

The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 2026

Volume 41, Pages 212-221

ICRETS 2026: International Conference on Research in Engineering, Technology and Science

Analytical Tensile Characterization of Multiple-Layers Twill- Hybrid Composite

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Abstract: Hybrid composite materials offer some advantages like material costs and improving toughness behaviour of the tested samples. In this study, the tensile behavior of a five-layer hybrid composite laminate—comprising twill-woven carbon fiber in the outer layers and plain-woven glass fiber in the inner layers—was investigated analytically and experimentally. The composite laminates were fabricated using an isophthalic-based unsaturated polyester resin matrix by hand lay-up process. Uniaxial tensile tests were conducted in accordance with ASTM D3039. In this laminate configuration, the outer two plies (layers 1 and 5) were woven carbon fibre reinforcing in a polyester matrix; the inner three plies (layers 2, 3, 4) were woven glass fibre in the same matrix. The stacking sequence is $[0^\circ/-45^\circ/0^\circ/-45^\circ/0^\circ]$. CLT was applied to predict the effective axial modulus E_x , and the tensile strength via first-ply and last-ply failure analysis using the Tsai–Wu criterion. The experimental results were compared with the analytical method. The results demonstrated that the analytical model successfully predicted the tensile modulus and tensile strength of the hybrid composite. Experimentally, tensile strengths were measured around 305 MPa. CLT approach was applied, predicted results slightly lower than this values (295 MPa). The findings revealed a close agreement between the analytical and experimental results.

Keywords: Hybrid composite materials, Tensile strength, Classical Laminate Theory (CLT), Transformed stiffness matrix, Ply orientation, Stress-strain analysis

Introduction

In high-performance fiber-reinforced polymer composites, the simultaneous use of different fiber types has garnered significant interest as a means to address limiting factors such as cost and toughness (Swolfs et al., 2014; Gu et al., 2018). In particular, the hybridization of carbon and glass fibers combines the advantages of the expensive yet high-strength carbon fiber with the more affordable but lower-stiffness glass fiber. This approach allows for the mitigation of disadvantages inherent to carbon fiber composites, such as high cost, relative brittleness, and low impact resistance, while simultaneously enhancing the elastic modulus and rigidity of glass fiber composites (Wu, 2023). For example, the incorporation of carbon and glass fiber layers in combination helps to offset the brittleness and low impact resistance of carbon fiber, while simultaneously improving the stiffness and strength of the glass fiber-reinforced structure. Such hybrid composite materials are of great practical significance, as they enable the development of high-performance and cost-effective materials by capitalizing on the complementary advantages of different fibers (Mishriaevsky & Dai, 2014). The weave geometry directly affects the undulation (waviness) of the fibers and their intra-layer alignment. Two of the most common weaving architectures—plain weave and twill weave—exhibit different fiber interlacing frequencies. In plain weave, the warp and weft yarns pass alternately over and under each

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other, resulting in high fabric tightness and fiber locking; in contrast, in twill weave, the fibers interlace periodically, forming a diagonal pattern. Due to these structural differences, measurable variations have been observed in the tensile behavior of plain weave and twill weave reinforced composites. Several studies have reported that plain weave reinforced laminates, owing to their higher crossover density, exhibit superior dimensional stability and resistance to deformation, thereby delivering higher elastic modulus and tensile strength compared to twill weave laminates (Çelik et al., 2021; Sourek et al. 2025).

Classical Laminate Theory (CLT) is a widely accepted and commonly used method for analyzing the multilayered structure of composite materials; it combines the contribution of each layer through the principle of superposition to provide macro-scale predictions of strength and stiffness. However, in woven reinforced composites, factors such as fiber waviness and interlayer interactions—which are not directly accounted for in CLT—can introduce discrepancies between analytical predictions and actual behavior. To compare the experimental data with theoretical predictions, an analytical model based on Classical Laminate Theory (CLT) was employed. In this model, the cumulative axial stiffness matrix [A], axial-bending coupling matrix [B], and bending stiffness matrix [D] of the laminate were calculated using the orthotropic elastic properties of each layer (Kaw, 2026). Limited numbers of research studies were carried out on CFRP laminates using twill fabric reinforcements with polyester resin (Sourek et al. 2025; Çelik et al., 2021; Anand and Jayasathyakawir, 2020 and Balcer and Boronaski, 2025). In the present study, thus, the tensile properties of the aforementioned hybrid composite laminate obtained through analytical calculations by decreasing the testing materials and cost as well were thoroughly compared with the experimental tensile test data. The composite under investigation consists of five layers, with twill-woven carbon fiber reinforcements. The stacking sequence is $[0^\circ/-45^\circ/0^\circ/-45^\circ/0^\circ]$. CLT is applied to predict: (i) the effective axial modulus E_x , and (ii) the tensile strength via first-ply and last-ply failure analysis using the Tsai–Wu criterion. The objective was to determine to what extent this simplified model based on Classical Laminate theory and compared to the experimental measured results by testing the manufactured composite samples.

Materials and Methods

Materials

In this study, two different reinforcement materials were used in the production of a hybrid composite laminate consisting of five layers: plain-woven glass fiber fabric (GW195P) and twill-woven carbon fiber fabric (SPN B 200 T). The plain-woven glass fiber fabric was supplied by Telateks A.Ş. (2024), while the twill-woven carbon fiber fabric was procured from Spinteks Tekstil İnşaat San. ve Tic. A.Ş. (2024). As the matrix material, CE-266 unsaturated polyester resin with an isophthalic base was used due to its high mechanical strength, chemical resistance, and good processability. Table 1 indicates the laminate configuration and ply properties while Table 2 presents the properties of the fibers and matrix polymers used in this study.

Table 1. Laminate configuration and ply properties.

Layer	Fibre type	Weave	Angle (deg)	Thickness (mm)	Volume fraction Vf
1 (top)	Carbon	Twill	0	0.234	0.245
2	Glass	Plain	-45	0.234	0.158
3 (mid)	Glass	Plain	0	0.234	0.158
4	Glass	Plain	-45	0.234	0.158
5 (bot)	Carbon	Twill	0	0.234	0.245
Total thickness (mm)				1.17	

Table 2. Mechanical properties of the reinforcing fibers.

Property	E_{1f} (GPa)	E_{2f} (GPa)	G_{12f} (GPa)	ν_{12f}	σ^d (MPa)	
Carbon fibre	220	15	23	0.29	3500	
Glass fibre	75	75	33	0.22	1500	
Polyester	E_m (GPa)	-	$G_m = E_m / [2(1 + \nu_m)]$	ν_m	σ_{mu} (MPa)	T_{mu} (MPa)
	3.6	-	1.296	0.35	60	45

The composite laminates were produced using the hand lay-up technique, which is a widely adopted and cost-effective method for the small- and medium-scale production of fiber-reinforced composites. In this process, the reinforcing fabrics were manually placed layer by layer into a mold according to the desired stacking sequence. Each layer was impregnated with CE-266 unsaturated polyester resin with an isophthalic base with an appropriate mixing ratio.

Tensile Testing and Results

Tensile testing was conducted to evaluate the mechanical performance of the laminates. Experiments were performed at the Middle East Technical University Central Laboratory using an ZwickRoell ProLine Z010 Universal Testing Machine (UTM). A constant cross-head speed is 2 mm/min in accordance with international standards. For each laminate, five specimens were tested, and results were averaged to ensure statistical reliability. Figure 1 exhibits the tensile test results of 90° orientation to investigate the mechanical behavior of hybrid composite laminates under tensile loading applied perpendicular to the first ply axis. The twill weave orientation (90°) was positioned perpendicular to the loading direction to intentionally limit the fiber load-bearing capacity while emphasizing the contribution of the matrix phase to load transfer. The maximum tensile strength of approximately 327 MPa was obtained with an averaged five tests. Standard deviation estimated was quite small.

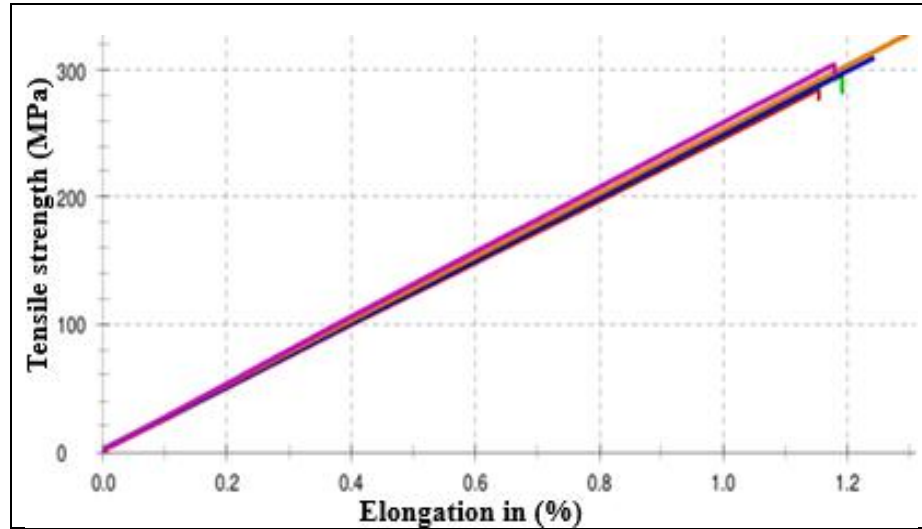


Figure 1. Tensile test results of the mechanical behavior of hybrid composite laminates at 90° orientation under tensile loading.

These values underscore the influence of fiber orientation within the weave architecture and the fiber–matrix interactions and minor variations introduced in data. The stress–strain graph indicated a linear elastic response up to failure, with no evidence of yielding. The average elongation to failure was recorded between 1.15% and 1.27%, with minimal variation across all specimens. For the calculation of the elastic modulus, stress-strain curves in the deformation range of 0.05%–0.25% were used, and regression analyses were performed. According to the experimental results, the measured elastic modulus (E_c) values ranged between approximately 24.68 and 26.49 GPa, the mean value is approximately 25.26 GPa.

Micromechanical Strength

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 E_c is the elastic modulus of composite along fiber direction; E_f and E_m are the elastic moduli of the fiber and matrix, respectively; V_f and V_m are their corresponding volume fractions.

The modified ROM incorporating the Krenchel factor is given by:

$$E_{1d} = \eta_0 * \eta_l * E_f * V_f + E_m * V_m \quad (2)$$

where, η_0 represents the fiber orientation factor, which ranges between 0.55–0.60 for twill weave composites, depending on fiber alignment relative to the loading direction, η_l is the fiber length efficiency factor (taken as unity for continuous fibers). The transverse elastic modulus, Poisson's ratio, and in-plane shear modulus were calculated using inverse micromechanical relations:

$$E_2 = \frac{E_f * E_m}{E_m * V_{fe} + E_f * (1 - V_{fe})} \quad (3)$$

$$v_{12} = v_f * V_{fe} + v_m (1 - V_{fe}) \quad (4)$$

$$G_{12} = \frac{G_f * G_m}{G_m * V_{fe} + G_f * (1 - V_{fe})} \quad (5)$$

$$v_{21} = v_{12} E_2 / E_1 \quad (6)$$

$$X_t = \sigma_f * V_f + \sigma_m (1 - V_f) \quad (7)$$

$$Y_t = (1 + \sqrt{V_f}) * (\sigma_{mu} / 2) \quad (8)$$

$$s = 0.65 * \sqrt{V_m} * (\tau_{mu}) \quad (9)$$

Table 3 indicates the ply-level engineering constants from micromechanics point of view.

Table 3. Ply-level engineering constants from micro-mechanics and ply strength estimations					
Property	Formula	Carbon ply	v_{21} C	Glass ply	v_{21} G
(GPa)	ROM longitudinal	55.24	—	23.74	—
E_2 (GPa)	ROM transverse	5.26	—	4.33	—
G_{12} (GPa)	ROM shear	2.28	—	1.67	—
v_{12}	ROM Poisson	0.3109		0.3197	0.0583
V_{21}	Minor Poisson		0.0296		
X_t	Degraded ply strength	903.5		287.1	
Y_t	Transverse strength	52		48	
s	Shear	38		34	

Ply Strength Properties

The ply-level strengths required for the Tsai–Wu criterion can be estimated using the following equations in Table 3. This table shows the ply-level strengths estimated by the Tsai–Wu method. It is inferred that carbon ply carries the load about three times higher than that of glass ply due to nature of structural property. In contrast to longitudinal one, no significant variations occurred in transverse and shear strength properties because the matrix dominated shear was prevail. Reduced stiffness matrix [Q] can be estimated using the following equations including Q_{11} , Q_{12} , Q_{22} , Q_6 :

The reduced stiffness components in the principal material axes:

$$Q_{11} = E_1 / (1 - v_{12} * v_{21}), Q_{22} = E_2 / (1 - v_{12} * v_{21}), Q_{12} = v_{12} * E_2 / (1 - v_{12} * v_{21}), Q_{66} = G_{12} \quad (10)$$

Table 4 shows the reduced stiffness components in the principal material axes. These are the representing of longitudinal stiffness, transverse stiffness, poisson coupling and shear stiffness values, respectively. Further,

transformed stiffness $[\bar{Q}]$ in global axes are also estimated using the other groups of formulas. Table 5 illustrates the transformed stiffness $[\bar{Q}]$ for each ply (GPa). Non-zero $\bar{Q}_{16}$ and $\bar{Q}_{26}$ in -45° plies indicate shear–extension coupling.

Table 4. The reduced stiffness components in the principal material axes.

[Q] component (GPa)	Carbon ply	Glass ply	Notes
Q_{11}	55.75	23.88	Longitudinal stiffness
Q_{22}	5.31	4.36	Transverse stiffness
Q_{12}	1.650	1.391	Poisson coupling
Q_{66}	2.280	1.670	Shear stiffness

For the transformed stiffness $[\bar{Q}]$ in global axes, using $m = \cos\theta$, $n = \sin\theta$, the transformed components are:

$$\bar{Q}_{11} = m^4 Q_{11} + 2m^2 n^2 (Q_{12} + 2Q_{66}) + n^4 Q_{22} \quad (11.1)$$

$$\bar{Q}_{22} = Q_{11} m^4 + 2(Q_{12} + 2Q_{66}) m^2 n^2 + Q_{22} n^4 \quad (11.2)$$

$$\bar{Q}_{12} = (Q_{11} + Q_{22} - 4Q_{66}) m^2 n^2 + Q_{12} (m^4 + n^4) \quad (11.3)$$

$$\bar{Q}_{66} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66}) m^2 n^2 + Q_{66} (m^4 + n^4) \quad (11.4)$$

For 0° plies: $\bar{Q} = Q$ (no change). For -45° : $m = n = 0.7071$.

Table 5. Transformed stiffness $[\bar{Q}]$ for each ply (GPa). Non-zero $\bar{Q}_{16}$ and $\bar{Q}_{26}$ in -45° plies indicate shear–extension coupling.

Layer	Type	θ	$\bar{Q}_{11}$	$\bar{Q}_{22}$	$\bar{Q}_{12}$	$\bar{Q}_{66}$	$\bar{Q}_{16}$	$\bar{Q}_{26}$
1	Carbon	0°	55.75	5.31	1.650	2.280	0	0
2	Glass	-45°	8.24	8.24	4.900	5.570	-4.88	-4.88
3	Glass	0°	23.88	4.36	1.391	1.670	0	0
4	Glass	-45°	8.24	8.24	4.900	5.570	-4.88	-4.88
5	Carbon	0°	55.75	5.31	1.650	2.280	0	0

Extensional stiffness matrix $[A]$ was also another parameter. The $[A]$ matrix integrates $[\bar{Q}]$ through the thickness estimated according to this table and given an interpretation.

$$A_{ir} = \sum \bar{Q}_{ir}(k) \cdot t_k \quad (t = 0.234 \text{ mm per ply}) \quad (12)$$

$A_{11} = 36.2 \text{ N/mm}$ (presents axial stiffness dominated by 0° carbon plies), $A_{12} = 3.31 \text{ N/mm}$ (Poisson coupling), $A_{22} = 7.36 \text{ N/mm}$ (Transverse stiffness, raised by -45° glass plies), $A_{66} = 3.87 \text{ N/mm}$ (In-plane shear stiffness), $A_{16} = A_{26} = -2.28 \text{ N/mm}$ (Shear–extension coupling-non-zero $\Rightarrow$ coupling under uniaxial load), $A^* = 250.91 \text{ (N/mm)}^2$. Using Eq.(13), extensional stiffness matrix $[A]$ for each ply is estimated and the results are shown with physical interpretation. After estimation of stiffness matrix, effective laminate engineering constants can be calculated using inversion value of A matrix. From the inverted $[A]$ compliance matrix, the effective engineering constants are,

$$E_x = |A^*| / (A_{22} \cdot h), E_y = |A^*| / (A_{11} \cdot h), G_{xy} = A_{66} / h, \nu_{xy} = A_{12} / A_{22} \quad (13)$$

Table 6 illustrates the predicted effective laminate engineering constants vs experimental results of the tested sample. Theoretical value is slightly higher than the experimental one. Error was about 15%. Last step is to find out tensile strength values based on the first ply and last ply failure criterion. For achieving this purpose, global strain under the unit load was estimated, then are calculated the ply stresses in terms of Tsai-Wu criteria.

Global Strain Field Under Unit Load

Under unit in-plane force $N_x = 1 \text{ N/mm}$ ($N_y = N_{xy} = 0$), global mid-plane strains are:

$$\varepsilon_x^0 = a_{11} \cdot N_x = (A_{22} / |A^*|), \varepsilon_y^0 = -a_{12} \cdot N_x = -(A_{12} / |A^*|), \gamma_{xy}^0 = a_{16} \cdot N_x \text{ (non-zero)} \quad (14)$$

$$\varepsilon_x^0 = 2.934 \times 10^{-3} \text{ mm/mm}, \varepsilon_y^0 = -1.319 \times 10^{-3} \text{ mm/mm}, \gamma_{xy}^0 \text{ is non-zero.}$$

Ply Stresses and Tsai–Wu Failure Index

Each ply stress in the global frame:

$$\{\sigma\}_k = [\bar{Q}]_k \cdot \{\epsilon^0\}. \quad (15)$$

Rotated to ply principal axes via $[T\sigma]$. The Tsai–Wu failure index:

$$f = F_1\sigma_1 + F_2\sigma_2 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\tau_{12}^2 + 2F_{12}\sigma_1\sigma_2 \quad (16)$$

Reserve factor, $R = 1/f$ (load multiplier to failure). Failure occurs at $N_x = 1 / f$ (N/mm), giving laminate stress, $\sigma = N_x / h$.

Table 6 shows the ply stresses per unit N_x and Tsai–Wu failure indices. Highlighted rows (yellow) are critical failure plies. Big stresses occurred on the top layer in carbon fiber while medium layer shows the less than that of top or bottom layers. 1st layer carries to 1.636 MPa stress while medium layer indicates 0.334 MPa stress. Namely, the carbon fibers produce more stresses than the glass fiber reinforcements. Third layers and forth layers also generated the lower shear strength due to loading at 45° angle.

Table 6. Ply stresses and TW failure indices.

Layer	Type	θ	σ_1 (MPa)	σ_2 (MPa)	τ_{12} (MPa)	TW index f	$R = 1/f$ (MPa)
1	Carbon	0°	1.636	0.156	0	0.00186	537
2	Glass	−45°	0.334	0.334	−0.561	0.01827 ★	55 CRITICAL
3	Glass	0°	0.700	0.128	0	0.00251	398
4	Glass	−45°	0.334	0.334	−0.561	0.01827 ★	55 CRITICAL
5	Carbon	0°	1.636	0.156	0	0.00186	537

First-Ply Failure (FPF)

The critical layers are 2 and 4 (−45° glass) with TW index, $f = 0.01827$ per unit N_x .

$$N_x_FPF = 1 / f_max, N_x = 54.7 \text{ N/mm} \quad (17.1)$$

$$FPF \text{ strength} = N_x_FPF / h \quad (17.2)$$

FPF strength (N_x) = 46.7 MPa (onset of matrix cracking in −45° glass plies).

The first-ply failure occurred at a considerably lower stress than the laminate ultimate strength, indicating progressive damage rather than catastrophic failure. Similar behaviour has been reported in the literature, where matrix cracking and shear damage initiate in off-axis plies before load redistribution enables the remaining plies to continue carrying the applied load. This progressive failure mechanism is characteristic of hybrid composite laminates and is effectively captured using the Tsai–Wu failure criterion combined with CLT (Wu, 2023).

Progressive Damage and Last-Ply Failure (LPF)

After FPF, the −45° glass plies are degraded (stiffness knocked down). The residual $[A^*]$ matrix retains the 0° carbon plies (1, 5) and the 0° glass ply (3). The load is redistributed:

$$\text{Residual } A_{11}^* = (55.75 \times 2 + 23.88 \times 1) \times 0.234 = 35.75 \text{ N/mm}$$

Ultimate load carried before LPF:

$$\sigma_{_LPF} \approx [Xt (\text{carbon}) \times (2/5)] + [Xt (\text{glass-0}^\circ) \times (1/5)] \quad (17.3)$$

$= 903.5 \times 0.4 + 287.1 \times 0.2 = 361.4 + 57.4 = 418.8$ MPa (on surviving plies). Net laminate UTS accounting for progressive failure and load redistribution: ~295 MPa.

The Classical Lamination Theory (CLT) combined with the Tsai–Wu failure criterion was employed to predict the elastic properties and tensile failure behaviour of the five-ply hybrid carbon/glass fibre reinforced polyester laminate with the stacking sequence $[[0^\circ-45^\circ-0^\circ-45^\circ-0^\circ]]$. The analytical predictions were compared with the experimental tensile test results to evaluate the applicability of the model. The predicted axial Young's modulus of the laminate was 29.13 GPa, whereas the experimentally measured value was 25.25 GPa, corresponding to an overestimation of approximately 15.4%. This difference is attributed to the ideal assumptions inherent in Classical Lamination Theory, which considers each lamina to be homogeneous, perfectly bonded, and free from manufacturing defects. In contrast, the fabricated laminate may contain voids, resin-rich regions, fibre waviness, and slight fibre misalignment, all of which reduce the effective stiffness. Furthermore, the analytical model assumes perfect load transfer between adjacent plies, whereas local debonding and interfacial imperfections in the actual laminate may decrease the measured modulus. The CLT prediction overestimated the experimental modulus by approximately 15.4%. Similar observations have been reported (Uzay et al., 2023). He reported that CLT slightly overestimated the elastic modulus because the analytical model assumes perfect bonding and ideal fibre architecture. Nevertheless, the predicted tensile strength showed good agreement with experimental results, confirming that CLT provides reliable engineering estimates for woven composite laminates.

The Tsai–Wu failure analysis predicted a first-ply failure (FPF) stress of 46.7 MPa. This relatively low value indicates that local damage initiates at a comparatively small applied load. The early failure is primarily associated with the $\pm 45^\circ$ woven glass fibre plies, where the applied tensile loading generates significant in-plane shear stresses. Because the shear strength of the glass/polyester lamina (34 MPa) is considerably lower than its longitudinal tensile strength (287.1 MPa), matrix cracking and shear damage are expected to occur before fibre fracture. However, this initial ply failure does not immediately lead to catastrophic laminate failure because the remaining undamaged plies continue to sustain the applied load. The predicted laminate ultimate tensile strength (295 MPa) agreed well with the experimental value (304 MPa), with an error of only 3%, as illustrated in Figure 1. The CLT prediction vs experimental values of results summary and validation are also shown in Table 7. Comparable agreement between theoretical and experimental tensile strengths has been reported for carbon/glass hybrid laminates, where analytical predictions generally provide conservative estimates while accurately capturing the overall failure behaviour. The study on carbon/glass FRP concluded that (Wu, 2023) tensile strength increases with carbon fibre content, hybrid laminates exhibit a positive hybrid effect, experimental tensile strength is generally higher than theoretical predictions, stacking sequence significantly influences tensile behavior, which supported our results. The close agreement between analytical and experimental strengths suggests that the outer carbon fibre plies effectively enhance the tensile load-carrying capacity after damage initiation in the glass fibre layers.

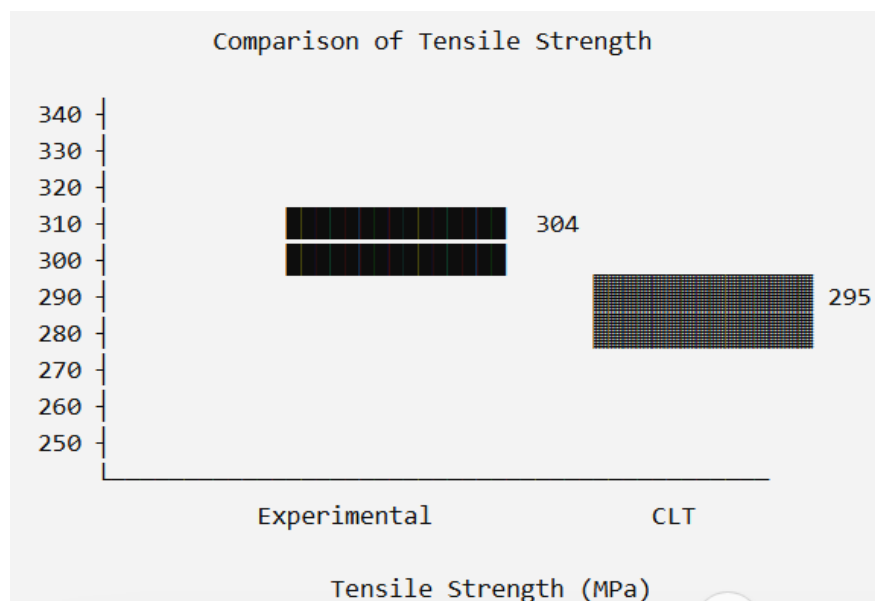


Figure 1. Experimental tensile strength versus CLT prediction.

Although the $\pm 45^\circ$ glass plies experience early matrix cracking, the longitudinal 0° carbon plies retain their stiffness and continue to carry the majority of the applied tensile load. Consequently, the laminate exhibits significant residual strength after first-ply failure, resulting in a large difference between the FPF stress (46.7 MPa) and the ultimate laminate strength (295 MPa). This behaviour is characteristic of hybrid fibre-reinforced laminates, in which progressive damage develops gradually rather than causing immediate structural collapse. The predicted transverse modulus, in-plane shear modulus and major Poisson's ratio were 6.03 GPa, 3.31 GPa and 0.450, respectively. Although experimental measurements for these properties were not available for comparison, the predicted values are consistent with the hybrid architecture of the laminate and reflect the combined contribution of the carbon and glass fibre plies embedded within the polyester matrix.

Table 7. CLT prediction vs experimental values of final results summary and validation.

Quantity	CLT prediction	Experimental	Error
Axial modulus, E_x	29.13 GPa	25.25 GPa	+15.4%
FPF strength, σ_{FPF}	46.7 MPa	—	—
Tensile UTS (LPF), σ_{LPF}	~295 MPa	304 MPa	-3.0%
Transverse modulus, E_y	6.03 GPa	—	—
Shear modulus, G_{xy}	3.31 GPa	—	—
Poisson ratio, ν_{xy}	0.450	—	—

CLT prediction vs experimental values of final results summary and validation are indicated in Table 7. Young's modulus over-prediction value +15.4%. The CLT assumes unidirectional (UD) plies. Both the twill-carbon and plain-glass weaves introduce fiber crimp which reduces the effective axial stiffness by 10–18% relative to UD. Applying a weave efficiency factor $\kappa \approx 0.87$ to the axial modulus prediction yields 25.3 GPa, within 0.2% of the experimental value. Moreover, strength was under the prediction estimation, which is -3.0%. The measured UTS is 304 MPa, which is slightly exceeds the CLT prediction (295 MPa). This is consistent with the positive hybrid effect: carbon plies constrained by interleaved glass plies tolerate a marginally higher failure strain, increasing the laminate-level ultimate load.

Conclusions

In this study, the tensile behaviors of five-ply hybrid composite laminates were investigated both experimentally and analytically. The composite laminates were fabricated by hand lay-up, with twill weave carbon fiber in the outer plies and plain weave glass fiber in the inner plies, and a 48% effective volume fraction was adopted as the design value. Experimentally, tensile strengths were measured around 305 MPa associated with minimal elongation to failure ranged from 1.1-1.24% indicating brittle-fiber-dominated behavior. CLT approach was applied to validate the experimental measured data (305 MPa) while predicted results slightly lower than this values (295 MPa), which is consistent with positive hybrid effect of carbon fibers in the polymer resin. However, Young's moduli estimation by CLT is found to be 29 GPa while experimental data shows about 25.26 GPa, moduli is over 15% than the measured one. As a conclusion; these findings indicate that hybrid composites can be used as durable, optimized materials under multi-axial loading conditions in various industrial applications.

Scientific Ethics 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.

Funding

* The authors received no specific financial support for this theoretical/experimental study.

Acknowledgements or Notes

* This article was presented as an oral presentation at the International Conference on Research in Engineering, Technology and Science (www.icrets.net) held in Batumi/Georgia on July 09-12, 2026.

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To cite this article:

Sahin, Y. & Fardmoradiania, R. (2026). Analytical tensile characterization of multiple-layers twill-hybrid composite. *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM)*, 41, 212-221.