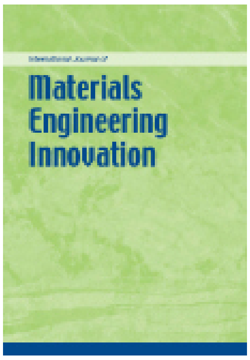

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Prediction of elastic properties of cotton waste reinforced epoxy composites for structural applications

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Abstract: Fibre reinforced composite materials have become a popular engineering material type. They have excellent mechanical characteristics, a wide range of flexibility in design, and are simple to fabricate. Fibre reinforced composites (FRP) are gradually displacing traditional materials in a wide range of applications, including aircraft, automobiles, containers, space vehicles, offshore constructions and pipelines, sporting goods, and electrical appliances. The mechanics of FRPs, on the other hand, are complicated due to their anisotropic and heterogeneous properties. To determine the elastic behaviour of the composite, a representative volume model was considered in this paper, and a finite element model incorporating the required boundary conditions was developed using FEA ABAQUS software. The results of the analysis are compared to those acquired from numerical calculations, and it is seen that they are in good agreement and are applicable to all volume fractions of the composite.

Keywords: cotton waste; effective elastic constants; ABAQUS; rule of mixture.

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1 Introduction

The study of composite materials at the matrix and fibre level is referred to as micromechanical analysis. Micromechanics enables researchers to anticipate microscopic properties of materials that are difficult to detect experimentally. The calculation of equivalent elastic constants of fibre reinforced composites has received a lot of attention, and numerous micromechanical models have been developed in the literature to predict these effective elastic characteristics. The following is a summary of the methodology utilised in these studies:

1 numerical approaches: finite difference and finite element methods

2 analytical methods: rule of mixtures (ROM) and semi-empirical Halpin-Tsai equation

3 experimental research at the macro, micro and nanoscales.

In the case of fibre reinforced composites, the needed directional qualities can be attained by carefully selecting fibre orientation, fibre volume fraction, fibre spacing, and fibre distribution in the matrix and layer sequence. The finite element method (FEM) is a popular computational method for solving engineering issues. Different methods, for examples sublevel mathematical algorithms, were also developed and employed in conjunction with FEM during the solution phase. Representative volume element (RVE) was one of the key approaches used to estimate the mechanical behaviour of the materials. The effective elastic moduli of the composite were acquired using RVE finite element analysis (Sun and Vaidya, 1996). Experiments were also carried out to defend the numerical results (Li et al., 1998). The results of two-dimensional (unit cell approach) and three-dimensional finite element analysis (FEA) with RVE were compared to those of experimental studies reported in Kang and Gao (2002). The commercial packages ABAQUS (Hbaieb et al., 2007; Lee et al., 2007; Qing, 2013), ANSYS (Sai et al., 2013), NASTRAN, and ALGOR-FEAS (Unterweger et al., 2014) were frequently used by researchers. In the literature survey (Godara and Mahato, 2020b; Kathavate et al., 2020; Chang et al., 2016; Cen et al., 2006), the numerically generated results were compared and analysed with analytical (Li et al., 1998; Lee et al., 2007; Jha et al., 2020; Godara and Mahato, 2020a; Dixit and Mali, 2013; Naresh et al., 2021) and experimental results. Geometrical factors can have a considerable impact on stress distributions in fibre/matrix micro droplets, and the micro droplet's interfacial edge angle is one of the main reasons for discrepancies in micro bond test findings between laboratories (Abadi, 2009). The micromechanical technique is widely used to measure the stress relaxation response of polymer composites made up of linearly viscoelastic matrices and transversely isotropic elastic fibres. A representative unit cell is exposed to predetermined shear and axial loadings to evaluate and the time-subordinate way of behaving of composite materials. In transverse axial and longitudinal shear loading, the stress apportioning factor is dependent on the time space and fibre volume percentage, but it is constant in transverse shear loading. For parametric investigations and finite element examinations of viscoelastic composite structures, the representative volume element model is useful (Akkaoui et al., 2017). The proposed micromechanical model is applied to compute the relevant microstructural and mechanical parameters of the ingredients of wood-aggregate concrete that influence its elastic properties. Micromechanical models provide predictive tools for such heterogeneous materials' behaviour (Vignoli et al., 2019). The recently constructed modified rule of mixing model has the best relationship with experimental values among ROM-based models, whereas asymptotic homogenisation has the best forecasts among elasticity-based models. Based on the qualities of individual materials and their volume fractions, they estimate the effective macro mechanical properties using ROM-based models. The effective macro mechanical parameters of the updated ROM model are more consistent with experimental evidence (Jha et al., 2020). The optimal elastic characteristics of composites were calculated considering Python code and RVE, and these properties were used to design efficient multi-directional epoxy/glass composite laminates. A three-dimensional model was created using the finite element programme ABAQUS, and the findings show that unidirectional laminates have better mechanical properties than other laminates, while angle ply laminates have the highest von Mises stresses (Godara and Mahato, 2020a). To forecast the properties of composites, different numerical approaches like as Fast Fourier transforms, finite element analysis, Mechanics of Structure Genome and others are utilised. The discretisation of the heterogeneous domain using finite elements is used heavily in these numerical algorithms that are suitable for solving on a modern computer (Hassanzadeh-Aghdam et al., 2018). To determine the elastic characteristics of carbon fibre (CF)-reinforced polymer hybrid composites, a multi scale micromechanical modelling approach is designed. The unidirectional fibres in this hybrid composite are coated with randomly arranged carbon nanotubes (CNTs). In addition, increasing the CNT volume fraction and decreasing the CNT diameter can improve the hybrid composite transverse elastic modulus (Kim and Lee, 2009). To evaluate the interfacial damage progression and effective elastic constant in fibre-reinforced composites, an RVE-based micromechanical elastic damage model with fibre size dependency is proposed. The current numerical test shows that when the radius of the fibre is less than 10% of the radius of the RVE, the RVE-based micromechanical technique that considers fibre size dependency produces essentially identical predictions as the infinite RVE-based micromechanical approach. With a decrease in fibre content, the stress concentration at the fibre-matrix contact increased. The higher stress region of the composites was influenced by differences in fibre content. The load shared by the fibres decreased as the stiffness of the fibres increased, while the value of shear stress at the matrix-fibre interface increased (Kim and Lee, 2009; Houshyar et al., 2009; Günay, 2016).

The aim of this investigation is to evaluate the mechanical properties of cotton waste via experimentally and effective elastic constants of cotton waste reinforced epoxy composites using both analytical and numerical approaches. Also to find the effect of properties of each constituent element on various fibre volume ratios. The results are compared to the Halphin-Tsai criteria, the rule of mixes and ABAQUS.

2 Methodology

2.1 Material property evaluation

In general, material scientists use a variety of experimental and numerical techniques to evaluate composite qualities in order to obtain exact results that include all essential variations. Cotton waste was used in this study, and it was a novel way for extracting the mechanical properties of individual constituents. The tensile test is carried out using special computerised universal testing equipment with a 10 tonne capacity and a cross head speed of 1 mm/min and the results are examined. ASTM D 3039 is used to prepare the test samples. The results of the test are averaged from five samples.

Figure 1 Computerised universal testing machine with a 10 ton capacity (see online version for colours)

Table 1 Experimentally obtained properties of cotton waste

Material properties	*Value*
Young's modulus (GPa)	7.75
Tensile strength (MPa)	442
Poisson's ratio	0.3
Density (g/cm^3)	1.55
Elongation (%)	7.0–8.0

Table 2 Properties of epoxy resin

Properties	*Value*
Young's modulus (GPa)	2.915
Poisson's ratio	0.33
Density (g/cm^3)	1.15
Shear modulus (%)	1.121

Source: Godara and Mahato (2020a)

Table 3 Chosen different volume ratio for the present analysis

Specimen ID	*Fibre volume (%)*	*Matrix volume (%)*
A	50	50
B	45	55
C	40	60
D	35	65

Few consistent methodologies are used for the current analysis from among the various techniques, and their processes are detailed in the following lines.

2.2 Analytical formulation

2.2.1 Rule of mixture

The micromechanical techniques were used to determine the equivalent elastic constants of composite materials based on the various elastic constants that comprise the composite material. The elastic constants E_L, E_T, ϑ_{12}, G_{12} of the fibre-reinforced-composite have been estimated analytically as far as the relative volume fractions V_f, V_m and elastic constants E_f, E_m, G_f, G_m, ϑ_f, ϑ_m of matrix and fibre. In order to get the comparable elastic constants, two main analytical methodologies in micromechanics of continuous fibre-matrix composite materials should be mentioned. The rule of mixtures (ROM) was the first, and the Halpin-Tsai semi-empirical model was the second (Li et al., 2020; Nagar et al., 2020). The matrix and fibre are assumed to be properly bonded under the uniaxial tensile load, with the same strain assumption for both the fibre and matrix materials. The following equations (Hassanzadeh-Aghdam et al., 2018; Melro et al., 2013) can be used to calculate the elasticity modulus of a fibre reinforced composite:

- Longitudinal Young's modulus

$$E_L = E_f V_f + E_m \left(1 - V_f\right) \tag{1}$$

- Transverse Young's modulus

$$\frac{1}{E_T} = \frac{V_f}{E_f} + \frac{\left(1 - V_f\right)}{E_m} \tag{2}$$

- Major Poisson's ratio

$$\vartheta_{12} = \vartheta_f V_f + \vartheta_m \left(1 - V_f\right) \tag{3}$$

- In-plane shear modulus

$$\frac{1}{G_{12}} = \frac{V_f}{G_f} + \frac{\left(1 - V_f\right)}{G_m} \tag{4}$$

where E_T and E_L are the modulus of elasticity of the composite component along the transverse and longitudinal directions respectively. Similarly, V_f the volume fractions of the reinforcement material, G_{12} is a shear modulus and ϑ_{12} is a Poisson's ratio.

Table 4 Results obtained from rule of mixture

Specimen ID	*Longitudinal Young's modulus (GPa)*	*Rigidity modulus (GPa)*	*Poisson's ratio*
A	5.648	2.035	0.315
B	5.091	1.954	0.316
C	4.851	1.882	0.318
D	4.607	1.802	0.319

2.2.2 Halpin-Tsai model

The Halpin-Tsai method is a semi-empirical approach for calculating the elastic modulus of composites with fibre and particle reinforcement. Because of its simplicity, this approach is common practice in both micro- and nano-mechanics. By fitting curves to elasticity-based results, Halpin and Tsai were able to develop their models as simple equations. The equations are semi-empirical in type since the curve fitting parameters have physical meaning.

- Young's modulus (E_1) on longitudinal scale:

$$E_1 = E_f V_f + E_m V_m \tag{5}$$

- Transverse Young's Modulus (E_2):

$$\frac{E_2}{E_m} = \frac{1+\xi\eta V_f}{1-\eta V_f} \tag{6}$$

$$\eta = \frac{(E_f / E_m) - 1}{(E_f / E_m) + \xi} \tag{7}$$

  The term ξ 'reinforcing factor' refers to the relationship between fibre geometry, packing geometry, and loading circumstances.

- Major Poisson's ratio (ϑ_{12}):

$$\vartheta_{12} = \vartheta_f V_f + \vartheta_m V_m \tag{8}$$

- In-plane shear modulus (G_{12}):

$$\frac{G_{12}}{G_m} = \frac{1+\xi\eta V_f}{1-\eta V_f} \tag{9}$$

By comparing equations (6) and (8) the values of ξ have been obtained with exact elasticity results, and comparing curve fitting results. The following is the generalised Hooke's law equation:

$$\sigma_i = C_{ij}\varepsilon_j \tag{10}$$

In this equation, σ_i is the stress vector, C_{ij} is the stiffness matrix, and ε_j is the strain vector components. In functional form, C_{ij} has been represented by equation (10) in terms of the elastic characteristics of the matrix, fibre, relative volume fractions of fibre and matrix.

$$C_{ij} = C_{ij}\left(E_f, \vartheta_f, V_f, E_m, \vartheta_m, V_m\right) \tag{11}$$

The basic analytical methods have been presented in most literature research without taking into account the contact traction across the end faces of the matrix and fibres and the stress concentration effects at the fibre ends (Sun and Vaidya, 1996; Li et al., 1998; Kang and Gao, 2002; Hbaieb et al., 2007; Lee et al., 2007; Qing, 2013; Sai et al., 2013; Unterweger et al., 2014; Godara and Mahato, 2020a, 2020b; Kathavate et al., 2020; Chang et al., 2016; Cen et al., 2006; Abadi, 2009; Akkaoui et al., 2017; Vignoli et al., 2019; Jha et al., 2020; Hassanzadeh-Aghdam et al., 2018; Melro et al., 2013; Kim and Lee, 2009; Houshyar et al., 2009; Günay, 2016).

Table 5 Results obtained from Halpin-Tsai model (H-T model)

Specimen ID	*Longitudinal Young's modulus (GPa)*	*Rigidity modulus (GPa)*	*Poisson's ratio*
A	5.648	2.931	0.315
B	5.091	2.786	0.316
C	4.851	2.654	0.318
D	4.607	2.519	0.319

3 Numerical analysis using ABAQUS FEA

To model and derive the effective elastic constants of composites, the commercial finite element software ABAQUS is employed. A modelling work completes the analytical investigation reported in the previous section. The goal of this research study is to build a predictive tool for the elastic property of cotton waste reinforced epoxy composites so that we can discover important factors which influence it. The micromechanical homogenisation approach is used to create this predictive tool. This homogenisation focuses on determining the rigidity matrix of the macroscopic medium in light of the microstructure and mechanical behaviour of its many elements in the context of elasticity. The meaning of the representative elementary volume (REV), the selection of an adequate mechanical stress on this REV, the calculation of localisation fields, and finally homogenisation are the essential processes in this practice (Dixit and Mali, 2013). The description of a REV entails describing the dimensions and composition of an elementary volume of heterogeneous material on which micromechanical analysis will be done. Chamis' micromechanical model equations (Hbaieb et al., 2007) and Mori-asymptotic Tanaka's mean-field homogenisation approach (Lee et al., 2007) are two theoretical homogenisation methods available. These approaches, on the other hand, are unable to account for the impact of geometrical differences in individual components at the micro scale. As a result, adopting a finite element-based numerical methodology viz., the representative volume element (RVE) homogenisation method to determine the effective elastic characteristics of composites is more precise, highly advisable, and is becoming the standard technique for composite materials (Sai et al., 2013). The different hybrid materials, viz. solids with voids, can be treated in the same way. In this study different fibre volume fractions are investigated with 50%, 45%, 40% and 35% respectively. The study is carried out using periodic boundary conditions code, and the elastic property for numerous volume fractions is determined.

The radius of the fibre is computed in relation to the volume of the fibre (Melro et al., 2013):

$$\text{Volume of RVE} = \text{Area} \times \text{Height mm}^3$$

$$1\ \text{mm}^3 = \pi r^2 h$$

For different fibre volume (FV) ratio:

$$0.5\text{FV} \times 1\ \text{mm}^3 = \pi r^2 h$$

$$0.5\ \text{mm}^3 = \pi r^2 1$$

$$r = 0.39894\ \text{mm}$$

Table 6 The size of fibre for different volume ratio

Specimen ID	*Fibre volume (%)*	*Matrix volume (%)*	*Radius of fibre (mm)*
A	50	50	0.3989
B	45	55	0.3785
C	40	60	0.3568
D	35	65	0.3338

The representative elementary volume (REV) (also known as the representative volume element (RVE) or the unit cell) is the minimal volume across which analysis can be conducted that yields a value indicative of the whole in composite materials theory. The study of a representative volume element is used in numerical or analytical micromechanical analysis of fibre reinforced composites (RVE). Despite the fact that fibres in real composites are dispersed randomly, many micromechanical models expect a periodic arrangement of fibres from which RVE may be easily extracted. The elastic constants and fibre volume percentage of the RVE are identical to those of the composite. RVE can be compared to a relative element with a significant number of crystals in general. The model is built on a 3D micromechanical RVE, with the circular cross section of the fibre serving as the RVE developer.

3.1 Geometrical modelling

In ABAQUS a unit dimension RVE is constructed by selecting an option called as part and drawing the geometry according to volume ratio of fibre and matrix of composite. The diameter of fibre changes with respect to fibre volume ratio and square RVE is shown in Figure 2. To add the mechanical properties to the fibre and matrix by selecting that respective section. Then after assembling the matrix and reinforcement, meshing was done to the RVE to desire meshing size to obtain the micro mechanical characteristics of unit RVE of composite.

3.2 Meshing

Figure 3 explains the meshing size (number node) increases the in RVE the effective young's modules of composite change at some instance and then it becomes almost straight line that indicates the result is converge. Then the same mess size is used to find other micromechanical properties of composite.

Figure 2 Square RVE with circular fibre (see online version for colours)

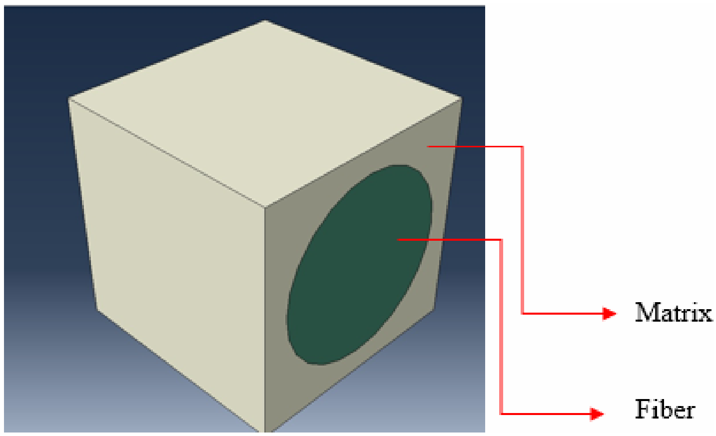
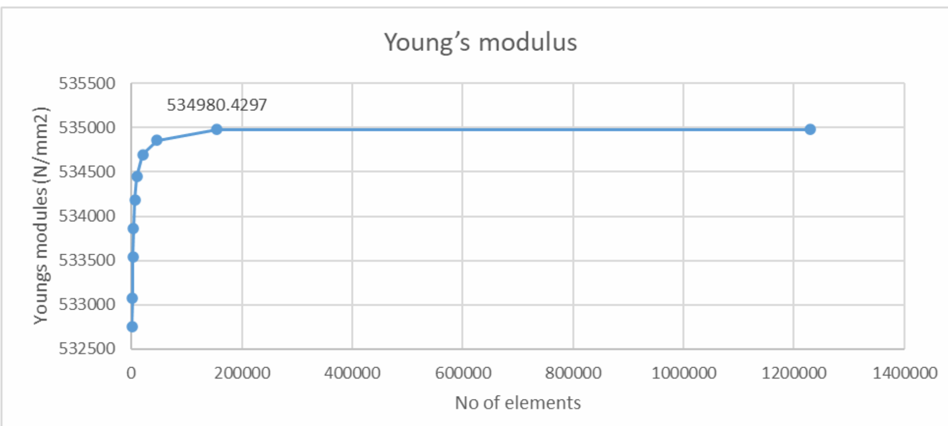


Figure 3 Convergence Criteria (see online version for colours)



3.3 Boundary conditions and post processing

The objective of RVE homogenisation is to assess the effective elastic characteristics of a composite model by numerically inducing homogeneous strains, as shown in Figure 4. In most cases, these strains are applied in several separate sets, each of which calculates distinct elastic material properties. Because the RVE is considered to be part of a periodic material, it is necessary to model the RVE's periodicity with the surrounding material in FE software after and before it's stressed. In previous homogenisation experiments, periodicity was obtained by setting boundary requirements that ensured RVE's planar border surfaces remained plane after deformation (Brockenbrough et al., 1991; Naik and Crews, 1993; Sun and Vaidya, 1996). Under longitudinal strains, this is only true for a transversely isotropic RVE. As a result, node-to-node periodic requirements must be applied, because distorted boundary surfaces can conort and no longer remain planar (Bonora and Ruggiero, 2006; Omairey et al., 2019).

Figure 4 Mesh model (see online version for colours)

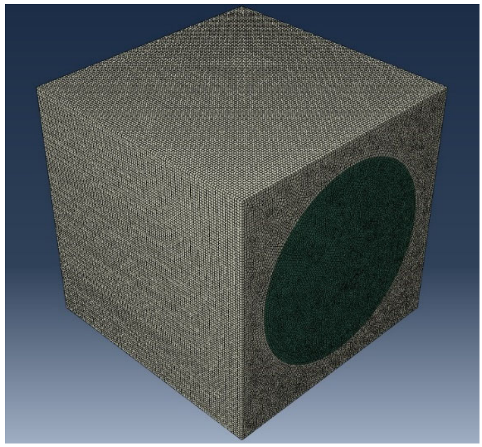
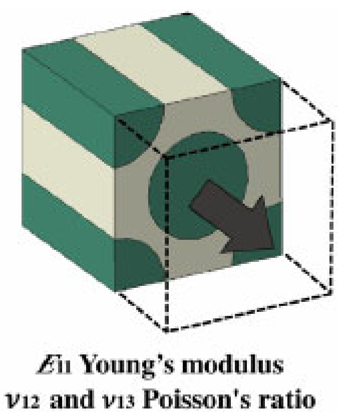


Figure 5 Diagrammatic illustration of displacement boundary conditions essential to determine the overall elastic properties (see online version for colours)



Source: Omairey et al. (2019)

3.4 Modelling using ABAQUS CAE

Step 1 Design the unit cell in part module of the interface.

Step 2 Switch to the next module, i.e., property module. Assigning all values of the attributes of the fibre and matrix using 'create material' option available. An edit material window will pop up where we enter the values of density, Poisson's ratio and elastic moduli for fibre and matrix.

Step 3 Selecting assembly module, create an instance and select the part which is being operated on.

Step 4 Get into mesh module and mesh the part. Assign mesh controls and select the part to be meshed and select the mesh type. For this analysis, we will use hex-dominated sweep option. The size of mesh is 0.2 mm.

Step 5 After meshing, update the part and select all the following properties which need to be found.

Table 7 The equations for liner restrictions and displacement boundary conditions

*Young's moduli (E_{11}, E_{22} and E_{33}) linear constraints equations and load boundary conditions**

Constraint equations: $A * U_{set1}^{DoF} + B * U_{set2}^{DoF} + C * U_{RP(i)}^{DoF} = 0$

Set 1	*Set 2*	*DoF*	*A*	*B*	*C*	*RP(i)*
TopS	BotS	1, 2, 3	1	–1	–1	N/A, 5, N/A
FrontS	BackS	1, 2, 3	1	–1	–1,0,0	4, N/A, N/A
LeftS	RightS	1, 2, 3	1	–1	0,0,–1	N/A, N/A, 6
F.T.edge	B.T.edge	1, 2, 3	1	–1	–1,0,0	4, N/A, N/A
B.B.edge	B.B.edge	1, 2, 3	1	–1	0,–1,0	N/A, 5, N/A
F.L.edge	F.B.edge	1, 2, 3	1	–1	1,0,0	4, N/A, N/A
B.L.edge	B.L.edge	1, 2, 3	1	–1	–1,0,0	4, N/A, N/A
B.R.edge	B.R.edge	1, 2, 3	1	–1	0,0,–1	N/A, N/A, 6
L.T.edge	F.R.edge	1, 2, 3	1	–1	1,0,0	4, N/A, N/A
L.T.edge	L.B.edge	1, 2, 3	1	–1	0,–1,0	N/A, 5, N/A
L.B.edge	R.B.edge	1, 2, 3	1	–1	0,0,–1	N/A, N/A, 6
R.B.edge	R.T.edge	1, 2, 3	1	–1	0,1,0	N/A, 5, N/A
C6	C2	1, 2, 3	1	–1	0,1,0	5
C2	C3	1, 2, 3	1	–1	0,0,–1	6
C3	C4	1, 2, 3	1	–1	1,0,0	4
C4	C8	1, 2, 3	1	–1	0,–1,0	5
C8	C5	1, 2, 3	1	–1	0,0,1	6
C5	C1	1, 2, 3	1	–1	0,1,0	5
C1	C7	1, 2, 3	1	–1	–1	4,5,6

Displacement boundary conditions

Elastic moduli	*Set*	*Boundary conditions values of*					
		Displacement DoF1	*Displacement DoF2*	*Displacement oF3*	*Rotation DoF1*	*Rotation DoF2*	*Rotation DoF3*
E11	RP4	Assigned value	Unset	Unset	Unset	Unset	Unset
E22	RP5	Unset	Unset	Unset	Unset	Unset	
E33	RP6	Unset	Unset	Assigned values	Unset	Unset	Unset

Table 8 Results obtained from ABAQUS

Specimen ID	*Longitudinal Young's modulus (GPa)*	*Rigidity modulus (GPa)*	*Poisson's ratio*
A	5.278	2.926	0.316
B	5.035	2.787	0.318
C	4.729	2.611	0.319
D	4.551	2.536	0.319

4 Results and discussion

4.1 Longitudinal Young's modulus (E_1)

Young's modulus is a measure of a material's capacity to withstand deformation when subjected to unidirectional compression or tension. The significance of Young's modulus on material stresses under load, and thus structure displacement, makes it a particularly important material parameter. Any computer simulation of structure behaviour requires engineers to know the value of this parameter.

Figure 6 Comparison of rule of mixtures, Halpin-Tsai and finite element, results for composite modulus E1 for different volume fraction of fibre (see online version for colours)

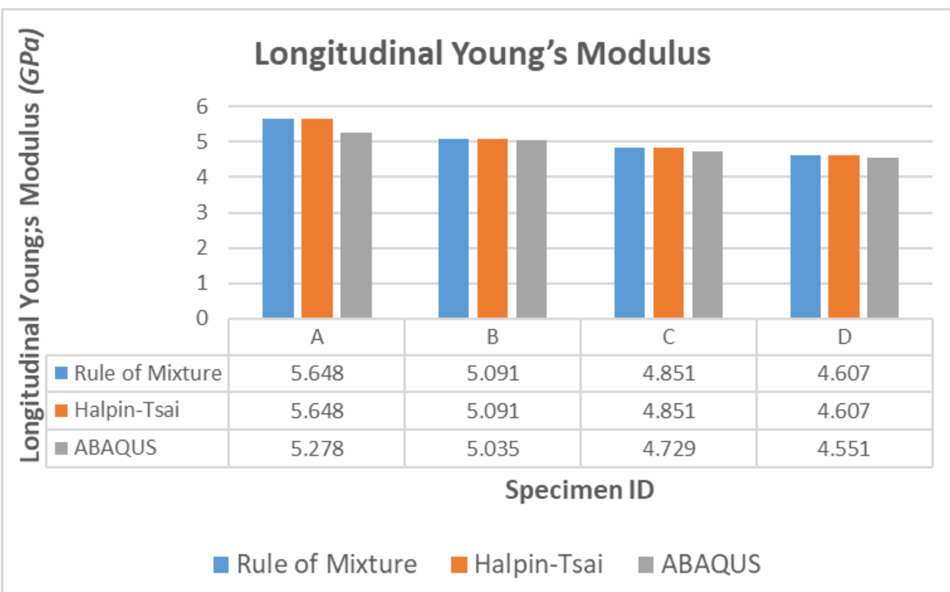
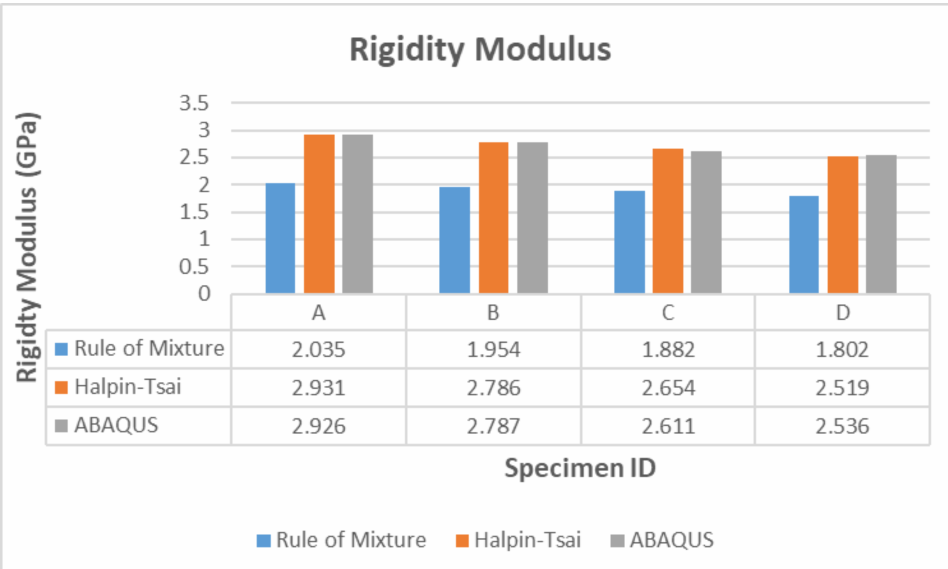


Figure 6 compares the findings of the rule of mixtures and the Halpin-Tasi finite element for composite modulus E_1 at various volume percentages. The rule of mixtures and the Halpin-Tsai analytical formulation produce the same results as the finite-element solution. The direct reliance of E_1 on fibre volume ratio is established, and the modulus increases as the fibre volume fraction grows, as expected (Naresh et al., 2021; Nagar et al., 2020).

4.2 Rigidity modulus (G)

The shear modulus is a numerical constant that characterises the elastic behaviour of any material when transverse forces are applied to it. This useful feature indicates how stable a material is to shearing deformation in advance. Shear energy will be transmitted quickly if a material is very resistant to shearing.

Figure 7 Comparison of rule of mixtures, Halpin-Tsai and finite element results for composite rigidity modulus G for different volume fraction of fibre (see online version for colours)

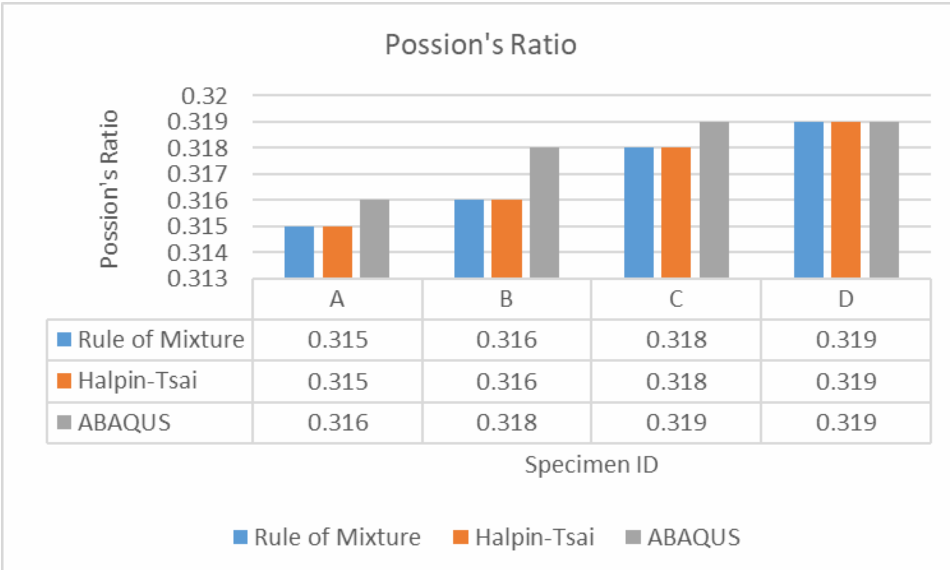


For composite rigidity modulus G at different volume fractions, Figure 7 provides a comparison of rule of mixtures, Halpin-Tsai, and finite element results. The Halpin-Tsai equation, the Rule of Mixtures model, and data from finite-element simulations are compared. In the Halpin Tsai equation, the term 'ξ' is referred to as the reinforcing factor, and it is dependent on fibre geometry, packing geometry, and loading state. The '$\xi = 2$' is adjusted to account for the variations in the composites as the fibres become circular and the packing density increases. The good agreement between finite element values in this Halpin-Tsai equation. However, there is no such parameter in the Rule of Mixture that may be evaluated for those adjustments. As a result, the rule of mixture does not appear to be in excellent agreement with finite element results (Naik and Crews, 1993; Sun and Vaidya, 1996).

4.3 Poisson's ratio

The major Poisson's ratio ϑ_{12} for the composite is defined as minus the ratio of strain in the transverse direction divided by the strain in the longitudinal direction when only the stress σ_x is applied.

Figure 8 Comparison of the rule of mixtures, Halpin-Tsai and finite element results ϑ_{12} for composite (see online version for colours)



The composite Poisson's ratio expression for the rule of mixtures is identical in form to the expression for E_1. Figure 8 shows that the analytical and numerical results are in perfect agreement, despite the fact that the values from the Rules of Mixtures is significantly less than the finite-element results.

5 Conclusions

- The required limits on the RVE under different loadings have been deduced from balance boundary conditions, producing an almost complete set of elastic constants for a 3-dimensional unidirectional composite.
- Several factors influence the mechanical properties of fibre-filled composites, including fibre type, type of matrix, fibre orientation, fibre geometry, fibre volume percentage, and the level of interfacial adhesion between the matrix and fibre.
- The HT model takes into account the polymer's modulus of elasticity (E_m), the fibre's modulus of elasticity (E_f), and the geometrical characteristic (aspect ratio) of the fibre. These components also aid in the showing of appropriate agreement with finite element data.
- The values of elastic moduli (E_1, G, v_{12}) obtained from FEA simulation when compared with those obtained from analytical method show that they are in close agreement.
- It has been found that variations in fibre volume fraction have a considerable impact on elastic characteristics.

- The values longitudinal Young's modulus, Poisson's ratio and rigidity modulus and showed an error 4.95%, 0.31% and 0.54%, respectively when compared with the values obtained from numerical method.

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