Fibre Reinforced Polymer (GFRP) since it is the major constituent in formation of Glass.

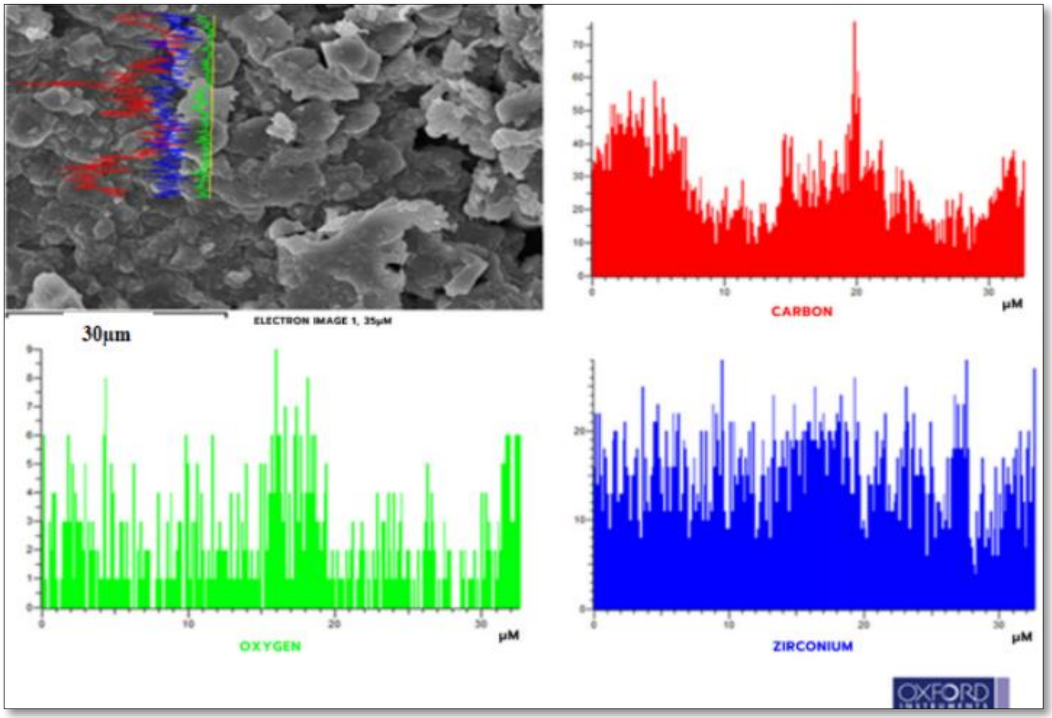


Figure 9: EDS Line Scan Profiles of Carbon Fibre Reinforced Polymer (CFRP) Sample

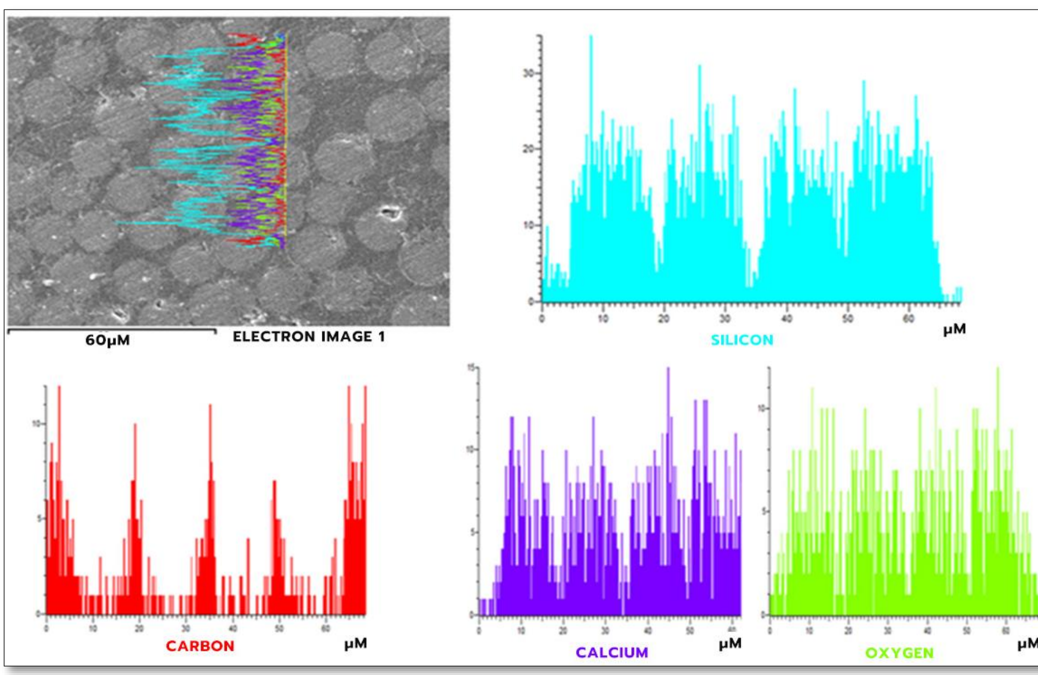


Figure 10: EDS Line Scan Profiles of Glass Fibre Reinforced Polymer (GFRP) Sample

Figure 11 shows the cross sectional view of GFRP unidirectional prepreg after curing, as observed using SEM at 1000 times magnification at 10µm. The diameter of GFRP as observed was around 11µm to 12.8 µm observed at 1000 times magnification.

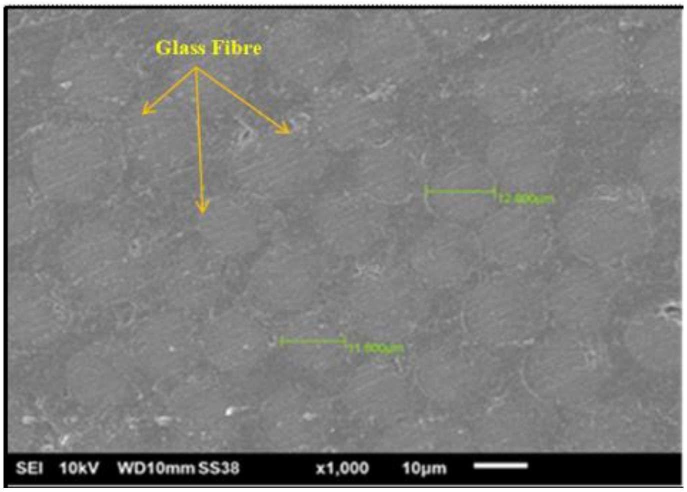


Figure 11: Unidirectional SEM Cross Sectional View

Carbon fibre diameter was computed ranging from 6µm to approximately 7µm. Meanwhile, glass fibre diameter obtained from the SEM is from ~11µm to ~12.5µm which approximately twice the diameter of carbon fibre as depicted in Figure 12 and Figure 13 respectively. Besides, the fibre arrangement and pack geometry can be seen clearly. The data are tabulated and volume fractions computed are shown in Table 1.

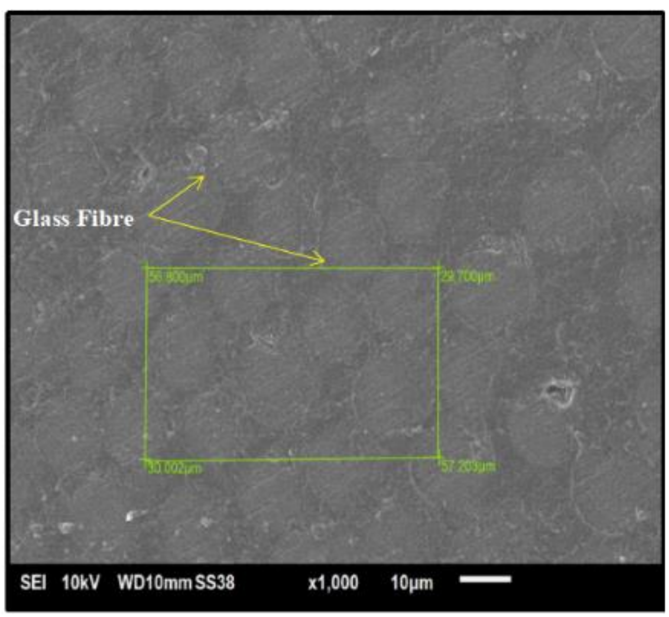


Figure 12: Volume Fraction of GFRP Determination via Computation Dimension of Fibre/Matrix

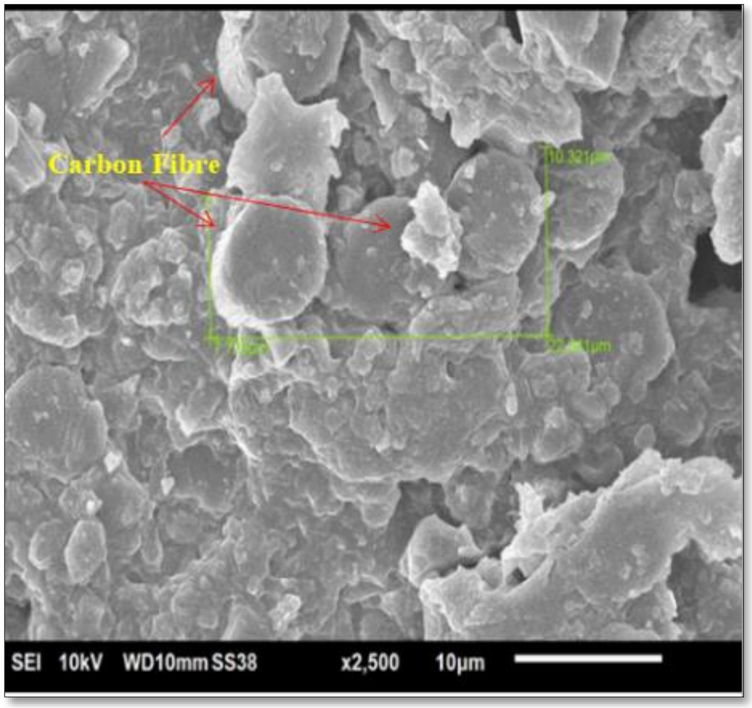


Figure 13: Volume Fraction of CFRP Determination via Computation Dimension of Fibre/Matrix.

Table 1: Summary of Dimension of Fibre/Matrix and Volume Fraction Obtained from SEM

	CFRP	GFRP
Length of box	15.14 µm	56.8µm
Height of box	12.52 µm	27.2 µm
Area of box	189.56 µm^2	1544.96 µm^2
Number of fibre inside the box	3	8
Fibre radius	7µm	12 µm
Area of fibres inside the box	115.47µm^2	904.89µm^2
Volume fraction	~0.61	~0.59

RVE Parametric Study on Unidirectional Composites

The computation of modulus of elasticity, which depended on volume fraction of the composite, was also performed on the basis of micromechanical theory and compared with FEM RVE. Table 3 and Table 4 exhibit parametric volume fraction sets at 30%, 43%,60% and 75% with their corresponding calculated Modulus of Elasticity, E_1 for CFRP and GFRP RVE respectively.

Table 2: Parametric Volume Fraction, Geometry and Results for CFRP RVE

Fibre Ratio (%)	Area Surface RVE (μm^2)	Width (μm)	Reaction (N)	σ_1 (GPa)	ε_1 ($\mu m/\mu m$)	E_1 RVE (GPa)	E_1 ROM (GPa)
30	128.28	11.32	0.09	0.7	0.01	70.37	82.7
43	89.49	9.46	0.089	0.99	0.01	99.41	100.83
60	64.14	8	0.088	1.37	0.01	137.37	139.36
75	51.31	7.16	0.087	1.71	0.01	170.88	173.35

Table 4: Parametric Volume Fraction, Geometry and Results for GFRP RVE

Fibre Ratio (%)	Area Surface RVE (μm^2)	Width (μm)	Reaction (N)	σ_1 (GPa)	ε_1 ($\mu m/\mu m$)	E_1 RVE (GPa)	E_1 ROM (GPa)
30	128.28	11.32	0.035	0.28	0.01	27.55	27.88
43	89.49	9.460	0.034	0.38	0.01	38.03	38.48
60	64.140	8.008	0.033	0.52	0.01	51.72	52.36
75	51.312	7.163	0.033	0.64	0.01	63.81	64.6

Figure 14 and Figure 15 display the Modulus of Elasticity, E_{11} computed for 3D RVE for CFRP and GFRP respectively based on results tabulated in Table 3 and Table 4. The variation between Modulus of Elasticity computed from both 3D RVE and Rule of Mixture were quite minimal for CFRP and GFRP cases. The incremental volume fraction had increased the modulus of elasticity proportionately for both cases of CFRP and GFRP.

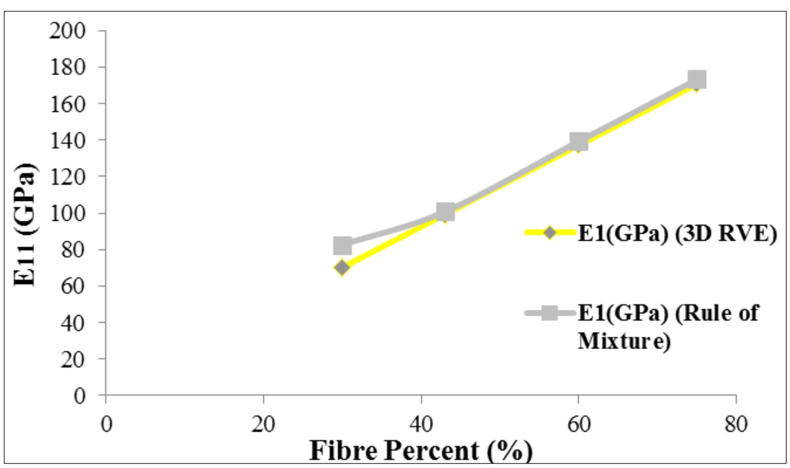


Figure 14. Modulus of Elasticity for CFRP using 3D RVE and Rule of Mixture (Analytical) at Different Volume Fraction

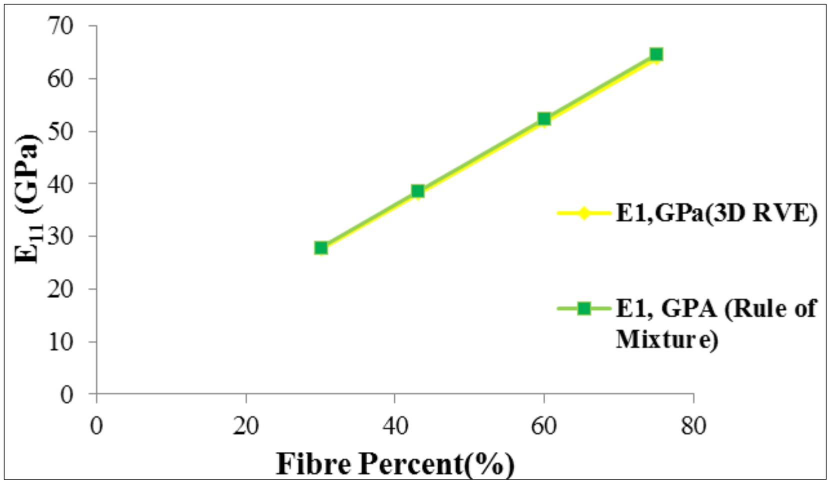


Figure 15: Modulus of Elasticity for GFRP using 3D RVE and Rule of Mixture (Analytical) at Different Volume Fraction

A parametric study is conducted using several fiber volumes fractions via RVE. Different with macro level method, the actual composite structure is replaced by equivalent homogenized material having the calculated effective properties to determine average stress and strain within homogenized structure. It is seen that the effective properties of composite material, GFRP and CFRP developed increases as the volume fraction increases. This is due the fact that the contribution of the properties from fibre, particularly the ones in fibre direction increases as the fibre volume fraction increases.

Conclusion

The simulation in static at micro level which represented in the RVE square shows that RVE can be utilized to represent homogenization of hybrid FRP to characterize loading behaviour. Concept of multiscale modelling using Representative Volume Element (RVE) also introduced in this paper as another practical approach in predicting modulus of elasticity of composites material. RVE which is based on micromechanical technique via FEM has been proven to be useful tool in predicting effective modulus of elasticity of composite CFRP and GFRP. Influence of fiber size effect on RVE considering both the constituents as isotropic in nature which reflect the volume fraction is observed to be in proportional to the increment of tensile modulus of CFRP and GFRP. The findings would be of beneficial to composite material community in terms of design and optimization activity for automotive and aerospace engineering.

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