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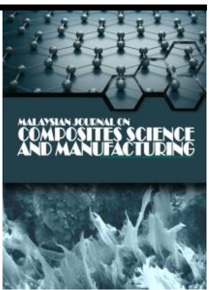

Effect of Fiber Orientation and Volume Fraction on Young's Modulus for Unidirectional Carbon Fiber Reinforced Composites: A Numerical Investigation

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ABSTRACT

The modulus of elasticity of unidirectional fiber-reinforced composites greatly depends on the fiber orientation and the fiber volume fraction. This paper investigates the effects of fiber orientation and fiber volume fraction using the commercially available Finite Element Analysis (FEA) software Abaqus. Carbon fiber is the reinforcing material, while epoxy is used as the matrix. Representative Volume Element (RVE) of the unidirectional carbon fiber reinforced composites are modeled in Abaqus, and the unidirectional tensile test is simulated to determine the modulus of elasticity for different fiber orientations and fiber volume fractions. The numerical results are verified by previously published results and by experimental results. It is found that the modulus of elasticity of the composite is maximum when the fiber inclination angle is 0°, i.e., the fibers are placed along the loading direction. As the fiber orientation angle increases, the modulus of elasticity also decreases and is almost constant after 45°. A linear increase in modulus of elasticity is observed for an increase in fiber volume fraction. This model will help the researcher to select the appropriate fiber orientation and volume fraction for a specific application.

Keywords:
Carbon Fiber, Fiber Orientation, Volume Fraction, Modulus of Elasticity

1. Introduction

The uses of fiber-reinforced composite materials are rapidly increasing day by day in various industries such as construction, automotive, aerospace, and sporting goods for their specific properties such as high strength, corrosion resistance, wear resistance, lightweight, chemically inert, and cheap, etc. [1-2]. Various natural and synthetic fibers are used in composite materials as reinforcements for these characteristics. Fiber-reinforced composite materials are increasingly being

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used to reduce aerospace vehicles' weight. These materials need to be stiffer and stronger than metallic materials while having a lower density to perform better than metals. Moreover, they must exhibit stability throughout a range of temperatures and resistance to deterioration, moisture absorption, and wear.

Numerous structural applications of advanced polymer matrix composites have been used effectively in the aircraft sector [3-4]. Carbon fibers can be utilized as fillers in the materials to enrich composite materials' thermal, electrical, and mechanical characteristics [5]. Carbon fiber-reinforced composites (CFRP) are the most common materials in the structural field. Its importance is rapidly increasing due to the rising need for greater structural and functional properties. They possess advantageous mechanical properties such as strong corrosion resistance, good flexural and tensile strength, lower value of drying shrinkage, higher value of specific heat, low value of thermal conductivity, high value of electrical conductivity, and weaker thermoelectric activity [6]. Many researchers investigated different aspects of carbon fiber-reinforced composites. Carbon fiber-reinforced epoxy composite shows behavior in a transversely isotropic manner. Many factors influence the reinforced composite's thermal, electrical, and mechanical characteristics. Such as volume fraction, composition, density, fiber orientation, fiber chemical treatment, fiber geometry, etc. The inclination of the fibers concerning the direction of loading and volume percentage of fibers are the most significant elements that affect the mechanical characteristics of the reinforced composite. However, Young's modulus has received little attention from theory, research, or computer simulation regarding this component [7].

Different analytical, numerical, and experimental approaches were utilized to evaluate the mechanical properties of composites. Such as Investigating the interaction of readily available anisotropic materials and changing their microstructural elements is possible by using numerical micromechanics models, such as Finite Element Analysis (FEA) models, which incorporate various nonlinear material behavior aspects [8]. The shear lag and various analytic designs that are predicated on simplified assumptions are mostly usable for the behavior of linear elastic materials and comparatively straightforward periodic micro geometries. They are frequently used to examine composites' multiple cracking and load transfer. In fiber bridge observation of elastic and homogeneous material cases, fracture mechanics-based models are frequently employed [9]. The Halpin-Tsai model, the rule of mixture, and periodic microstructure were used to accomplish the analytical solution for elastic characteristics. The thermal investigation also made use of the rule of mixture, the Chawla, and the Hashin models, respectively [10]. Results were examined analytically and quantitatively. Analytical techniques Nielson, Halpin-Tsai, Chamis, and the rule of the mixture were contrasted with finite element analysis [11]. To inspect the tensile properties (E and v) of Alfa-polyester reinforced composite material, both analytical and experimental processes were applied to enumerate the role of fiber inclination and volume content on the mechanical characteristics [12]. It was possible to estimate the mechanical characteristics of E-glass/epoxy-reinforced composite using the experimental methodology. Properties were assessed for various fiber orientations and fixed volume percentages. This analysis involved using tensile, compressive, flexural, and interlaminar shear tests [13]. A numerical observation regarding the onset of damage to glass fiber epoxy-reinforced composite material with single fiber and multi-fiber unit cells is also included. All fibers, homogeneous and non-homogeneous boundary surfaces, and single and different damageable sections were also discovered [14].

An audit of the Young's modulus was completed for multi-phased glass fibre epoxy-reinforced hybrid composites. The aggregate elastic modulus was calculated using the Tendon-Weng mode, strain-strain theory, and laminating analogies [15]. Furthermore, an experimental exploration was done regarding the tensile characteristics of glass-epoxy composite for various strain rates [16]. An analytical approach was adopted to determine the elastic moduli of anisotropic graphite/epoxy composite materials [8]. Another work has been done to estimate the elastic moduli for unidirectional glass-epoxy reinforced composites with the variation of fiber volume content and different fiber orientations both numerical and experimental methods [7]. An experimental and micromechanical analysis was accomplished to find out the lateral moduli of different high-moduli carbon fibers (M40, M46, and K63712). It shows that the value of transverse fiber moduli was evaluated by adopting both techniques whenever longitudinal fiber moduli increased [17].

Fiber architecture seriously influences composite materials' strength and deformation natures. Some systems are almost linear before a final brittle collapse, whilst others show a clear nonlinearity. It is discovered that both the weave architecture and the fiber volume percentage influence the composite tensile strength [18]. Different mechanical characteristics of carbon fiber-reinforced epoxy/clay nanocomposites were estimated in another research work. It was shown that clay-containing polymeric nanocomposite (CPNC) has several benefits compared to conventional polymer matrix composites. The most significant enhancements pertain to modulus, the strength of impact, heat resistance, stability of dimensions, barrier properties, flame retardancy, optics behavior, the conductivity of ions, and thermal stability [19]. Various mechanical properties of carbon fiber reinforced aluminium-based metal matrix composites were also studied [20]. The toughness and Brinell hardness of composites made of an aluminum matrix with carbon fiber reinforcement have significantly improved. The improvement of mechanical properties are the result of good wetting of the fibers. As an effect, the fibers are evenly distributed throughout the matrix. This work involved only experimental procedures. The tests included estimation of torsional properties, tensile properties, and hardness testing.

Based on the above discussion, it is clear that numerous research has been conducted to predict the behavior of fiber-reinforced composites theoretically and experimentally. However, in this work, a computational model is developed to predict the modulus of elasticity of unidirectional carbon fiber-reinforced composites with different fiber orientation angles and fiber volume fractions, which will reduce the cost of manufacturing and testing of actual composites because this model can reliably predict the modulus of elasticity.

2. Computational Details

2.1 Materials

In the current study, carbon fiber is used as the reinforcement, while epoxy is the matrix material. The mechanical properties of carbon fiber and the epoxy matrix are given in Table 1.

Table 1
Material Properties [21]

Material	Modulus of Elasticity, GPa	Poisson's Ratio
Carbon Fiber	228	0.28
Epoxy	3.79	0.35

2.2 Methodology

To investigate the effect of fiber orientation, unidirectional carbon fiber-reinforced epoxy-based composites are considered for analysis using the commercially available FEA software, Abaqus. Fiber orientations of 0°, 15°, 30°, 45°, 60°, 75° and 90° are considered for analysis. Fig. **1** shows the epoxy matrix's schematic of different fiber orientation angles. To investigate the effect of fiber volume fraction on the modulus of elasticity, fiber volume fractions of 10% to 55% are considered with 5% increments.

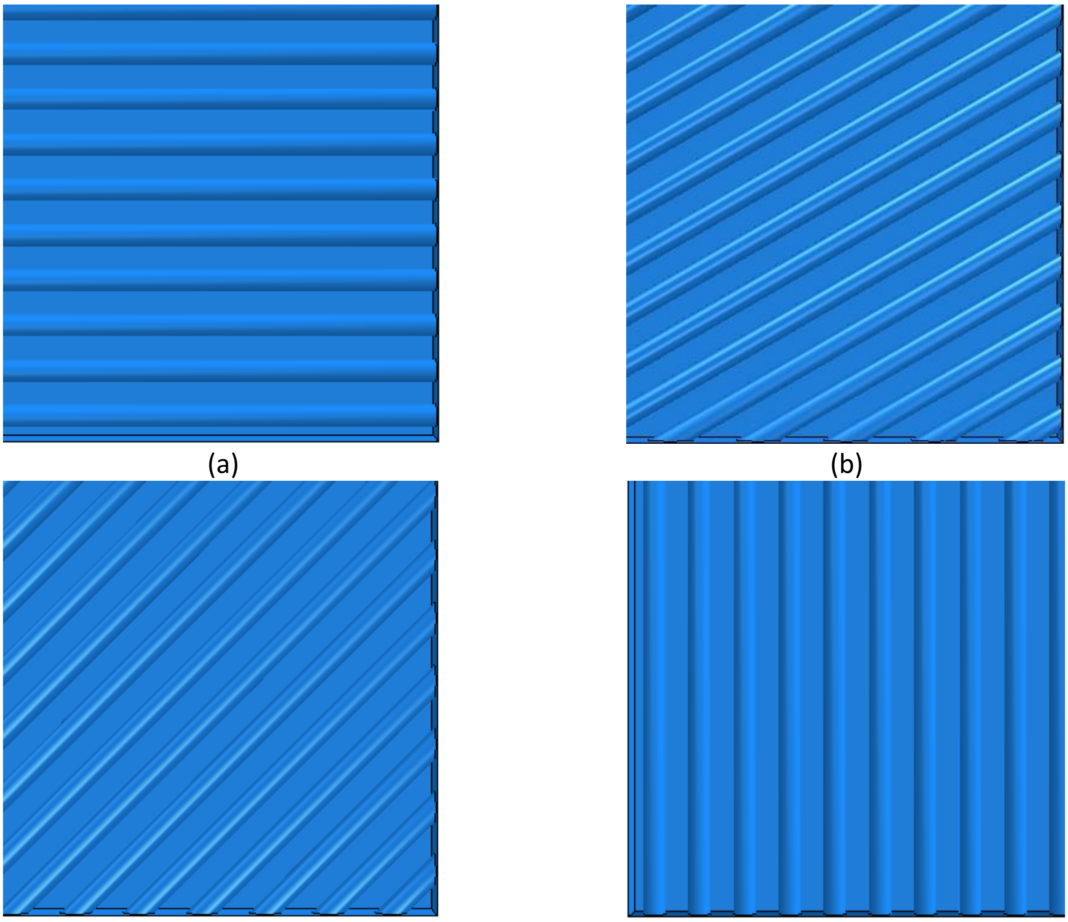

(a) (b)
(c) (d)

Fig. 1. Orientation of carbon fiber in the epoxy matrix in (a) 0°, (b) 30°, (c) 60° and (d) 90° orientation

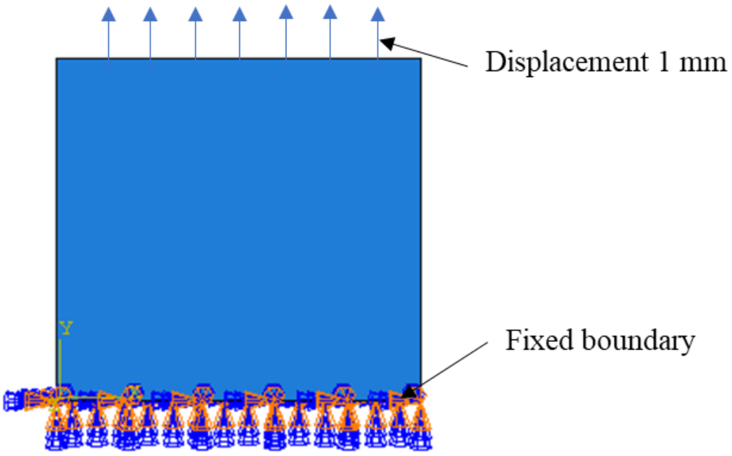


Fig. 2. Loading and boundary conditions

A linear elastic analysis is performed on the Representative Volume Element (RVE) where the bottom surface is kept fixed, as shown in Fig. **2**. In contrast, on the top surface, a fixed displacement of 1 mm was used to simulate the actual experiment on the displacement control method. An equation constraint (Eq. 1) was used on the top surface of the RVE with a reference point so that all the nodes on the top surface are tied with the reference point only in the vertical direction, and the fixed 1 mm displacement was applied on that reference point. The equation constraint ensures that all the node points on the top surface experience a displacement of 1 mm.

$$u_2 \; of \; top \; surface - u_2 \; of \; reference \; point = 0 \tag{1}$$

where the top surface indicates the top surface of the RVE, the reference point is a point chosen on the top surface, and u_2 is displacement along the vertical direction (y-direction).

C3D10R elements were used to mesh the RVE in Abaqus, a 3-dimensional 10-node quadratic tetrahedral element with reduced integration. This element type is suitable for modeling irregularly shaped geometry for stress analysis. Fig. **3** shows the typical mesh on the RVE.

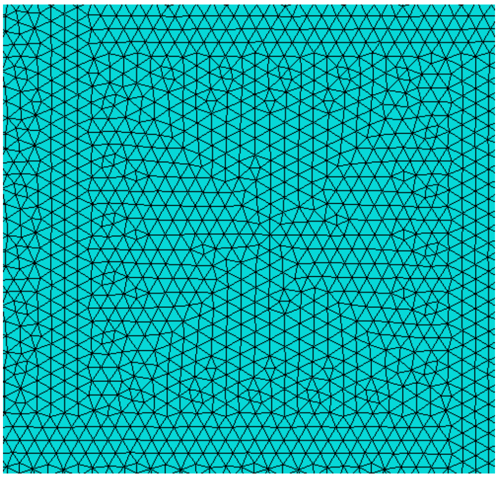


Fig. 3. Typical tetrahedral elements on an RVE

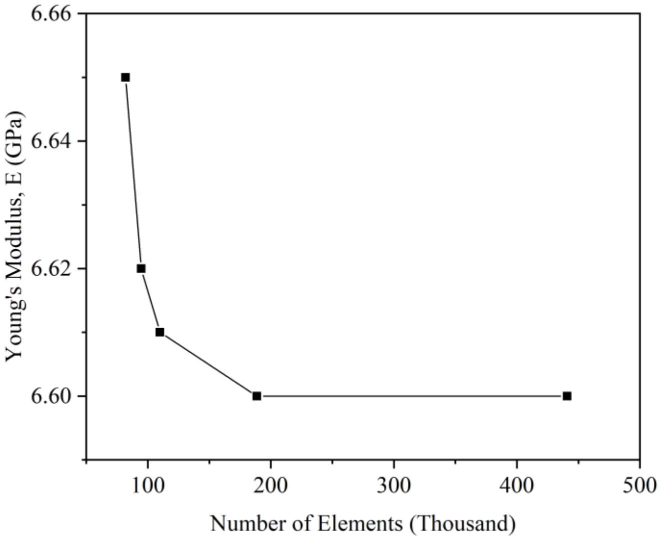


Fig. 4. Variation of modulus of elasticity with number of elements for 45° orientation

Mesh sensitivity analysis was performed on each of the models since the geometry of the models is different, and the mesh was refined so that the results do not depend on the mesh size. A global mesh size of 0.125 mm was used for all the models, and approximately 440000 elements were used for all the models. The number of elements for all the models is not fixed because the fiber orientation angle in each model is different, which causes a slight change in the geometry that eventually changes the number of elements in the models. Fig. **4** shows the variation of the modulus of elasticity with a 45° fiber orientation. It is found from this figure that the modulus of elasticity is reduced with the increase in the number of elements. When the number of elements is approximately 190000, the value of the modulus of elasticity becomes constant. So, if the number of elements is greater or equal to 190000, then the computational results do not depend on the mesh size.

3. Results and Discussions

3.1 Model Validation

Wang et al. [7] predicted the modulus of elasticity of glass fiber-reinforced polymers (GFRP) at different fiber orientation angles with 20% fiber volume fraction. In the present analysis, the variation of GFRP with a 20% fiber volume fraction was also analyzed, and Fig. **5** shows the comparison of the modulus of elasticity found from the present model with that of Wang et al. [7]. It is observed from the figure that the present model coincides with Wang et al. with a maximum variation of 1.1% for a 15° fiber orientation angle.

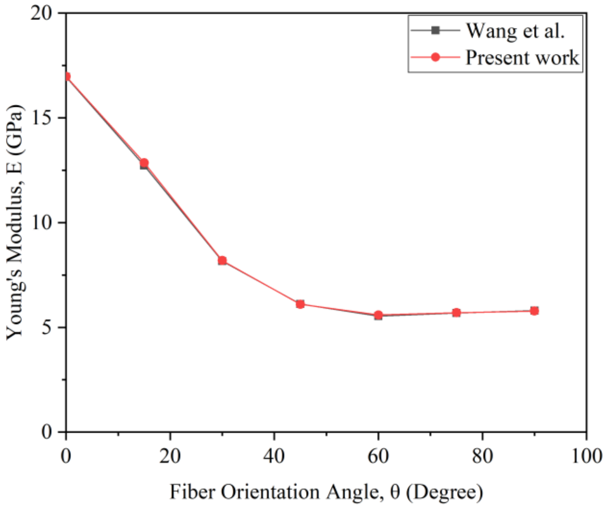
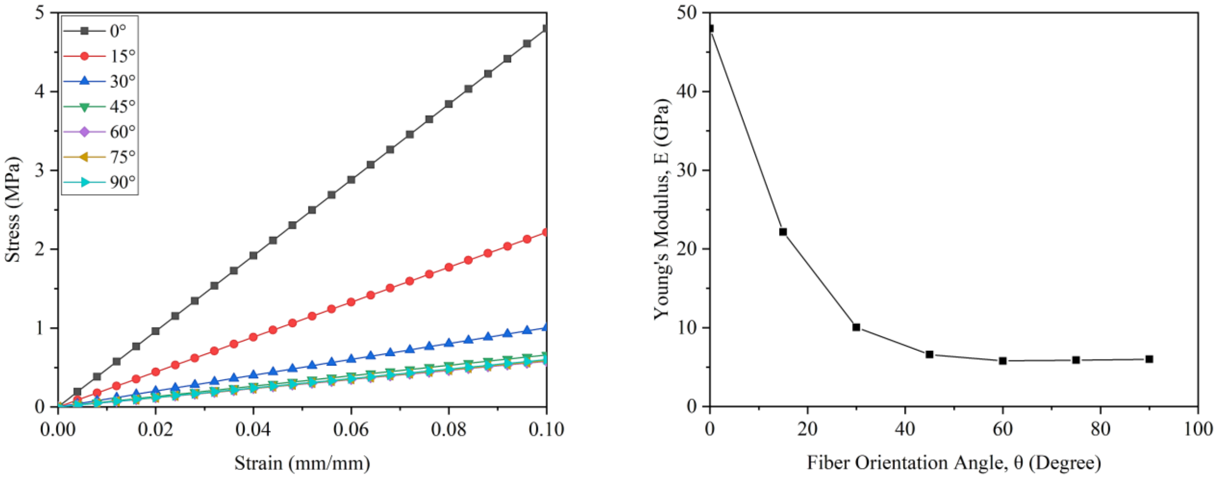


Fig. 5. Variation of modulus of elasticity with fiber orientation angle for GFRP

Unidirectional glass fiber reinforced polymer composite with 20% fiber volume fraction with epoxy matrix was fabricated using the hand lay-up technique and the tensile test was performed on the manufactured laminate both in the longitudinal (0° fiber orientation) and transverse direction (90° fiber orientation). The modulus of elasticity along the longitudinal and transverse directions was 16.73 GPa and 2.67 GPa, respectively, taken from the experiment. The numerical results found for this particular fiber ($E = 72$ GPa and $\nu = 0.22$) and epoxy ($E = 1.81$ GPa and $\nu = 0.29$) are 18.61 GPa and 2.88 GPa along the longitudinal and transverse directions. This shows a variation of 11.24% and 7.85% from the experimental results, which are very close. The current model is validated using both the computational work by Wang et al. and experimental results, and this model is in good agreement with previously published computational results and experimental results and can be utilized for further analysis.

3.2 Effect of Fiber Orientation

The stress-strain diagram of the RVE for different fiber orientation angle is shown in Figure 6(a). It is observed from this figure that the slope of the stress-strain diagram for 0° fiber orientation is maximum which suggests that the modulus of elasticity for 0° fiber orientation will be maximum. Figure 6(b) justifies this statement where the variation of modulus of elasticity for CFRP with different fiber orientation angles is shown. It is observed from this figure that the modulus of elasticity decreases with the increase in the fiber orientation angle, and it is maximum (48 GPa) for the 0° orientation and sharply decreases with the increase in orientation angle up to 30° and then gradually decreases up to 90°. This is because when the angle is 0° the entire load is carried by the fiber, which is load bearing element but when the orientation angle increases, a part of the load is carried by the fiber. The remaining part is carried by the matrix, which has a lower mechanical property than the fiber. The modulus of elasticity is minimum for the 90° fiber orientation because this represents the transverse direction of the CFRP laminate, and the mechanical property along this direction is dominated by the matrix [3].



(a) (b)

Fig. 6. (a) Stress-strain diagram and (b) variation of modulus of elasticity with different fiber orientation

The rule of mixture, as shown in Eq. 2 was also used to calculate the modulus of elasticity for 0° fiber orientation.

$$E_c = E_f V_f + E_m (1 - V_f) \tag{2}$$

where E_c, E_f and E_m are the modulus of elasticity of the composite, fiber and matrix, respectively, while V_f is the fiber volume fraction. The modulus of elasticity of the composite found by using the rule of mixture is 48.63 GPa, and the modulus of elasticity found from the present analysis is 48.00 GPa. The present model's deviation from that of the rule of mixture is 1.30%.

3.3 Effect of Fiber Volume Fraction

Fig. **7** shows the variation of modulus of elasticity with fiber volume fraction. This figure shows that the modulus of elasticity of unidirectional CFRP laminate increases linearly with the increase in fiber volume fraction, which is also observed by Pramudia et al. [22]. The following equation can express the variation-

$$E = 2.25V_f + 3.79 \tag{3}$$

where E represents the modulus of elasticity of the laminate in GPa and V_f represents the fiber volume fraction. It is observed from Eq. 3 that when the fiber volume fraction is zero then the modulus of elasticity is equal to the modulus of elasticity of the matrix as no fiber is being used in the laminate. Although, the increase in fiber volume fraction increases the modulus of elasticity practically the fiber volume fraction is kept within the limit between 40% to 50% [23], because a further increase in the fiber volume fraction increases the void percentage and fiber agglomeration which affects the interfacial bonding between the fiber and the matrix and hence reduces the modulus of elasticity along with other mechanical properties.

The von Mises stress distribution for 10% and 40% fiber volume fraction is shown in Fig. **8**. It is found that the maximum von Mises stress for a 10% fiber volume fraction is 17.38 MPa while for a 40% fiber volume fraction, it is 29.44 MPa. If the fiber volume fraction is increased by 30%, then the maximum von Mises stress is increased by 69.39%. This is because the fiber carries the maximum load and when the fiber content increases, maximum von Mises stress increases, as shown in Figure 8.

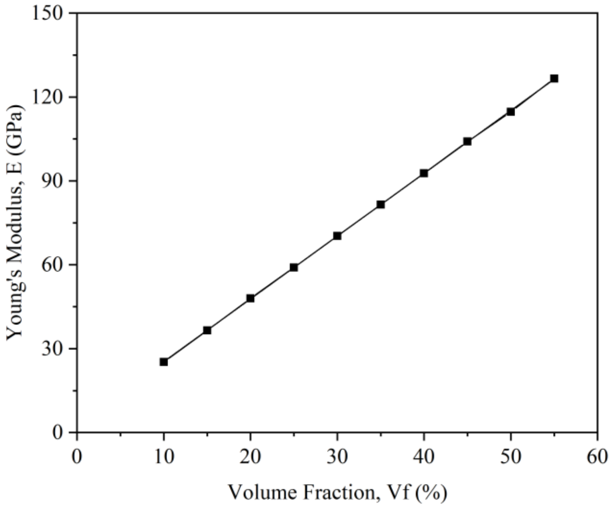
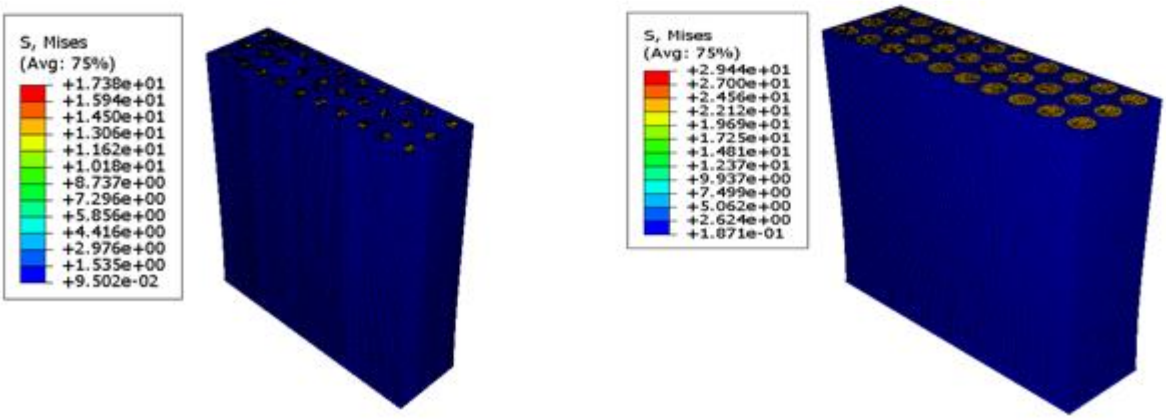


Fig. 7. Variation of modulus of elasticity with fiber volume fraction



(a) (b)

Fig. 8. Von-Mises stress distribution for (a) 10% and (b) 40% fiber volume fraction

4. Conclusions

This paper analyses the influence of fiber orientation and volume fraction on the modulus of elasticity in a unidirectional carbon fiber-reinforced epoxy composite. The investigation was conducted using the numerical simulation software Abaqus. The findings of this study reveal that the highest modulus of elasticity is 48 GPa when the fiber orientation is at 0°, and it gradually decreases as the orientation angle increases. Moreover, the modulus of elasticity demonstrates an upward trend with increasing fiber volume fraction. The maximum von Mises stress also increases as the fiber volume fraction increases. For a 30% increase in the fiber volume fraction, the modulus of elasticity is increased by 69.39%. This research provides valuable insights into the mechanical behavior of carbon fiber-reinforced unidirectional composite materials.

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