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Experimental Investigation on Tensile Property of Plain-Woven Glass/Polyester Composite

Yusuf Sahin
OSTIM Technical University

Halil Ridvan Oz
OSTIM Technical University

Ceren Cetinkaya
OSTIM Technical University

Abstract: Due to their cost efficiency and superior mechanical properties, Glass Fiber-Reinforced Polymer (GFRP) composites are attracting increasing attention across various industrial sectors, including aeronautics, automotive, marine, chemical, and sporting goods industries. This study investigates the tensile behavior of plain-woven GFRP laminates through experimental characterization. The laminates were fabricated using unsaturated polyester resin via the Vacuum Bagging (VB) technique, employing a single stacking sequence of $[0/90°]_5$. Uniaxial tensile tests were conducted in accordance with ASTM standards. In addition, Hooke's law equations for two-dimensional composites were applied to determine the local stresses and strains in each ply. The results demonstrated a high sensitivity of tensile properties to fiber orientation. The $[0/90°]_5$ laminates tested at 0° orientation exhibited the highest tensile strength of 317 MPa and a Young's modulus of 18.94 GPa, while specimens tested at 30° orientation showed significantly reduced performance, yielding a tensile strength of 114 MPa and a Young's modulus of 10.6 GPa. Furthermore, the maximum and minimum local stresses (σ_1) in the 1st and 2nd plies were approximately 4.085×10^4 Pa and -1.63×10^4 Pa, respectively, for the glass/epoxy lamina, while the corresponding maximum and minimum strains (ε_1) in the 1st and 2nd plies were approximately 9.9×10^{-7} and 7.785×10^{-8}, respectively.

Keywords: GFRP; Polyester resin, Vacuum bagging, Tensile properties, Young's modulus, Fiber orientation, Plain-woven fabric, Laminate

Introduction

Composite materials are advanced multiphase systems consisting of continuous fibers or fabrics embedded within a polymer matrix. By combining two or more constituents, these materials overcome the limitations of their individual components, offering high specific stiffness/stiffness, higher corrosion resistance, design flexibility and lightweight properties. As a result of these properties, Glass Fiber Reinforced Polymers (GFRP) and Carbon Fiber Reinforced Polymers (CFRP) have become primary materials in the automotive, aerospace, and marine sectors (Zhang &Xu, 2022; Sarfnaz et al., 2021; Mallick et al., 2020). While carbon fibers offer superior stiffness and sterngth, but very britlle and costly. Due to cost-efficiency alongside mechanical performance, especially for impact behavior, glass fibers are often preferred in practical applications, such as wind turbine blades (Steigmann et al.2016; Mishnaevsky et al.2017). The mechanical performance of GFRP is significantly influenced by fiber loading and volume fraction (Kumar &Singh, 2021). While unidirectional (UD) composites provide exceptional properties along the fiber axis, textile (woven) composites have gained prominence in aerospace for their improved toughness, ease of handling, and near-net-shape manufacturing capabilities. However, the interlaced architecture of warp and weft yarns introduces complex stress distributions, making analytical modeling challenging (Selek & Sahin, 2023; Uzay et al. 2024).

Recent literature highlights the sensitivity of GFRP to external factors. Some sesearches on GFRP showed that hygrothermal effects, alkaline environments can reduce tensile strength by over 60%, a degradation often accelerated with high temperatures or sustained mechanical loads (Bazli et al., 2019, Bazli et al., 2026; Tefera et al., 2022; Zhu et al., 2022; Jin et al., 2020). Furthermore, GFRP exhibits rate-dependent behavior; Ou et al. (2016) noted a nearly 50% increase in tensile strength under high strain rates, though Young's modulus remains more sensitive to temperature than loading speed. Naito (2022) studied the **s**tatic and fatigue tensile properties of carbon/glass hybrid fiber-reinforced epoxy composites. Explores the hybridization of PAN-based carbon (IMS60) and E-glass fibers. Static loading results showed linear stress-strain behavior for most hybrids, but specific layups ([E-glass/IMS60]) displayed jagged failure traces, indicating progressive internal damage. Huang et al. (2025) studied the experimental investigation of static strength in CFRP and Aluminium Lugs subjected to uniaxial tensile loading. This study compares twill woven CFRP lugs with conventional aluminum (L-Al). Experimental results show that Quasi-Isotropic layups can surpass aluminum in load-bearing capacity (450-550 MPa), while "soft" layups exhibit matrix cracking near bore holes that mimics metallic stress relief.

Lopresto et al. (2024) showed that mechanical characterisation of basalt fibre reinforced plastic: A comparison with glass-fibre reinforced composite (BFRP) under the same conditions. It is proved that BFRP has 25% higher impact and tensile strength than GFRP under the same conditions. Şahin and Selek (2025) showed that BFRP strength drops sharply when the load applied at 45° to the fiber direction, highlighting high anisotropy, in terms of fiber orientation. Dorigato and Pegoretti (2025) concluded that the tensile results had superior for BFRP before the first ply failure (FPF) compared to E-glass. Biswas et al. (2011) experimentally investigated that effect of fiber orientations on mechanical behaviors of glass fiber/epoxy composites. It is found that the 30° fiber orientation composites showed that superior microhardness compare with other fiber orientations irrespective of fiber loading. Similar studies on the effect of fiber orientation on the mechanical behavior are conducted at various composites (Kaw, 2006; Şahin, 2022, 2024; Ozsoy, 2015; Vinay et al., 2022), most of them reported the conflicting results, which are related to performance of tensile strengths, especially woven fabric reinforced composite in terms of bi-directional (warpt or fill) testing conditions.

In the present study, therefore, GFRP plates were manufactured using a VB technique with an polymeric resin. Uniaxial tensile tests were conducted to determine the elastic modulus and ultimate tensile strength of five-layer plain-woven laminates with stacking sequences of ($[0/90°]_5$). The primary objective is to determine the mechanical properties such as tensile strength, elongation and elastic modulus using standard testing machine, and tested under 0° and 30° orientation. Moreover, the stresses generated among the layers of the glass/polyester lamina was estimated using 2D stress-strain of Hooke law's equations.

Materials and Methods

Materials and Manufacturing

In this study, glass fiber–reinforced polymer (GFRP) composite laminates were manufactured using the VB technique. The reinforcements consisted of five layers of plain-woven glass fiber fabrics, supplied by Spinteks Tekstil İnşaat San. and Tic. A.Ş. The fabric possessed an areal density of 200 g/m². The matrix system used was unsaturated polyester resin, selected for its high mechanical strength and chemical resistance. The physical and mechanical properties of the constituent materials are summarized in Table 1 (Manufacturer's data sheet).

Table 1. Mechanical and physical properties of the reinforcing fibers and matrix.

	Polyester Resin	Glass Fibers	Unit
Density	1.12-1.15	2.6	g/cm^3
Elastic modulus	3.0-3.2	72	GPa
Tensile strength	65	2000	MPa
Tensile elongation	2.6-4.0	2.8	%

The composite plates, with nominal dimensions of 400 times 400 times mm^2, were designed with three distinct symmetrical stacking sequence of ($[0/90°]_5$) configuration, resulting in laminates with an average thickness of approximately 1.0 mm. The laminates were fabricated using the VB process. Following the stacking of the 5 plies, the laminates were subjected to a curing cycle at 80ºC for a duration of 8 hours. The fiber volume fraction (Vf) of the laminates was 0.55. After resin impregnation, the thickness of each layer was determined to be approximately 0.185 mm, and the total laminate thickness was approximately 1.1 mm. After curing, the plates were precision-cut into test specimens at orientations of 0°, 30° using water-jet cutting to minimize heat-affected zones and ensure edge quality.

Tensile Testing

Tensile tests were conducted to evaluate the mechanical performance of the manufactured laminates. The experiments were performed at the Middle East Technical University Central Laboratory using a ZwickRoell ProLine Z010 Universal Testing Machine (UTM). Tests were carried out at a constant cross-head speed of 2 mm/min in accordance with international standards, as shown in Figure 1. For each laminate configuration, five specimens were tested, and the results were averaged to ensure statistical reliability.

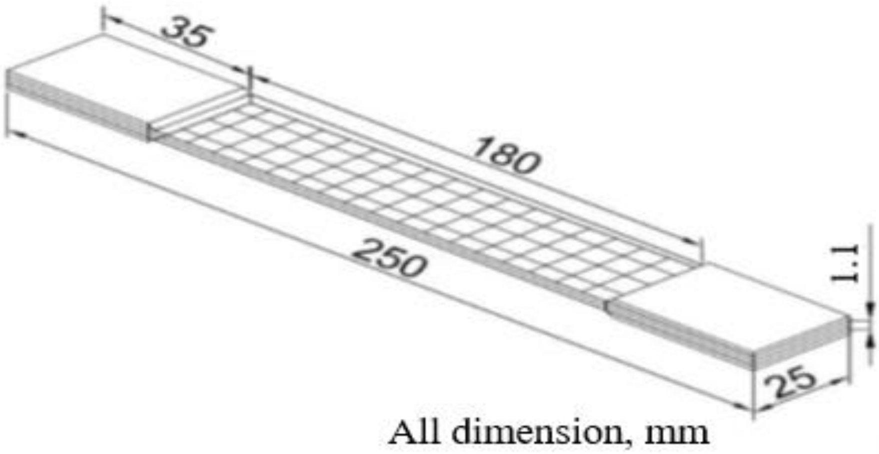

Figure 1. Schematic of composite specimen.

Micromechanical Analysis

The elastic properties of the laminate, including the longitudinal modulus (E1), transverse modulus (E2), in-plane shear modulus (G_{12}), Poisson's ratio (ν_{12}), were determined through micromechanical relations in Eqs. (1)–(6) [2].

To predict the tensile modulus of composite, Rule of Mixtures (ROM) was employed. This model assumes perfect interfacial bonding between fibers and matrix. The classical ROM is expressed as:

$$E_1 = E_f * V_f + E_m * V_m \quad (1)$$

where E1 is the elastic modulus of composite along fiber direction; Ef and Em are the elastic moduli of the fiber and matrix, respectively; Vf and Vm are their corresponding volume fractions.

The transverse elastic modulus, Poisson's ratio, and in-plane shear modulus were calculated using inverse micromechanical relations:

$$E_2 = \frac{E_f * E_m}{E_m * Vf_e + E_f * (1 - V_{fe})} \quad (2)$$

$$\nu_{12} = \nu_f * V_{fe} + \nu_m \left(1 - V_{fe}\right) \quad (3)$$

$$G_{12} = \frac{G_f * G_m}{G_m * Vf_e + G_f * (1 - V_{fe})} \quad (4)$$

Macromechanical Analysis (Classical Laminate Theory)

To determine the mechanical strength of the whole laminate composites the classical laminate theory (CLT) is utilized. By using this CLT, the stresses and strains in local axes can be found by Eq.(1). According to the classical laminated theory (Kaw, 2006), the relation between stress and strain can be expressed as follows:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{bmatrix} \quad (5)$$

The elements of the Q matrix (reduced stiffnes coefficients) are dependent on material constants and can be calculated using the following equations:v12,v21 are poisson's ratios in the 1-2 and 2-1 planes.

$$Q_{11} = \frac{E_1}{1-\nu_{12}\nu_{21}},\ Q_{12} = \frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}},\quad Q_{22} = \frac{E_2}{1-\nu_{12}\nu_{21}},\ Q_{66} = G_{12} \quad (6)$$

where $E_{1,2}$ are the Young's modulus in the direction 1 and 2, G_{12} is the shear modulus in the 1-2 plane,

Q_bar also estimated by using the transformation matrix, which is based on the c=cos(theta) and s=sin(thete) angle.

$$T = \begin{bmatrix} c^2 & s^2 & 2sc \\ s^2 & c^2 & -2sc \\ -sc & sc & c^2 - s^2 \end{bmatrix} \quad (7)$$

Local stress and strains also related to the global stress and strains.

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = [T]^{-1} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} \quad (8)$$

The above equations are used to determine the stress and strains for a single composite laminate layer. Since the composites are multi-layered structures, equations in this case must be set up in Eq.(9).

$$\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{bmatrix} \varepsilon^0 \\ K \end{bmatrix} \quad (9)$$

where N is the vector of resulting forces; M is the vector of resulting moments, Ɛxo is the vector of the mid-plane strains; k is the regarding with the global co-ordinates, as shown in the folowing equation:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \varepsilon_{xo} \\ \varepsilon_{yo} \\ \gamma_{xyo} \end{bmatrix} + \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix} \quad (10)$$

where z is an arbitrary distance from the mid-plane. The A, B, D matrix are known as the extensional, coupling and bending stiffness matrices, respectively. Since the composites is symetrical, B = 0 and D= 0. The A matrix can be calculated Eq.(11).

$$A_{ij} = \sum_{k=1}^{n} [\bar{Q}_{ij}]k\ (h_k - h_{k-1}) \qquad İ = 1,2,6;\ J = 1,2,6, \quad (11)$$

where n is the number of layers; $[\overline{Q\imath\jmath}]k$ is the i-th, j-th element of the $[\bar{Q}]$ matrix of the k-th layer; h_k is the distance of the top or bottom of the k-th layer from the mid-plane of the composite laminate.

Under in-plane loading conditions, the governing equation reduces to:

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{21} & A_{22} & A_{26} \\ A_{61} & A_{62} & A_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix} \quad (12)$$

Under uniaxial tensile loading, only Nx was nonzero other forces Ny, Nz become zero, but axial and transverse strains and shear strain can ocur. Thus, the matrix given in Eq.(12) is transformed into a new form to provide the relation between the Nx and ε_x. Furthermore, the relationship between the internal force per unit width (length) Nx and the strain of mid-plane, ε_{xo}, can be expressed as,

$$N_x = [A]\varepsilon_{xo} \tag{13}$$

Then the axial strain is expressed as,

$\varepsilon_x = [A]^{-1} N\text{x}$

Results and Discussion

Experimental Tensile Strength

The tensile tests were carried out to determine the mechanical performance of the GFRP composite laminates at 2 mm/min cross-head speed. The tensile test results of five-ply polyester - glass fiber reinforced composites are presented in Figures 2, 3 for fiber orientations of 0°, 30°, respectively. The fiber volume fraction was about 0.55. To investigate the tensile behavior of the hybrid composite laminates in the direction of the first ply axis (0°), five specimens were prepared and subjected to tensile tests. In all specimens, the 0° plain ply was aligned with the loading direction, thereby maximizing the load-carrying capacity of the fibers under tension.

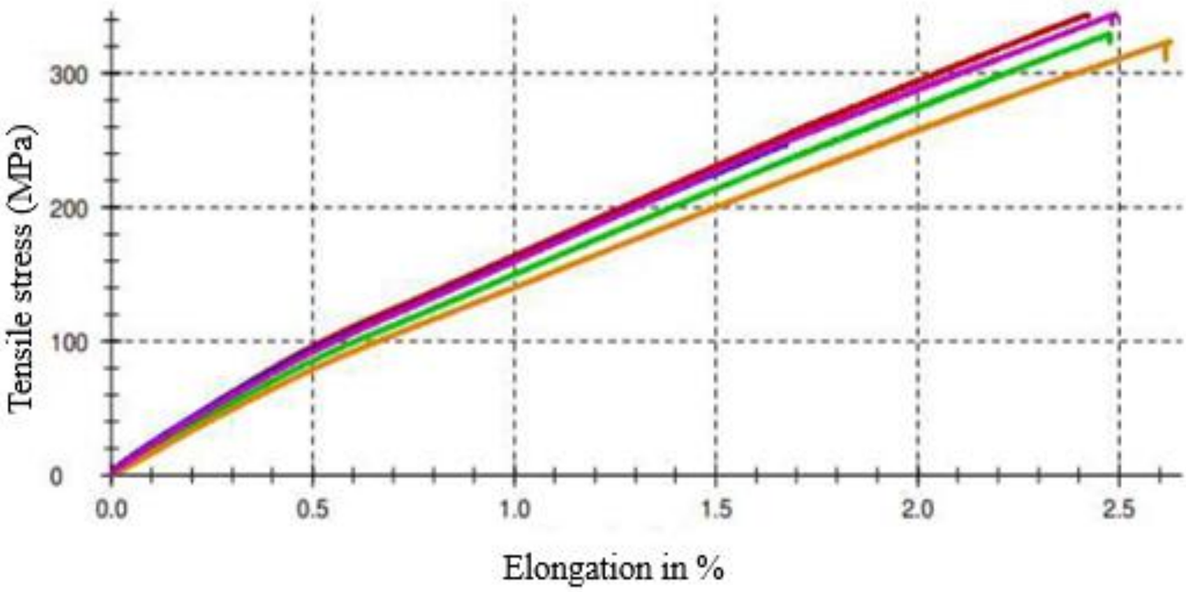

Figure 2. Tensile test results of the GFRP composite laminates at 0∘ orientation under tensile loading.

The ultimate tensile strengths (σ) ranged from 323.6 MPa to 343.8 MPa, indicating the influence of fiber orientation in the weave structure and minor variations introduced in data. The standard deviation was estimated in terms of four data as about 10.2 MPa. The stress–strain curve displayed a linear elastic response up to failure, with no evidence of yielding or plastic deformation. For only one sample, elongation slightly increased. Failure occurred abruptly following the elastic region at maximum load of approximately 7000 N. The average elongation to failure was measured between 2.5% and 2.7%, with all specimens exhibiting similar elongation at break due to the fiber effect. Additionally, cross-sectional measurements of the test specimens were recorded, and the experimental cross-sectional areas (A_0) were found approximately 22 mm² on average. The elastic modulus was measured from all the specimens. According to the experimental results, the measured elastic moduli varied between approximately 17.136 GPa and 20.979 GPa, and their mean value recorded was at 18.95 GPa. These experimental results are significant in this direction for representing the fiber-dominated load-carrying and stiffness of the pliers. During tensile tests, the elongation values of the test specimens were recorded under loads ranging from 600 N to 7000 N.

Figure 3 illustrates the tensile test results of the GFRP composite laminates at 30° orientation under tensile loading. Five specimens were repeated at this orientation. The ultimate tensile strengths ranged from 103.5 MPa to 121 MPa, indicating the influence of fiber orientation in the weave structure and minor variations occurred in data. The standard deviation was estimated about 6.72. The stress–strain curve was very different, because the first small area was linear, then it started to plastic deformation region up to about 116 MPa, after this maximum point, decreasing trends were observed. For these samples, elongation increased significantly. Namely, the average elongation to failure was measured over 20%, not all specimens exhibiting similar elongation at break due to the angle-ply fiber and delaminated layers effect. Further, the measured elastic modulus values raveraged approximately 10.6 GPa. Failure occurred abruptly following the elastic region at maximum load of approximately 2700 N.

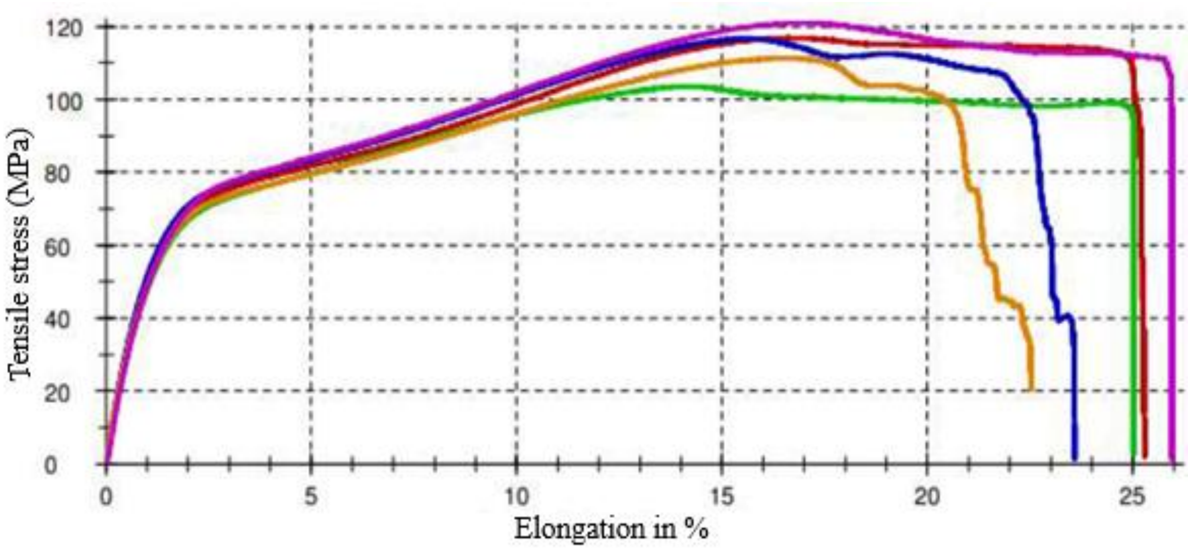

Figure 3. Tensile test results of the GFRP composite laminates at 30∘ orientation under tensile loading.

Table 2 shows the experimental tensile strength results and standard deviations for the GFRP composites. The results indicate a strong dependence of tensile strength on fiber orientation. The ($[0/90°]_5$) laminate composites when tested at 0º exhibited the highest tensile strength (318 MPa), while a considerable reduction was observed for the 30° laminate which is about (114 MPa). These results are quite reasonable, even though glass fibers were used with polyester-based resin. The previous study (Selek&Sahin 2023) on the tensile strength of CFRPs obtained values of approximately 428 MPa and 520 MPa for the 0° and 0/90° directions, respectively; for the 45° orientation, the strength was approximately 120 MPa. Comparable studies (Şahin 2024; Cecen&Sarıkanat; Ozsoy et al. 2015) reported that the tensile performance of the 0° orientation was superior to that of 0/90° samples in plain-woven and twill-woven CFRPs, depending on laminate thickness and improved processing conditions. Other researchers (Kumar&Singh 2021; Vinay et al.2022; Abdua &Ibrahim 2025; Kumaresan et al.2015) also reported that the 0/90° configuration showed better performance, while off-axis loading resulted in drastic strength reductions for the composites, which is the case for this study.

In the current GFRP samples, the strength enhancement observed in the 0° orientations may result from the longitudinal fibers providing increased resistance. The significant reduction in strength for the off-axis 30° orientation on the conclusion that the resin matrix becomes the primary load-carrier as the fiber orientation deviates from the loading direction, leading to shear-dominated failure modes. Error bars are included exclusively for the experimental data to account for specimen-to-specimen variability. Coefficient variation (CV) also estimated and it ranged from 5.39 to 12.6% are quite reasonable. The measured tensile strength/Young’s modulus decreased as the fiber orientation deviated from the loading axis, resulting in the order:

$$(0°) > (30°)$$

Table 2. Experimental tensile strength results for the GFRP composites and their standard deviations.

Tested composite samples						Measured results		
Lamina. types	1st sample	2nd sample	3rd sample	4th sample	5th sample	Mean tensile strength (MPa)	Standard deviations, SD (MPa)	Coeffient variation, CV (%)
0°	343.7	329.2	(247.4)	323.6	344	318	±(40)/10.3	(12.6)/2.98
30°	116.8	103.5	116.7	111.3	121	113.86	±6.72	5.90

Elastic Modulus vs. Orientation

The elastic modulus was determined from the slope of the linear elastic region of the stress–strain curves in Figure 2 and 3. Figure 4 shows the **e**xperimental elastic modulus comparison of five-ply woven glass/polyester laminates with different fiber orientations 0° and 30°. Error bars are also shown only for the experimental results and represent the corresponding standard deviations (see Table 3). The results clearly demonstrate the strong influence of fiber orientation and fabric architecture on the tensile stiffness of the composites. For 0° orientation, the measured Young's modulus was approximately 18.94 GPa, which is consistent with the stiffness reduction associated with woven fabric architecture and fiber crimp effects while 30° orientation in Young's modulus was measured approximately 10.3 GPa. The composite tested under 30° orientation produced lower rigidity because of dominating the shear + fiber rotation, whereas, the 0° orientation was larger than 30° orientation because of carrying the load along the fiber axis. The standard deviation was estimated for all tested directions. They were approximately 1.47 and 0.28 for 0º and 30º, respectively.

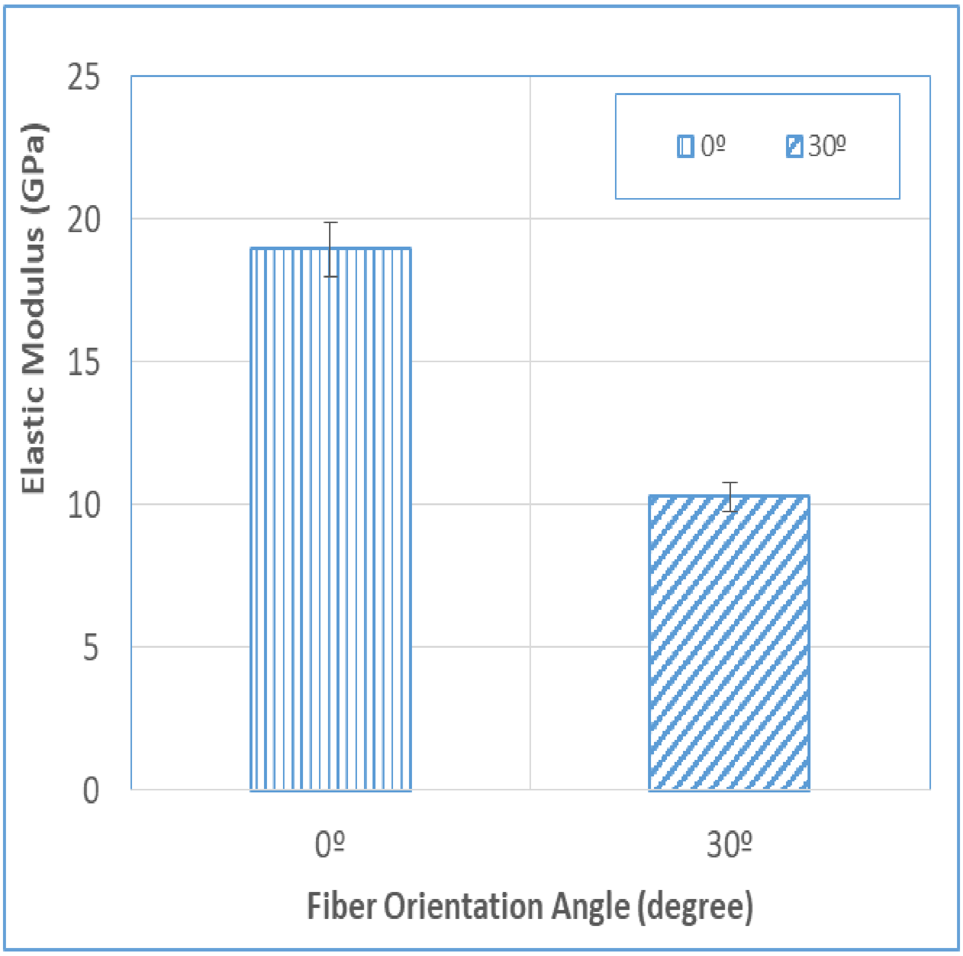

Figure 4. Elastic modulus vs. fiber orientation effects of ($[0/90^o]_5$) laminate composites.

Stresses and Strains on Layers

The behaviour of the laminas is simulated under different loading conditions to understand how to respondd to stress and strains. The lamina level is used to describe it as the macroscale. Table 3 depicts the stress and strain induced the each lamina of tested glass/fiber/resin samples under tensile loading conditions. The maximum stresses are developed at the top and bottom lamina (4.085×10^4 Pa) , while the minimum stresses (-1.632×10^4 MPa) generated at the second layer and fourth layer of the glass fiber/resin lamina, respectively. The maximum strains generated for 1st ply and 2nd pliers are about 9.9x10-7, 7.78×10^{-8}, respectively. On the other hand, the stress is induced less in the second and fourth layers than the bottom and top lamina of GFRP laminate. The shear stresses and shear angles can be neglected because the obtained values are around 8.121×10^{-14}, -3.5917x10^{-13} and 3.8246×10^{-23}, -1.691×10^{-22}, respectively.

Table 3. Stress and strains induced in the each lamina of the GFRP composites.

Stresses/strains produced among the layers and their levels			
Plies	σ1	σ2	τ_{12}
Ply 1 (0º)	4.0851e+04	1.0882e+03	8.1217e-14
Ply 2 (90º)	-1.6323e+04	6.223e+03	-3.5917e-13
Ply 3 (0º)	4.0851e+04	1.0882e+03	8.1217e-14
Ply 4 (90º)	-1.6323e+04	6.223e+03	-3.5917e-13
Ply 5(0º)	4.0851e+04	1.0882e+03	8.1217e-14
Strain (-)			
Plies	ε1	ε2	γ_{12}
Ply 1 (0º)	9.909e-07	-7.785e-08	3.8246e-23
Ply 2 (90º)	-7.785e-08	9.9095e-07	-1.6914e-22
Ply 3 (0º)	9.9095e-07	-7.7853e-08	3.8246e-23
Ply 4 (90º)	-7.7853e-08	9.9095e-07	-3.3827e-22
Ply 5(0º)	9.9095e-07	-7.7853e-08	3.8246e-23

Conclusions

In this study, five-ply plain-woven GFRP laminates were fabricated via the Vacuum bagging method and subjected to experimental investigations. The mechanical response was evaluated across ($[0/90^o]_5$) configurations at three diffrent orientatiıns like 0° and 30°, respectively.

The following conclusions are drawn from the investigation:

- The GFRP laminates exhibited a high degree of anisotropy. For the ($[0^o]_5$) laminate configuration, the highest tensile strength was obtained at 318 MPa for the 0° direction while the laminate tested at 30º orientation showed the lowest performance was provided at around 114 MPa due to dominant matrix shear and fiber rotation.
- Coefficient deviations remained low, but ranged from 5.39 to 12.64%, indicating a reasonable value.
- The maximum stress is developed at the top and bottom lamina (4.085×10^4 Pa), while the minimum stress is generated at the second and forth layers (-1.63×10^4 Pa) of the glass fiber/polymeric lamina while the shear stresses and shear angles was neglected.
- Overall, this study confirms that twill-woven GFRP laminates offer a versatile balance between stiffness, strength, and energy absorption depending on fiber orientation, and that careful orientation design is essential for tailoring composite performance to specific structural applications.

Further research is recommended to evaluate its applicability to different weave architectures (e.g., satin weave, 3D weave) and manufacturing techniques (e.g., vacuum infusion). It is recommended to employ micromechanical models or advanced numerical simulations (e.g., finite element analysis) by considering the fiber crimp factor that can better represent fiber–matrix interactions.

Scientific Ethic Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Yusuf Sahin
OSTIM Technical University, Department of Mechanical Engineering, , Ostim, Ankara, Türkiye
Contact e-mail: yusuf.sahin@ostimteknik.edu.tr
ORCID iD: https://orcid.org/0000-0001-9615-6437

Halil Ridvan Oz
OSTIM Technical University, Department of Mechanical Engineering, Ostim, Ankara, Türkiye
ORCID iD: https://orcid.org/0000-0002-3032-1388

Ceren Cetinkaya
OSTIM Technical University, Graduation School of Institute of Science and Technology, Ostim, Ankara, Türkiye
ORCID iD: https://orcid.org/0009-0001-1245-5657

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