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Nomenclature

<i>CFRP</i>	Carbon Fiber Reinforced Polymer
<i>E</i>	Young's modulus
<i>GFRP</i>	Glass Fiber Reinforced Polymer
<i>H</i>	Fiber layer thickness
<i>K</i>	Permeability
<i>L</i>	Flow length
<i>N</i>	Number of fiber layers

<i>q</i>	Resin flow rate per unit width
<i>VARTM</i>	Vacuum-assisted resin transfer molding
Greek Symbols	
σ_t, σ_c	Engineering Tensile and compression stress respectively.
ε	Engineering strain
μ	Dynamic viscosity of resin
ΔP	Pressure difference

2. Theoretical background

Since the permeability of each fiber layer is not identical, the vertical section of a multilayer preform can be treated as a non-homogeneous porous medium. During resin injection from one side to the other, the pressure gradient acts mainly along the fiber layers. In this analysis, gravity and capillary effects are neglected because the pressure generated during VARTM is much higher than the capillary pressure between the fibers and the resin [22]. Figure 1A shows the cross-section of a fully infiltrated fiber layer. Based on Darcy's law, the flow rate per unit width q_i in each layer can be calculated, and the total flow rate q is obtained by summing the flow rates of all layers.

$$q = \sum_{i=1}^N q_i \quad (1)$$

$$H = \sum_{i=1}^N H_i \quad (2)$$

$$q_i = \frac{k_i H_i}{\mu} \frac{\Delta P}{L} \quad (3)$$

$$u_i = \frac{q_i}{H_i} = \frac{k_i \Delta P}{\mu L} \quad (4)$$

where k_i , H_i , and q_i denote the permeability (m^2), thickness (m), and flow rate per unit width (m^2/s) of layer i , ΔP is the pressure difference between the two ends of the fiber layer (Pa), L is the infiltration path (m), N is the number of fiber layers, and μ is the dynamic viscosity of the resin ($Pa \cdot s$) [22]. The pressure gradient $\Delta P/L$ remains constant within each layer; therefore, we obtain the following [22].

$$q = \sum_{i=1}^N q_i = \sum_{i=1}^N \frac{k_i H_i}{\mu} \frac{\Delta P}{L} = \frac{\Delta P}{\mu L} \sum_{i=1}^N k_i H_i \quad (5)$$

$$q = \frac{\Delta P}{\mu L} \int_0^H k(z) dz \quad (6)$$

The following gives the integral form of the in-plane equivalent infiltration velocity [22].

$$\bar{u} = \frac{\bar{q}_h}{H} = \frac{\Delta P}{\mu H L} \int_0^H k(z) dz \quad (7)$$

A summary of previous studies on notch effects and fiber orientation in fiber-reinforced polymers is presented in Table 1.

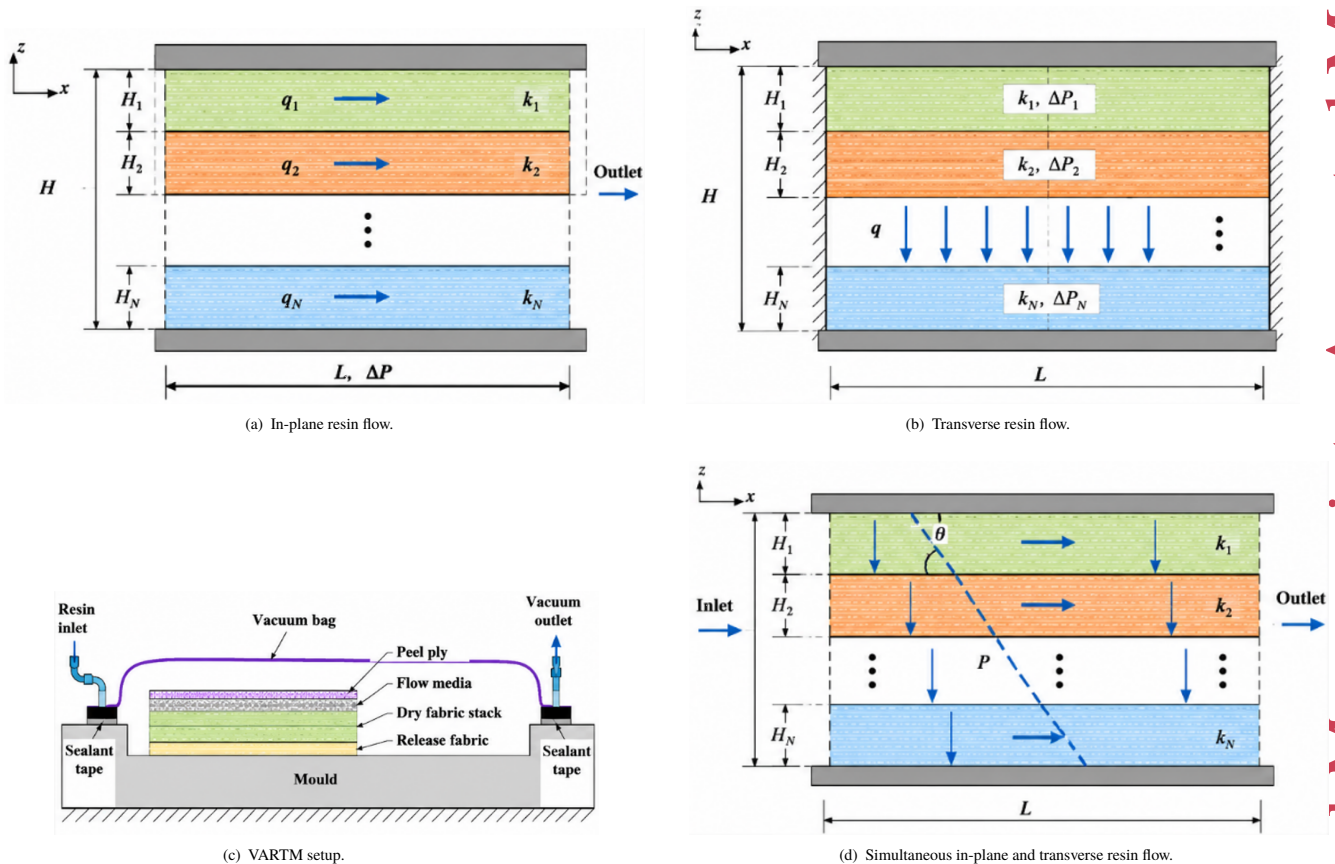


Figure 1. Schematic illustration of resin flow mechanisms during the VARTM process, redrawn by the authors based on [22]: (A) in-plane resin flow within the fiber layers, (B) transverse resin flow within and between the fiber layers, (C) VARTM setup after resin injection into the vacuum bag, and (D) simultaneous in-plane and transverse resin flow. The arrows indicate the resin-flow direction, and P represents the pressure exerted on the resin flow.

Table 1. Study of notch effects and fiber orientation in FRPs.

Year	Reference	Study	Results
2020	[23]	Use of Recyclable Acrylic Thermoplastic Resin in the VARTM Process for GFRP Panel Production.	- Resin flow and panel quality were optimized using recyclable thermoplastic resin. - Full fiber wetting and low void content were achieved. - Full polymerization of the resin was confirmed at ambient temperature.
2021	[24]	Low-Velocity Impact Behavior of Glass Fiber Reinforced Epoxy (GF/Epoxy) Composite using Numerical Modeling	- Strong correlation between experimental and numerical results. - Increase in impact energy results in higher peak force and energy absorption. - Impactor diameter affects peak force, displacement, and perforation energy
2022	[25]	Comparison of Off-Axis Tensile Performance of 3D Fiber Reinforced Composites with Two Matrix Types	- Thermoplastic 3D-FRCs exhibited higher failure stresses (30% higher) and energy absorption (33% higher). - Thermoplastic composites were notch-insensitive, while thermoset composites were notch-sensitive.
2024	[26]	Enhanced VARTM Technique and Pressure Effects on Resin Infusion and Composite Performance	- The 7.3% increase in tensile strength, improved fiber volume fraction, and reduced porosity. - Porosity reduced to less than 1%, fiber volume fraction increased from 55% to 62%. - Panel thickness reduced by 4%.
2025	[27]	Investigation of Hybrid Carbon and Glass Fiber Reinforced Epoxy Composites Under Dynamic Loading	- Hybrid carbon/glass fiber composites demonstrated higher energy absorption and impact resistance compared to pure glass fiber composites. - The introduction of carbon fibers reduced the peak force by 12%, while improving the overall toughness. - The composites exhibited better post-impact residual strength and durability.

3. Materials and method

3.1 Carbon fiber

Unidirectional CFRP sheets (Sika Wrap 231C) were used as the carbon-fiber reinforcement. The sheet was bonded using Sikadur-330 adhesive, which consists of high-strength and high-modulus components. The main properties of the CFRP sheet and the epoxy adhesive are listed in Table 2 according to the manufacturer's data. The CFRP system has a tensile strength of 4000 MPa, a tensile modulus of 230 GPa, and an areal weight of 304 g/m². Figure 1 illustrates the resin flow mechanisms during the VARTM process, including in-plane and transverse infiltration within and between the fiber layers [22].

Table 2. Mechanical properties of CFRP sheets and epoxy adhesive.

Material	properties	Values
CFRP	Fiber orientation	0°
	Areal weight	304 g/m ²
	Fabric design thickness	0.167 mm
	Tensile strength of fibers	4000 MPa
	Tensile E—E-modulus of fibers	230,000 MPa
	Fabric width	500 mm
Epoxy	Elongation at break	1.7%
	Appearance	Light gray
	Density	1.1 g/cm ³
	Mixing ratio	4:1 by weight
	Open time	30 min
	Tensile strength	33.8 MPa
	E-modulus flexure	3489 MPa
	Elongation	1.2%

3.2 Glass fiber

Glass fiber was selected because it combines low weight with good strength and stiffness. Compared with many metallic materials, glass fiber offers favorable specific mechanical properties. In this work, randomly oriented E-glass fiber mats were used as reinforcement in an unsaturated polyester matrix. The properties of the E-glass fiber and the polyester resin are presented in Table 3.

3.3 Polyester resin

Unsaturated polyester resin is supplied as a liquid and hardens after adding the appropriate catalyst. In the present work, Methyl Ethyl Ketone Peroxide (MEKP) was used to initiate curing at room temperature. The randomly oriented E-glass mats were embedded in the polyester matrix and cured with MEKP. The basic mechanical and physical properties of the materials are given in Table 3.

Table 3. Properties of E glass fiber and unsaturated polyester resin.

Property	σ_t (MPa)	σ_c (MPa)	E , (GPa)	ρ , (g/cm ³)
E-glass	3445	1080	73	2.58
Unsaturated polyester	90	55	3.23	1.35

3.4 Specimens preparation

CFRP and GFRP laminates were fabricated using a modified Vacuum-Assisted Resin Transfer Molding (VARTM) procedure. This method was chosen because it provides controlled wet-out of the fiber preform, acceptable void control, and a relatively simple route for producing composite panels. The main preparation steps are described below.

3.4.1 Mold and Tooling Preparation

- Mold Material: Aluminum alloy flat-bottom mold (dimensions: 300 mm × 300 mm × 10 mm).
- Surface Preparation: The mold surface was cleaned and coated with a release agent (Zyvax® or equivalent) to prevent resin adhesion.
- Lay-Up Configuration: A dry fiber preform (either unidirectional CFRP fabric or randomly oriented E-glass mats) was cut to 250 mm × 250 mm and placed onto the mold surface.

3.4.2 Vacuum bagging setup

- Stack Sequence: The fiber preform was covered with peel ply, a distribution medium, and a vacuum bagging film.
- Sealant Tape: High-temperature sealant tape was used to hermetically seal the vacuum bag perimeter.
- Vacuum Port: A resin inlet tube and a vacuum outlet tube were connected using RTM-compatible nylon fittings. The vacuum port was linked to a two-stage rotary vane vacuum pump (Brand: ULVAC, Model: G-50DA).

3.4.3 Resin Infusion

Resin types:

- CFRP: Momentive Epikote epoxy resin with hardener (mix ratio 100:35 by weight).
- GFRP: Unsaturated polyester resin with MEKP catalyst.

Infusion parameters:

- Vacuum Level: -0.85 bar (measured with analog vacuum gauge).
- Resin Temperature: 25°C (controlled using a resin preheater).
- Infusion Time: 15 ↔ 20 minutes, depending on fabric permeability.

3.4.4 Curing time and demolding the specimen

- Initial Cure: After full wet-out, the laminate was left under vacuum for 24 hours at ambient temperature (25°C).
- Post-Curing: Laminates were then placed in a laboratory oven (Memmert UN260) at 60°C for 2 hours to enhance crosslinking and mechanical properties.
- The cured laminates were demolded and inspected visually for defects such as voids or dry spots.
- Specimens were cut to size (ASTM D638 Type I) using a CNC diamond saw cutter (Brand: Buehler IsoMet 5000).
- Notches of 0 mm, 2 mm, 4 mm, and 6 mm were introduced using a high-precision Dremel rotary tool with calibrated bit diameters.

Furthermore, the VARTM mold used for specimen fabrication is shown in Fig. 2. Tensile specimens were prepared according to ASTM D638 Type I. The final coupon dimensions were $165 \times 13 \times 3$ mm. A CNC diamond blade cutter was used to obtain clean edges and consistent dimensions, as shown in Fig. 2.

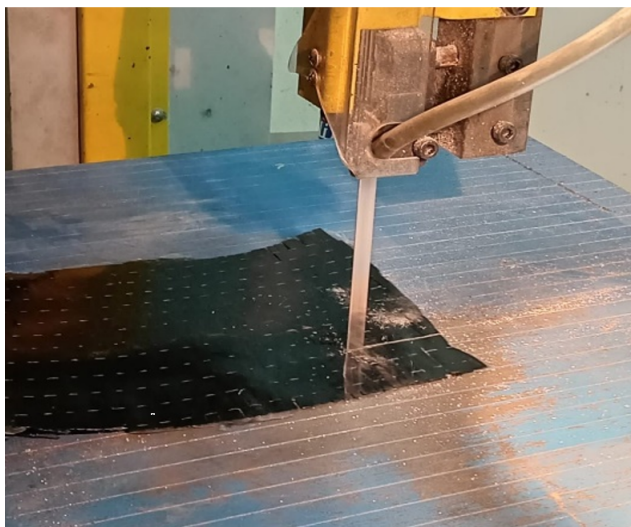


Figure 2. VARTM cutting process's mold.

Finally, the notches with widths of 0, 2, 4, and 6 mm were introduced using a precision drill. For each testing condition, three specimens were prepared to improve the reliability of the results. All CFRP and GFRP specimens used in this work were manufactured by VARTM under controlled conditions. A modified setup was also used to improve resin distribution and reduce void content.

- The carbon or glass fiber preforms were manually arranged inside the mold. Peel ply, release film, and vacuum bagging film were then placed over the preform, and RTM-compatible adhesive was used to seal the mold.
- Resin infusion was started by maintaining a vacuum of -0.85 bar to remove air.
- Under vacuum pressure, low-viscosity epoxy (for CFRP) or polyester (for GFRP) resin was injected at ambient temperature (around 25°C).
- Curing: The mold was held under vacuum for 24 hours at room temperature post-infusion, then oven post-cured at 60°C for two hours.
- Using CNC saw cutting, laminates were removed and cut to the required size.
- The visible inspection window and pressure gauge were used to monitor the process and help maintain uniform resin flow with minimum void formation.

Specimens were prepared for both basic mechanical characterization and structural response assessment. As shown in Fig. 3, a detachable pressure chamber was used to control the pressure during resin injection and curing. The mold, vacuum bag, release cloth, and fiber layer were placed inside the chamber. Resin and vacuum lines were passed through the chamber wall and sealed with RTM adhesive. Carbon-fiber laminates were produced using an aluminum alloy flat-bottom mold of 300×300 mm and a reinforcement size of 250×250 mm. The three-way pipe connected to the pressure chamber allowed the system

to operate under vacuum during mold filling and under positive air pressure during the filling and curing stages when required. A pressure gauge provided real-time monitoring, while the glass window allowed visual observation of the resin front. The modified VARTM setup and pressure chamber arrangement are presented in Fig. 3.

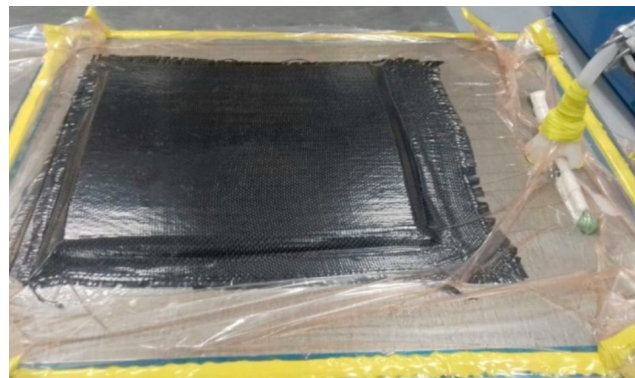


Figure 3. VARTM vacuum process's mold step.

Basic elastic and peak-stress properties were obtained from coupon tensile tests, which are commonly used for the characterization of polymers, metals, and composite materials. Unnotched tension testing based on ASTM D3039 is a typical example of this approach. In the present study, unidirectional specimens were tested in the longitudinal 0° direction and the transverse 90° direction at a loading rate of 50 mm/min. Notch widths of 0, 2, 4, and 6 mm were used, and three specimens were tested for each condition. As shown in Figs. 5, 6, 7, and 8, the fabricated composite laminates were cut by CNC saw to obtain the required tensile-test geometry according to ASTM D638. The tests were conducted at room temperature and 40% relative humidity using a universal testing machine. During testing, tensile stress was recorded as the strain increased until fracture. The load-strain data were then used to draw the stress-strain curves. Tensile testing was carried out on an Instron 3382 machine at a crosshead speed of 50 mm/min under ambient conditions (25°C and 40% RH). Rubber inserts were used in the grips to reduce slippage. Axial strain was measured using a clip-on extensometer with a 50 mm gauge length. Because digital image correlation was not available, transverse deformation was monitored manually for selected specimens.

3.5 Uniaxial tensile test

Tensile testing was used to determine the main tensile properties, including tensile strength, strain, elongation, and Young's modulus. In this test, the specimen is clamped in the machine grips and loaded gradually until failure. The elongation in the gauge section is measured with respect to the applied force, and the tensile modulus is calculated from the initial linear region. In this work, specimen dimensions, crosshead speed, and gauge length were selected according to ASTM D638. The tensile tests were performed using a floor-mounted Instron 3382 universal testing machine, as shown in Fig. 4.



Figure 4. Typical tensile test of composite specimen.

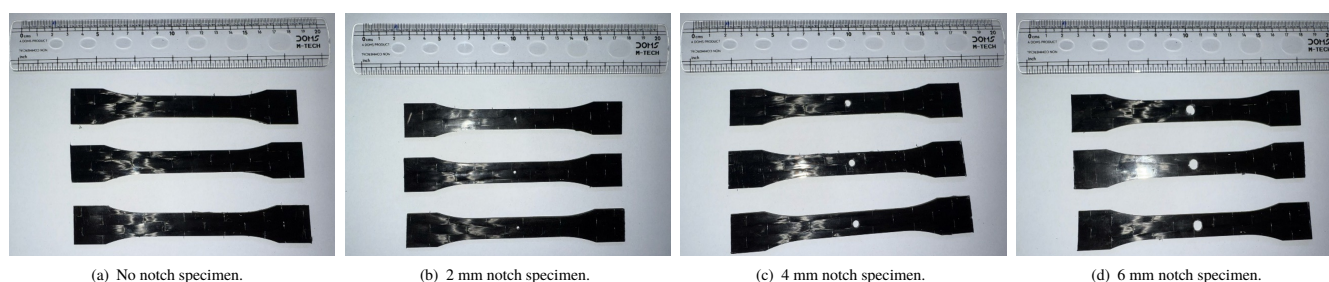


Figure 5. Coupon samples of carbon-fiber polymer for mechanical property testing with 0° orientation.

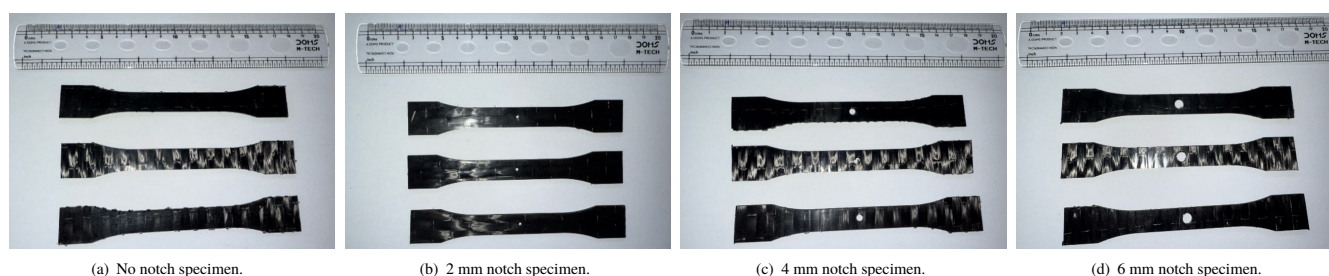


Figure 6. Coupon samples of carbon-fiber polymer for mechanical property testing with 90° orientation.

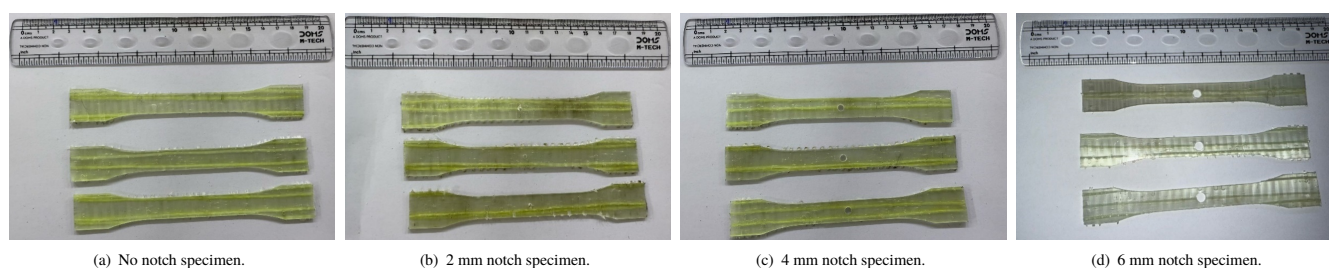


Figure 7. Coupon samples of glass-fiber polymer for mechanical property testing with 0° orientation.

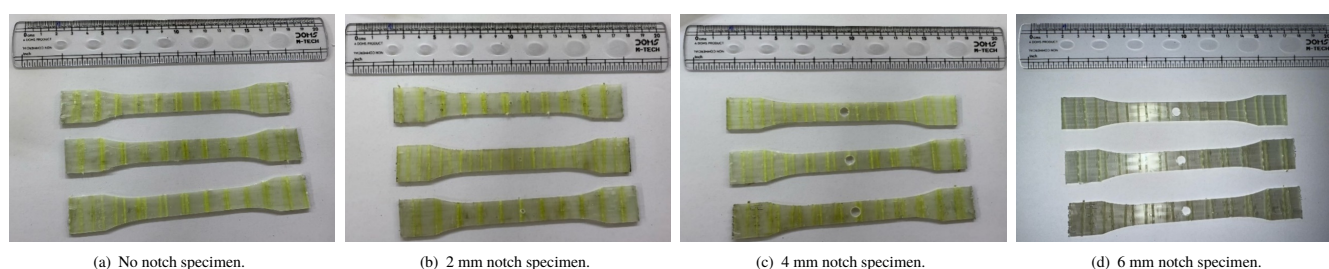


Figure 8. Coupon samples of glass-fiber polymer for mechanical property testing with 90° orientation.

4. Results and discussions

4.1 Stress-Strain analysis

The tensile behavior of carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP) composites is largely influenced by two key factors: fiber orientation relative to the loading direction and the presence and size of geometric discontinuities, such as notches. The analysis of stress-strain curves for CFRP and GFRP specimens provides critical insights into the material's strength, stiffness, and failure mechanisms under tensile stress.

4.1.1 Influence of Fiber Orientation

The orientation of the fibers has a significant impact on the stress response of the composite. At 0° orientation, fiber orientation (parallel to loading direction), the fibers directly resist the tensile load, resulting in: High maximum stress values, indicating excellent load-bearing capacity. A steep linear portion in the stress-strain curve, reflecting high stiffness (modulus of elasticity E). Brittle

failure, typically occurring with little plastic deformation, due to the dominant role of stiff carbon and glass fibers. At 90° orientation (fibers perpendicular to loading), the matrix bears most of the tensile load, while the fibers contribute minimally. This results in significantly lower stress and stiffness values. The stress-strain curve shows a less steep slope, and failure is often preceded by matrix cracking, delamination, and fiber pull-out, leading to a more gradual and ductile failure behavior. These observations confirm that loading CFRP and GFRP along the fiber direction (0° orientation) results in superior mechanical performance compared to the 90° orientation, as shown in [Fig. 9a](#) and [Fig. 10a](#). In contrast, the 90° orientation exhibits lower tensile strength and stiffness, as illustrated in [Fig. 9b](#) and [Fig. 10b](#).

4.1.2 Effect of notch on stress behavior

The presence and size of a notch introduce stress concentrations that significantly impact mechanical behavior.

Reference (unnotched) specimens: Show the highest stress values, indicating that continuous fiber paths and undisturbed cross-sectional areas provide optimal tensile strength. For 2 mm notch specimens, experience slightly reduced stress values compared to reference samples, but still maintain relatively good mechanical performance. The small notch causes moderate stress concentration but allows partial redistribution of stress around the notch tip.

Specimens with 4–6 mm notches exhibit substantial reductions in peak stress due to increased notch severity. The larger the notch, the more the cross-sectional area is compromised, resulting in early crack initiation and reduced ultimate tensile strength. These specimens often fractured prematurely, showing that the notch acts as a critical weakness, especially when aligned with the fiber direction. This behavior is reflected in Figs. 9 and 10, where the peak tensile stress decreases as the notch width increases from 0 to 6 mm.

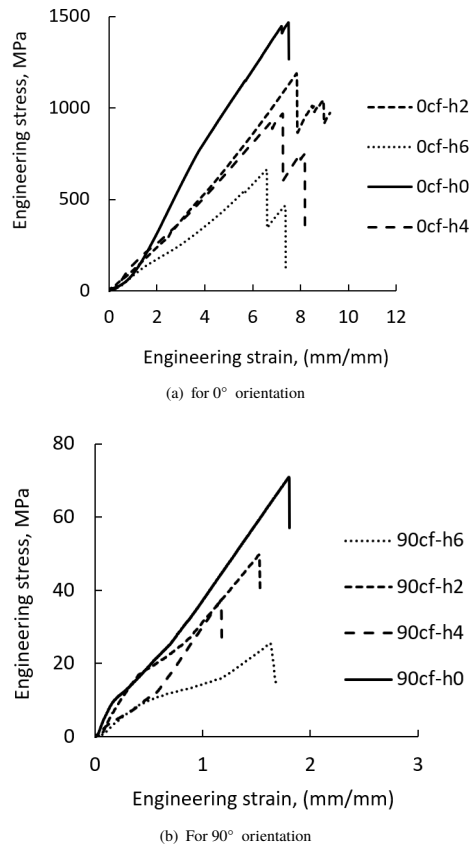


Figure 9. stress-strain behavior of the CFRP composite.

4.1.3 Comparative the behavior of CFRP verses GFRP

In addition to analyzing individual behaviors, a comparison between carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP) specimens under tensile loading reveals notable differences in mechanical performance are listed in Table 4. The stress-strain curves for carbon fiber composites demonstrate significantly improved mechanical behavior when compared to glass fiber composites. Specifically, Higher maximum stress values were achieved in CFRP specimens, especially those with fibers aligned in the loading direction (0°orientation). This is due to the inherently higher tensile strength of carbon fibers. The initial linear region of the stress-strain curve in CFRP samples is much steeper, indicating greater stiffness (higher modulus of elasticity E). Carbon fibers are known for their rigidity and low elongation under stress. Both carbon and glass fibers show a clear reduction in tensile strength and strain as notch size increases, especially at 90°orientation. This highlights the importance of minimizing notches or defects in materials to maintain their mechanical properties.: Carbon fibers perform significantly better at the 0°orientation, whereas glass fibers, though weaker overall, also perform better at 0°orientation than at 90°orientation. The data shows that both carbon and glass fibers exhibit modulus E degradation and reduced strain energy absorption as notch size increases, indicating increased notch sensitivity. Carbon fibers are less affected by notches, especially at the 0°orientation, where they maintain higher tensile strength and strain values. However, at the 90°orientation, the modulus and strain drop significantly with increasing

notch size, suggesting higher vulnerability at this orientation. Glass fibers are more sensitive to notches, particularly at the 90°orientation. Both their tensile strength and strain decrease sharply with larger notches, indicating a significant loss in performance under such conditions. These trends are confirmed by the comparative stress-strain curves shown in Figs. 9 and 10.

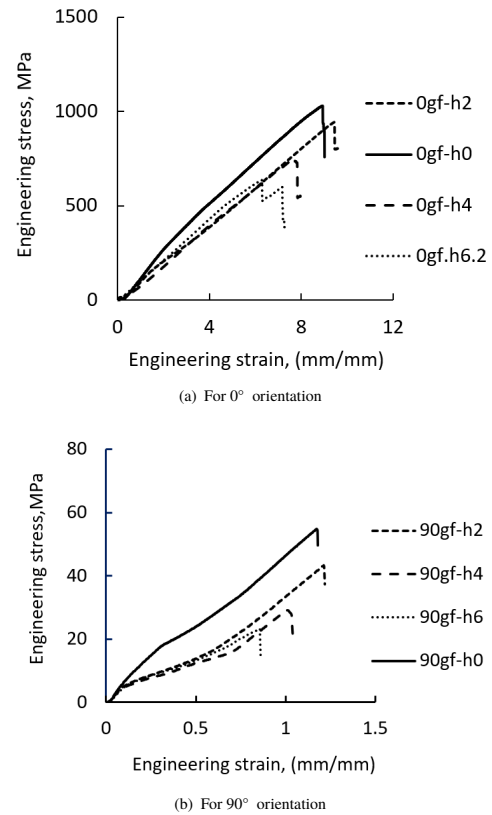


Figure 10. stress-strain behavior of the GFRP composite.

Table 4. Results of the stress-strain behaviour of the GfRP and CFRP.

Fiber	Orientation	Notch (mm)	Tensile strength (MPa)	Elastic Modulus (MPa)
Carbon	0°	0h	1345	134.77
		2h	1185.8	124.30
		4h	966.7	133.15
		6h	716.2	116.99
	90°	0h	70.83	39.35
		2h	69	39.43
		4h	37.33	31.91
		6h	34.66	28.41
Glass	0°	0h	1004.16	112.45
		2h	910	106.56
		4h	750	97.28
		6h	534.17	77.42
	90°	0h	56.67	719.75
		2h	40	735.09
		4h	30.33	33.70
		6h	21	29.58

4.2 Fracture analysis

The mechanical behavior of fiber-reinforced polymer (FRP) composites under tensile loading varies significantly with fiber orientation and the presence of geometrical discontinuities (e.g., notches). In this work, fracture patterns were observed for both carbon-fiber and glass-fiber reinforced coupon specimens with varying notch widths and two principal fiber orientations: 0°orientation and 90°orientation. Every outcome is the mean of three repeats. Tensile strength and modulus data had their standard deviation computed and published. Visual inspection and alignment checks before testing confirmed

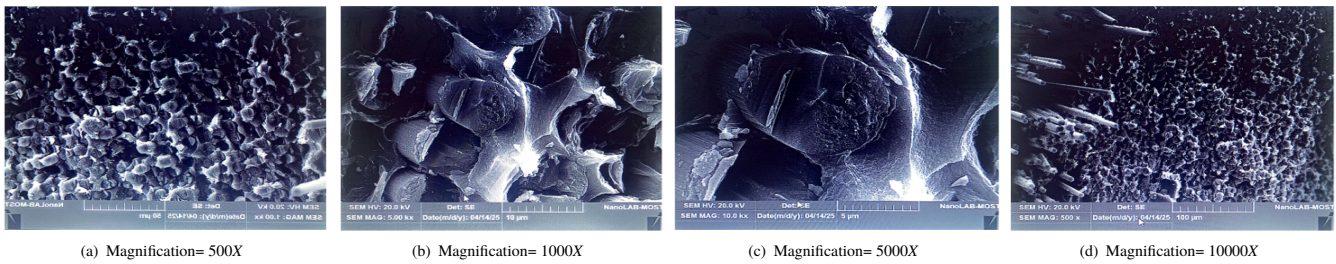


Figure 11. SEM micrographs of CFRP specimen (0° fiber orientation, 6 mm notch) at different magnifications.



Figure 12. Comparison of fracture modes between CFRP and GFRP specimens under tensile loading.

consistency among samples. Figure 11 presents the SEM micrographs of carbon fiber reinforced polymer (CFRP) specimens with fibers oriented at 0°orientation, aligned parallel to the direction of loading, and containing a 6 mm notch. This configuration ensures that the carbon fibers directly contribute to load-bearing, significantly influencing the fracture behavior.

4.2.1 Behavior at 90° orientation Fiber Orientation

At a 90° orientation, the fiber alignment is parallel to the applied tensile load. The failure behavior under this configuration revealed several key characteristics. Specimens with 4–6 mm notches at mid-span showed a clear, localized fracture at the center of the specimen. The failure initiated directly at the notch tip, indicating high stress concentration due to the reduced cross-sectional area and increased notch severity. As the notch width increased from 4 mm to 6 mm, the structural integrity of the specimen further degraded, accelerating the onset of crack propagation and failure. Specimens with a 2 mm notch exhibited a slightly different failure pattern. In these cases, the fracture happened on the far side of the middle, slightly offset from the notch. This suggests that the stress distribution in narrower notches allows for some redistribution of load, delaying fracture directly at the notch. Reference specimens (no notch) also showed fracture occurred on the far side of the middle. However, the fracture was less localized and appeared to occur at a natural point of material weakness, such as microvoids or fiber misalignment, rather than a predefined geometrical feature. These observations indicate that at 90° orientation, fracture is primarily governed by axial tensile stresses, and the presence of a notch strongly influences the location and severity of failure. The corresponding fracture modes are illustrated in [Fig. 12a](#) for carbon-fiber specimens and [Fig. 12b](#) for glass-fiber specimens.

4.2.2 Behavior at 0° orientation fiber Orientation

In contrast, specimens with fibers oriented at 0° to the loading axis displayed entirely different mechanical behavior. No complete fracture was observed in any of the specimens with this orientation, regardless of whether a notch was present or not. Instead of fracturing, the samples exhibited fiber tearing or splitting along the fiber direction. The matrix material showed signs of cracking, but the fibers themselves resisted complete rupture. The load was

mainly carried by the matrix rather than the fibers in this configuration, leading to delamination and interfacial failure rather than catastrophic failure. These findings suggest that when the load is applied perpendicular to the fiber direction, the composite fails in a more ductile, progressive manner, with energy dissipated through fiber-matrix debonding and matrix cracking, rather than through sudden brittle fracture, as shown in Fig. 12a and Fig. 12b respectively.

5. Conclusions

This study experimentally evaluated the influence of fiber orientation and notch geometry on the tensile behavior of CFRP and GFRP composites manufactured by VARTM. The results show that fiber orientation has a major role in mechanical performance. Specimens aligned at 0° achieved higher tensile strength and stiffness than those tested at 90° . Notch width was also important; 4 and 6 mm notches created strong stress concentrations and led to earlier failure, while unnotched and 2 mm notched specimens retained better structural integrity and were easier to manufacture. These findings indicate that fiber orientation is the dominant factor, but notch geometry must also be considered when designing polymer-matrix composite components. The study was limited to unidirectional orientations and static tensile loading, so the results should be extended carefully to more complex loading cases. For applications where tensile strength is critical, aligning the fibers with the load direction is recommended because this condition produced about 40% higher tensile strength. Future investigations should include multidirectional layups, hybrid reinforcement systems, and cyclic or impact loading to better represent service conditions. Full-field strain measurement using digital image correlation and finite-element modeling would also help explain the local stress distribution around notches and support the design of more damage-tolerant composite structures.

Authors' contribution

Sabaa R. Al-Gubbanchi: conceptualization, methodology, investigation, data curation, formal analysis, writing – original draft, and writing – review and editing **Nassier a. Nassir:** conceptualization, methodology, supervision, validation, data curation, formal analysis, and writing – review and editing.

