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Research Article

Investigation of mechanical properties and damage types of E-glass fiber reinforced epoxy matrix composites under various loadings

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ABSTRACT

This study presents a comprehensive experimental investigation to determine the elastic material properties of a unidirectional E-glass fiber/epoxy composite. Tension, compression, in-plane shear, and flexural tests were conducted in both longitudinal and transverse directions. The composite laminates were manufactured using vacuum-assisted resin transfer molding (VARTM) with a 65% fiber weight fraction. Mechanical tests were performed according to ASTM standards, and special fixtures were used for shear and compression tests. The damage mechanisms were interpreted for each test, revealing fiber splitting in tension and kink band failure in compression were dominant damage modes. The findings provide valuable insights into the behavior and performance of the composite under various loading conditions, which may help in its application in different engineering fields.

1. Introduction

Polymer matrix composites find widespread utilization in various fields like aerospace, automotive, marine, and defense due to their remarkable properties, including high stiffness and strength-to-weight ratio, low density, and exceptional impact resistance [1-5]. Moreover, these composites offer design flexibility through options like fiber orientation [6], hybridization variations [7-11], and stacking sequence [12-13]. These materials exhibit the ability to carry the extensive loading until they fail by various damage mechanisms, including delamination [14], matrix cracking [15] and fiber breakage [16-17]. Glass fiber reinforced polymer matrix composites have been using in various application area such as ballistic impact [18-21], shock response [22] and low velocity impact [23-27]. Dong and Davies [28] investigated the flexural properties of glass and carbon fiber reinforced epoxy matrix hybrid composites. They presented composites using three combinations of carbon and glass fibers, namely S-2&T700S, S-2&TR30S, and E&TR30S. They determined that compressive failure was the dominant mode of failure. To gain further insights, finite element analysis was employed to simulate flexural behavior. Both experimental results and finite element analysis indicated that the flexural modulus decreased as the percentage of glass fibers increased. Additionally, substituting carbon fibers with glass fibers on the compressive surface showed positive hybrid effects.

Evci and Gülgeç [23] studied impact response of unidirectional E-Glass, woven E-Glass, and woven Aramid composites. The research revealed that woven composites surpass unidirectional composites in their ability to withstand low-velocity impacts, and furthermore, damage propagation within woven composites was limited with a smaller area. It is concluded that the strength of the composite materials significantly increases under dynamic loading in comparison to static loading due to their sensitivity to strain rate.

Subagia and Kim [29] carried out a series of experimental studies to understand flexural properties of carbon-basalt/epoxy hybrid laminates. They revealed an approximate solution for flexural strength and modulus of the hybrid composite depending on the number of basalt fabrics. The flexural properties of carbon-basalt/epoxy hybrid composites were found to be highly influenced by stacking sequence of the carbon and basalt fabric layers.

Baky et al. [30] studied tensile, flexural and impact properties of flax/basalt/E-glass fibers reinforced epoxy composites. There was a noticeable improvement in the flexural and impact resistances of the material by

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incorporating high-strength fibers into the outer layers of the composite. However, it was observed that this enhancement in performance came at the cost of reduced tensile properties. In other words, the composite exhibited improved resistance to bending and impact loadings but experienced a decrease in its ability to withstand tension loadings. This trade-off between flexural/impact properties and tensile properties should be carefully considered when selecting the optimal fiber arrangement for specific engineering applications.

Fiber, matrix, and interface properties of composites have an effect on in-plane shear behavior of polymer matrix composites [31]. It has been observed that shear behavior of carbon fiber reinforced epoxy matrix composites includes two regions. One of these is controlled by matrix yielding and the second is controlled by elastic deformation of reinforcement material. Yield strength of matrix and interface strength properties are the key parameter on in-plane shear behavior of composite materials while the properties of reinforcement material have no effect on it.

This study has been presenting a series of experimental studies including tension, compression, in-plane shear, and flexural tests to get elastic material properties for using them in numerical studies. Each of the experiments was conducted in both 0° (longitudinal) and 90° (transverse) directions. Additionally, damage mechanisms were interpreted for tension, compression, in-plane shear, and flexural test. The specific results obtained throughout this study will be a data set for numerical studies which includes unidirectional E-glass reinforced epoxy matrix composites.

2. Materials and Method

330 g/m^2 areal density unidirectional (UD) E-glass fiber fabric and Araldite LY1564/Aradur 3486 epoxy resin/hardener were used in this study. The hardener was used 34 g for 100 g of epoxy resin as described in datasheet. 12 layers of fabric was used to obtain 3 mm of thickness plate (Figure 1). The composite plate was manufactured by vacuum-assisted resin transfer molding (VARTM) method. First, the aluminum plate was heated, and epoxy resin mixture was transferred through resin flow medium (Figure 1b) into the UD E-glass fabrics and kept under 100 °C for 1 h. Then, it was cooled to the room temperature for 24 h. Tabbing with same material was applied to tension and compression test specimens to prevent specimens from crushing. 65% fiber weight fraction (w_f) was determined by dividing used fabric weight (W_f) to composite plate weight (W_c) after cutting process as shown in Equation (1). Specimens were cut via CNC water jet machine (Figure 1f).

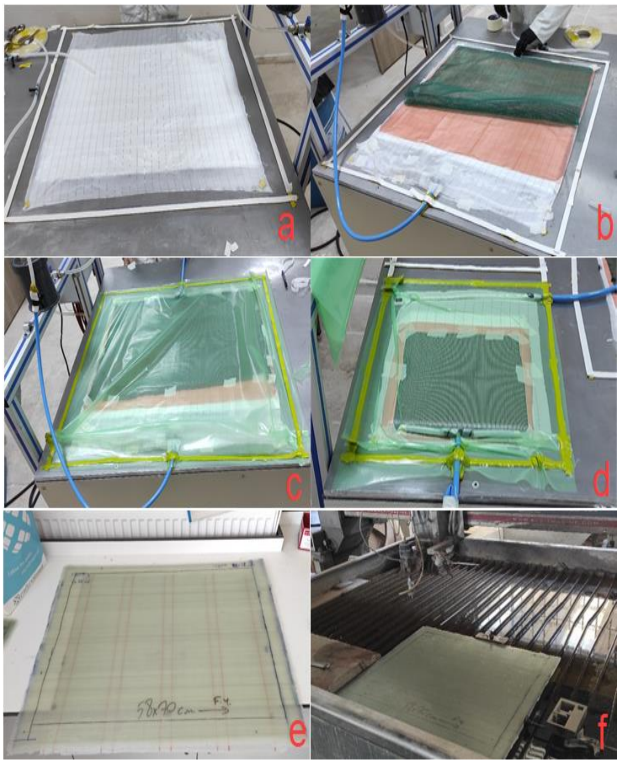

Figure 1. Manufacturing and sample preparation steps for composite plate. a) Application of sealant tapes and peel ply (white color), b) putting release film (orange color), resin flow medium (dark green color), polyethylene tube (blue color) c) covering vacuum bagging film (green color), d) after vacuum was applied, e) obtained composite plate, f) positioning of composite plate on CNC water-jet machine for cutting test samples.

The mechanical tests were conducted using a universal electromechanical test device equipped with a 50 kN load cell (Shimadzu AGSX series, manufactured by Shimadzu Scientific Instruments). Tension, in-plane compression, in-plane shear test and flexural tests were performed according to ASTM D3039, ASTM D6641, ASTM D7078, ASTM D790 standards, respectively. During the experiments, the tensile and shear samples were subjected to a test speed of 2 mm/min, while the compression and flexural samples were tested at a speed of 1.3 and 1 mm/min, as specified in the corresponding ASTM standards. To prevent buckling during the compression tests, the gage length of the samples was set at 13 mm. Special test fixtures were manufactured for the shear and compression tests. The complete set of mechanical tests applied to the composite samples can be found in Figure 2a-d.

$$w_f = \frac{W_f}{W_c} \quad (1)$$

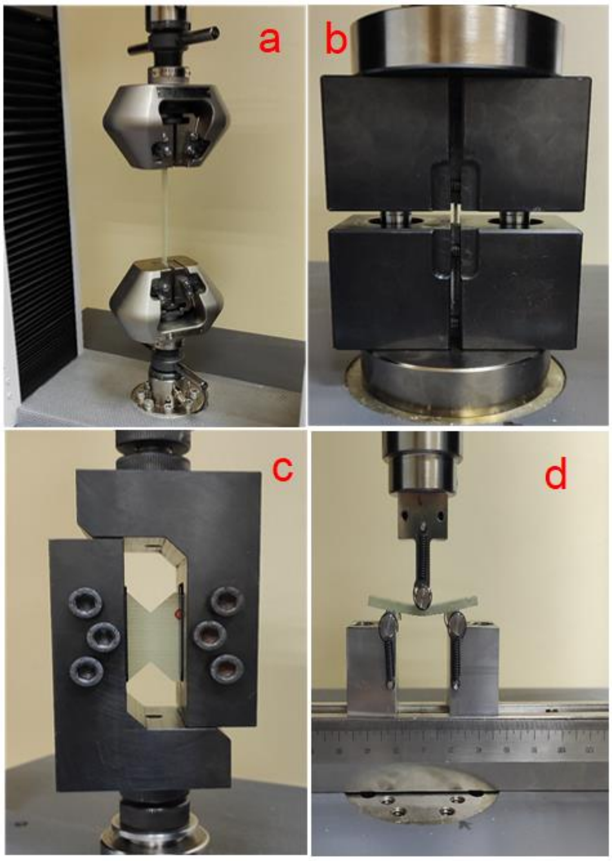

Figure 2. Mechanical test fixtures which were used throughout the study. a) Tension, b) in-plane compression, c) in-plane shear (V-notched) test, d) flexural test.

Among various shear tests such as short-beam shear, two-rail shear, three-rail shear, and +45° tensile shear available for composites, the V-notched rail shear test was selected for its ability to apply a uniform shear stress to the test samples. To ensure accurate and reliable results, the bolts of the shear test apparatus were tightened to a torque of 55 Nm. Using a torque lower than this value could potentially lead to slipping of the sample between the grips, which could compromise the test results. By applying the appropriate torque, the shear test apparatus would firmly hold the specimen in place, preventing any undesired movement during the test.

3. Results and Discussion

The mechanical properties of the UD E-glass fiber/epoxy composite, with a fiber weight ratio of 65%, were determined through various tests, including tensile, compression, in-plane shear, and flexural tests (Figure 3 and 4). In the case of the tensile test at longitudinal direction, the sample failed at 628.4 MPa of stress and 5.62% of strain while these values were 73.57 MPa and 2.83% for the tensile test at transverse direction. For compression test, the maximum compression strength and failure strain were determined as 375 MPa and %23 at longitudinal direction while they are 118 MPa and 15.5% for transverse compression test. Additionally, the maximum shear stress was observed at 56.68 MPa at the strain of 17.8% for longitudinal direction and 51.3 MPa and 18% for transverse direction. Finally, maximum load observed in flexural test was 1.93 kN at 3.33 mm displacement for longitudinal direction while they were 0.484 kN at 2.62 mm displacement value for transverse direction.

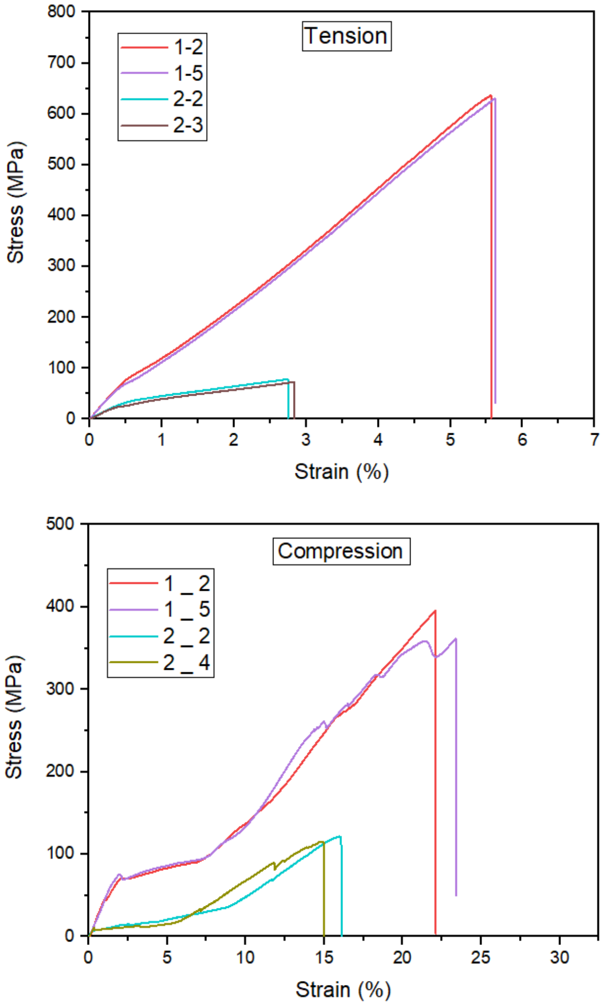

Figure 3. Tension and compression results of unidirectional E-glass fiber reinforced composite

For V-notched shear test curves, the results of both fiber direction (0° and 90°) specimen behavior are similar to each other until their maximum loading point. Sudden load drop has been occurring in transverse direction specimen because the loading and fiber have the same direction. This situation will force the specimen for shear breakage as can be seen in Figure 6a (specimen 2-4). On the other hand, fibers have been performing extension because the fibers are perpendicular to the loading direction like in Figure 6a (specimens 1-3 and 1-4). The loading in the V-notched shear test for the specimens having longitudinal direction is not like a pure tensile loading, that’s why the fibers did not break at the low strain values like in tensile test.

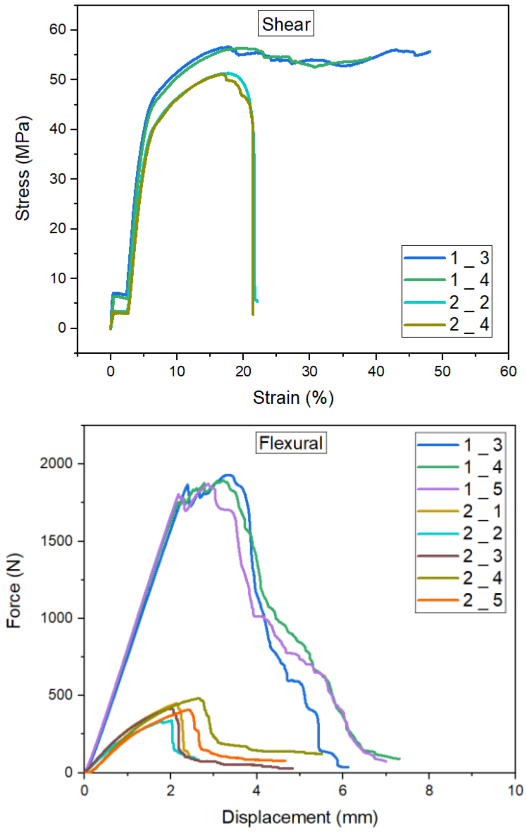

Figure 4. Shear and flexural test results of unidirectional E-glass fiber reinforced composite

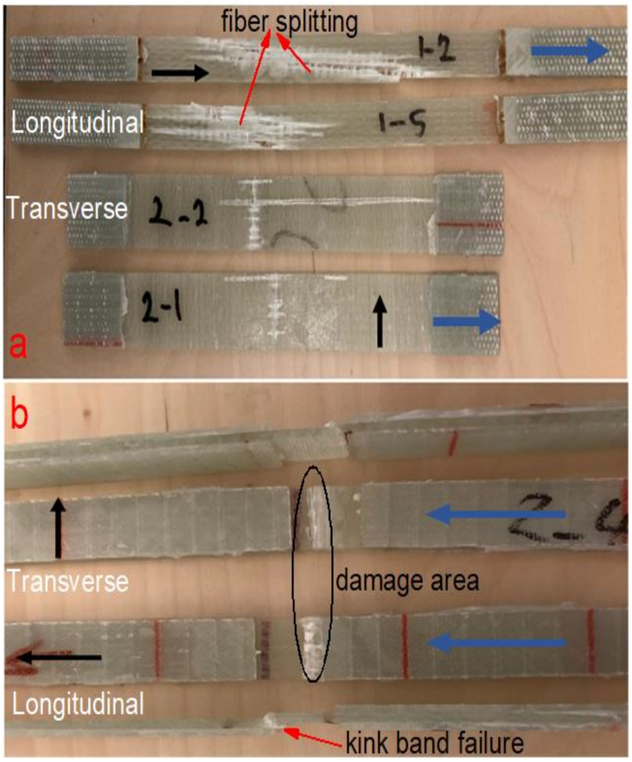

Figure 5. Damage patterns occurred at the end of a) 0° (longitudinal) and 90°(transverse) tension, b) 0° and 90° compression test. Blue arrows indicate loading direction. Black arrows indicate fiber direction.

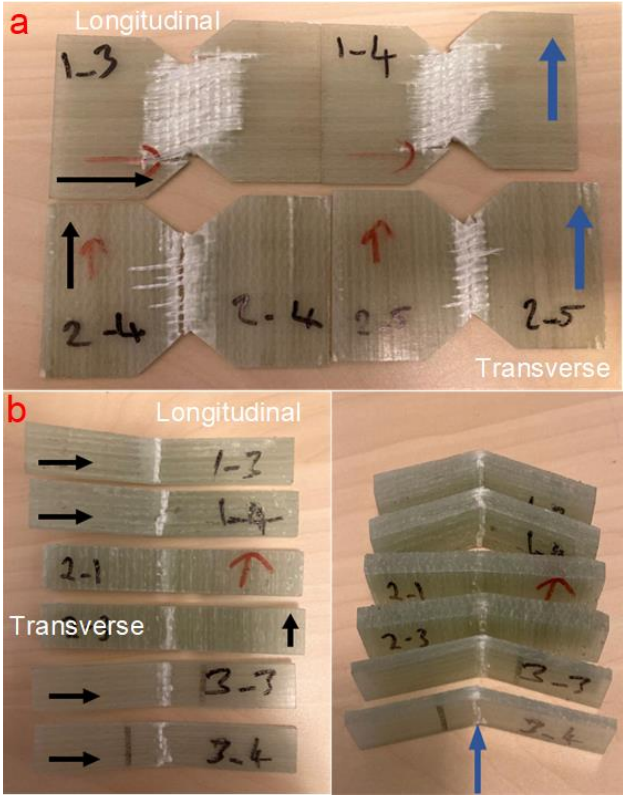

Figure 6. Damage patterns occurred at the end of a) 0° and 90° shear, b) 0° and 90° flexural test. Blue arrows indicate loading direction. Black arrows indicate fiber direction.

In Figure 4, the flexural test curves perform a linear elastic behavior until 2 mm deflection values. At this point, the matrix cracking started, and it caused small vibrations in the curves. Then the load drastically drops due to the fiber breakage [32].

Figure 5a and 5b show damage zones that occurred at the end of tension and compression tests in longitudinal and transverse directions. Fiber splitting damage mechanism is dominant in 0° (longitudinal) test specimens (1-2 and 1-5). There is no damage around tab region, so it can be said that experiments are valid [33]. For transverse direction, a discontinuity was observed in specimen 2-2. One of the fiber bundles failed throughout tabbing. On the other hand, the curve of specimen 2-2 in Figure 3 does not include any instability. Edge delamination failure can be seen in specimen 2-1. It means the stress waves propagated through the edge due to the fiber direction.

In Figure 5b, damage occurred in the gage section, and it is close to the tabbing because gage length is 13 mm. Herein, side views are important to understand whether experiments are valid or not. If there is no propagated damage through the edges of specimen, it may be assumed experiment is valid [33]. Kink band failure can be seen at the below specimen in Figure 5b because compression loading was applied in longitudinal direction. This type of failure has been commonly observed in longitudinal compression [34-35].

Table 1. Mechanical properties of E-glass fiber reinforced epoxy matrix composite material

Experiment	Modulus (GPa)	Strength (MPa)	Strain at failure (%)
0°-Tensile	16.53	636	5.62
90°-Tensile	6.81	73.57	2.83
0°-Compression	3.75	375	23
90°-Compression	0.31	118	15.5
In-plane shear	1.18	56.68	18

Figure 6a presents in-plane shear test specimens for 0° and 90° fiber direction. When this figure is evaluated with shear test curves in Figure 4, it will be more understandable. The first difference between the two specimens is the damage area. In specimens 1-3 and 1-4, fiber direction is vertical to the loading direction. This is the reason why the damage area in 1-3 and 1-4 is bigger than 2-4 and 2-5. Fibers in specimens 1-3 and 1-4 have been subjected to tension-dominated loading.

These mechanical test results provide valuable insights into the behavior and performance of the UD E-glass fiber reinforced epoxy matrix composite under different loading conditions, contributing to a better understanding of its mechanical properties and potential applications.

4. Conclusions

Tension, compression, in-plane shear, and flexural tests were performed in both longitudinal and transverse directions to characterize the material behavior under various loading conditions. The results of this study provide valuable insights into the mechanical behavior and performance of the E-glass fiber reinforced epoxy composite. The key findings from the mechanical tests are summarized below:

- In tension tests, the composite exhibited a tensile strength of 628.4 MPa and 73.57 MPa in the longitudinal and transverse directions, respectively. The corresponding strain at failure was 5.62% and 2.83%, highlighting the anisotropic nature of the material.
- In compression tests, the composite displayed a maximum compression strength of 375 MPa in the longitudinal direction and 118 MPa in the transverse direction, with failure strains of 23% and 15.5%, respectively.
- The maximum shear stress observed was 56.68 MPa for longitudinal shear and 51.3 MPa for transverse shear, both at a strain of 18%. In flexural tests, the composite exhibited a maximum load of 1.93 kN and 0.484 kN for longitudinal and transverse flexure, respectively. All mechanical properties were presented in Table 1.

Fiber splitting was identified as the dominant failure mode in tension tests, while kink band failure was prominent in compression tests. In-plane shear tests showed varying damage areas depending on the fiber orientation.

These comprehensive mechanical characterizations provided essential material model parameters for future numerical studies and simulations involving this E-glass fiber reinforced epoxy composite. The presented mechanical properties data, including modulus, strength, and strain at failure, can serve as a fundamental for modeling and predicting the behavior of this material in various engineering applications.

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