

Research Paper

Effect of Manufacturing Route and Fiber Orientation on the Mechanical Performance of Carbon Fiber Composites for Automotive Lightweight Components

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Abstract

This study evaluates the effects of manufacturing method and fiber orientation on the mechanical performance of carbon fiber-reinforced polymer (CFRP) composites for automotive applications. Unidirectional CFRP laminates were fabricated using vacuum bagging (VB), vacuum-assisted resin infusion (VARI), and hand lay-up (HLU). Specimens with 0° and 90° fiber orientations were tested under tensile and compressive loading, while ±45° specimens were evaluated for in-plane shear response through tensile testing. Short-beam and V-notched beam tests were conducted to determine interlaminar shear and shear properties. Microstructural characterization of the manufactured laminates and fractured specimens was performed using CT-scan and SEM, supported by finite element validation. Unlike previous studies focusing on limited properties or a single manufacturing route, this work provides a comprehensive comparison of HLU, VB, and VARI CFRP laminates by integrating mechanical testing, defect analysis, fracture observations, and numerical assessment. The results show that VARI produced superior laminate compactness and the highest tensile-related properties, although this improvement did not correspond to higher interlaminar shear strength, highlighting the influence of manufacturing-induced laminate architecture. For 0° specimens, ultimate tensile strengths were 507.72 ± 52.14 MPa for HLU, 685.69 ± 62.65 MPa for VB, and 774.31 ± 58.18 MPa for VARI. At ±45°, tensile strengths were 20.85 ± 0.82, 21.20 ± 0.45, and 22.18 ± 0.81 MPa, respectively. At 90°, manufacturing method had no significant effect on tensile strength, although tensile modulus remained method-dependent. The highest 0° compressive strength was obtained by HLU at 124.8 ± 13.1 MPa, whereas VARI showed the highest 90° compressive strength at 44.60 ± 0.82 MPa. VARI exhibited lower shear and interlaminar shear strengths of 15.31 ± 1.01 and 13.68 ± 0.85 MPa, respectively, indicating that increased fiber volume fraction did not substantially improve these properties. Nevertheless, VARI achieved the highest tensile and shear moduli, reaching 39.31 ± 4.58 GPa and 1.50 ± 0.15 GPa. Microstructural observations confirmed that improved resin distribution, reduced defects, and stronger fiber-matrix bonding in VARI contributed to enhanced overall mechanical performance. These findings demonstrate that manufacturing route governs different failure mechanisms and should therefore be selected according to the dominant loading mode and required laminate properties.

Keywords: CFRP; Vacuum bagging; Vacuum-assisted Resin infusion; Fiber orientation; Mechanical properties



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1. Introduction

Transportation is one of the highest contributors to CO₂ emissions, along with other sectors such as power generation [1]. To reduce CO₂ emissions and improve energy efficiency, the utilization of lightweight materials such as composites is important in the automotive industry [2], [3], [4], [5]. A composite is a material composed of two or more materials with different characteristics, resulting in a material with properties that differ from those of its basic materials [6]. Fiber-reinforced polymers (FRP) are a type of composite material being used to replace metal materials [7], [8], [9], [10], [11], [12]. One type of FRP composite used in various industries is carbon fiber-reinforced polymer (CFRP) [13]. Its application has likewise expanded across the automotive, aerospace, marine, wind turbine, military, sports, and civil engineering sectors [14], [15], [16], [17], [18], [19]. This is due to the high specific modulus, stiffness, and strength, as well as its reliability, high impact resistance, fatigue resistance, corrosion resistance, chemical resistance, temperature resistance, wear resistance, and dimensional stability [20], [21], [22], [23], [24]. CFRP provides several significant benefits that can be used in most automotive applications, such as underbody structures, roofs, floors, and body panels that are stiffness-driven [25]. Initially, CFRP was used in high-end racing cars and supercars, with the first CFRP monocoque chassis appearing in 1981 and the first CFRP body shell in 1996. However, CFRP is now used to reduce CO₂ emissions in the automotive industry, as the use of lightweight CFRP materials improves fuel efficiency [13]. A 10% weight reduction improves fuel economy by 6.9% and increases acceleration from 0-60 mph by 7% in combustion engine vehicles [4].

Several studies have used CFRP composite materials for automotive applications. Among them is a comparative study between high-strength steel and CFRP/polyester manufactured using compression and sheet molding processes for the Ford Fusion I4 engine subframe [1]. A study by Hiremath *et al.* compared the mechanical properties of two types of CFRP composites fabricated using vacuum consolidation and vacuum infusion processes [25]. Another study by Caltagirone *et al.* used recycled carbon fiber/epoxy prepreg scrap manufactured using an injection

molding process [26]. Similar to Caltagirone *et al.*, Meng *et al.* also conducted a study on the use of recycled carbon fiber/epoxy prepreg with compression molding and injection molding processes for automotive applications [27]. The study by Irez and Yakar used recycled carbon fiber prepreg manufactured using an extrusion process for application in automotive industry components [28]. Meanwhile, Gardie *et al.* [6] and Zhang *et al.* [2] conducted numerical analysis studies on the application of CFRP materials as wheel and floor materials for automobiles, respectively.

Several studies have used composite materials with reinforcements other than carbon fiber. Among them is the use of fiberglass mat/polyester composites for motorcycle body cover applications [29]. Another study by Perkasa *et al.* used natural Ramie-Polylactic Acid (PLA) composites for electric vehicle chassis applications [30]. Meanwhile, many studies have used composites with natural reinforcement materials for brake pad applications [31], [32], [33], [34]. Although natural composites have the advantage of being biodegradable, their mechanical performance is inferior to that of CFRP composites, especially for applications requiring materials with high stiffness and strength. Therefore, CFRP composites are still the primary choice for automotive component applications.

A variety of methods may be employed when fabricating composites from dry fibers and liquid resin effectively. The methods comprise wet hand lay-up (HLU), vacuum-assisted resin infusion (VARI), and vacuum bagging (VB). The VARI process has attracted growing interest because it can produce large composite structures with outstanding mechanical properties [14]. The common of the VARI technique variants are Controlled Atmospheric Pressure Resin Infusion (CAPRI), Seemann Composites Resin Infusion Molding Process (SCRIMP), Vacuum-Assisted Resin Transfer Molding (VARTM), Vacuum-Assisted Process (VAP), Pulsed Infusion (PI), and Double Bag Vacuum Infusion (DBVI) [7], [16]. VARTM represents the simplest technique of resin infusion, lacking a resin flow medium to assist wetting [16]. SCRIMP resembles VARTM, yet incorporates a flow medium that facilitates resin movement across the laminate surface, thereby shortening wetting time [16]. CAPRI is an

SCRIMP-based technique that enhances dry fiber compaction and limits laminate thickness growth by repeatedly cycling the bag pressure between atmospheric pressure and high vacuum 10–20 times prior to resin infusion [16]. A semi-permeable membrane is employed in the VAP to degas the lamination zone, thereby reducing the risk of resin locking and enabling the large-scale dry-point process pioneered by European Aeronautic Defence and Space Company (EADS)/Airbus [16], [35]. DBVI employs two vacuum bags to reduce laminate relaxation and enhance vacuum integrity [16]. PI is a new infusion technique that uses pressure pulsation and a reusable silicon pressure distributor as a medium for resin flow to save consumable costs and improve mechanical qualities. The aircraft manufacturer has now introduced the vacuum-assisted resin infusion process for fabricating wing covers, as exemplified by the Bombardier C Series (now the Airbus A220) [36].

Several previous studies have investigated the impact of different manufacturing methods on the mechanical and functional performance of CFRP composites. A study by Toldy *et al.* revealed that the flame-retardant performance of unidirectional carbon composites is enhanced by vacuum infusion compared with HLU followed by hot pressing [23]. Kubit *et al.* reported that plain-weave carbon fiber composites manufactured by vacuum bagging, vacuum infusion, and autoclave processes exhibit superior tensile and flexural properties when the fibers are in the 0° direction using the autoclave process compared with 45° [37]. Ula *et al.* found that unidirectional carbon fiber sandwich composites fabricated by the VARI method exhibit the highest natural frequency compared with those produced by VB and HLU [38]. Other studies on glass and basalt composites have consistently shown that VARI-processed laminates represent superior properties compared with those manufactured by vacuum bagging or hand lay-up methods [39], [40]. Other studies on glass fiber and ramie-reinforced composites indicate that VARI-processed laminates exhibit mechanical performance comparable to that of composites manufactured by hand lay-up [41], [42]. In contrast to most reports, studies by Scalici *et al.* [43] and Esnaola *et al.* [44] showed that basalt and glass fiber composites manufactured by HLU and VB exhibited superior properties compared

with those produced using the VARI method. Although previous studies have partially investigated the influence of manufacturing techniques and fiber orientation on composite performance, their scope remains limited. For instance, the study by Scalici *et al.* [43] compared only VB and VARI in unidirectional basalt fiber-reinforced composites, focusing mainly on tensile properties at 0° and 90°, shear strength, and interlaminar shear strength (ILSS), without considering HLU processing or compressive properties. Similarly, Kubit *et al.* [37] evaluated the effect of VB and VARI on unidirectional carbon fiber composites, but their investigation was restricted to tensile behavior at 0° and 45° fiber orientations, excluding 90° tensile performance as well as compressive, shear, and ILSS characteristics.

Although several studies have investigated the influence of manufacturing methods on CFRP composites, most have focused on limited loading conditions, specific fiber architectures, or single mechanical responses, without systematically evaluating the combined influence of fabrication route and fiber orientation on the overall mechanical performance relevant to automotive structures. The reported findings remain fragmented and sometimes inconsistent due to differences in fiber architecture, constituent materials, and testing scope. Most existing studies focus on selected manufacturing routes or limited mechanical responses, while a comprehensive comparison integrating multiple fabrication methods (HLU, VB, and VARI), fiber orientations, defect characterization (CT-scan and SEM), and numerical validation for unidirectional T300 CFRP laminates remains limited. Therefore, this study addresses this gap by comprehensively investigating the effects of HLU, VB, and VARI processes combined with 0°, 90°, and ±45° fiber orientations on the tensile, compressive, shear, and interlaminar shear properties of CFRP, supported by CT-scan, SEM, and finite element analysis to establish a more comprehensive performance–manufacturing relationship for lightweight automotive applications. The novelty of this study lies in establishing an integrated process–structure–property relationship for unidirectional T300 CFRP laminates fabricated using HLU, vacuum bagging VB, and VARI. Unlike previous studies that mainly focused on

selected manufacturing methods or isolated mechanical responses, this work systematically correlates manufacturing-induced laminate characteristics (fiber volume fraction, density, thickness, and void distribution) with mechanical behavior, failure mechanisms, SEM observations, and finite element predictions across multiple fiber orientations. Furthermore, this study provides new insight into the finding that improved laminate compactness and tensile-related properties do not necessarily correspond to enhanced interlaminar shear performance, highlighting the critical role of matrix-dominated interfacial behavior in composite design. This work aims to systematically investigate the influences of manufacturing methods—VARI, HLU, and VB—and fiber direction on the tensile, compressive, shear, and interlaminar shear properties of CFRP. This research employs epoxy resin as a matrix and carbon fiber as reinforcement. The mechanical qualities, failure modes, microstructural features, and finite element analysis are studied.

2. Methods

2.1. Materials

The specimens were manufactured from carbon-fiber/epoxy composite materials. The material utilised was unidirectional carbon fiber 12K T300, and the epoxy resin was Bisphenol-A epoxy resin Eposchon 1011 A, together with the cycloaliphatic amine hardener Eposchon 1011B, both of which are commonly used in composites, adhesives, and coatings. The recommended formulation required mixing epoxy with hardener in a 2:1 ratio. The materials used to fabricate the composites were sourced from Perdana Chemindo Perkasa for carbon fiber and Justus Kimia Raya Indonesia for epoxy resin. Unidirectional 12K T300 carbon fiber was made from carbon fiber yarn with a 12K rating (12,000 filaments per bundle), featuring a unidirectional orientation, with a basis weight of 300 gsm (grams per square meter). The fiber architecture was predominantly aligned along the principal direction (0°), consisting of approximately 90–95% carbon fibers in the longitudinal direction and 5–10% transverse binding yarns to maintain fabric integrity and dimensional stability. The technical characteristics of the carbon fiber included a density of 1.8 g/cm^3 , a nominal thickness of 0.167

mm, and a filament diameter of approximately $7 \text{ }\mu\text{m}$. Eposchon 1011A is the standard unmodified liquid purpose epichlorohydrin bisphenol A epoxy resin, having medium-high viscosity and high heat distortion temperature. The technical properties of the Eposchon 1011 epoxy resin are presented in [Table 1](#).

2.2. Fabrication Process

VARI, VB, and manual HLU composite processes were used to create the CFRP panels. The manufacturing process was performed at room temperature. For each manufacturing method, the CFRP laminates were fabricated with carbon fiber orientations of 0° and 90° for tensile and compressive tests, $\pm 45^\circ$ for in-plane shear response by tensile test, and 0° for the v-notched beam test and short beam shear test. Different fiber orientations were intentionally employed to characterize the anisotropic mechanical behavior of CFRP composites under various loading conditions. Specifically, 0° and 90° fiber orientations were used to evaluate longitudinal and transverse tensile/compressive responses, whereas the $\pm 45^\circ$ orientation was employed to characterize the in-plane shear response according to ASTM D3518. The v-notched beam and short beam tests were performed using 0° laminates following the respective ASTM recommendations (ASTM D5379 and ASTM D2344). The comparison in this study was conducted between different manufacturing methods (HLU, VB, and VARI) under the same fiber orientation and loading condition, rather than between different fiber orientations. The mechanical property data obtained from multiple fiber directions are intended to provide directional material properties required for the structural analysis and design of anisotropic CFRP automotive components.

Accordingly, a total of three CFRP panels were fabricated with a 0° fiber orientation with a stacking sequence of $[0]_4$, three panels with a 90° fiber orientation with a stacking sequence of $[90]_8$, and three panels with a $\pm 45^\circ$ fiber orientation with a stacking sequence of $[+45/-45/+45/-45]_s$ for tensile test specimens. Similar to the tensile specimens, three CFRP panels with 0° fiber orientation and three with 90° orientation, each consisting of ten plies with stacking sequences of $[0]_{10}$ and $[90]_{10}$, were fabricated for compression

Table 1. The technical properties of the Eposchon 1011

Properties	Unit	Value
Epoxy number	%	22.7 ± 0.6
Epoxy equivalent	g/equiv.	189 ± 5
Epoxy value	Equiv./100 g	0.53 ± 0.01
Total chlorine content	%	< 0.2
Hydrolyzable chlorine content	%	< 0.05
Volatile content at 3 h, 140 °C	%	< 0.2

testing. In addition, three CFRP panels were fabricated with fiber orientations of 0° with stacking sequences of [0]₁₃ and [0]₂₀ for the short beam and v-notched beam test, respectively.

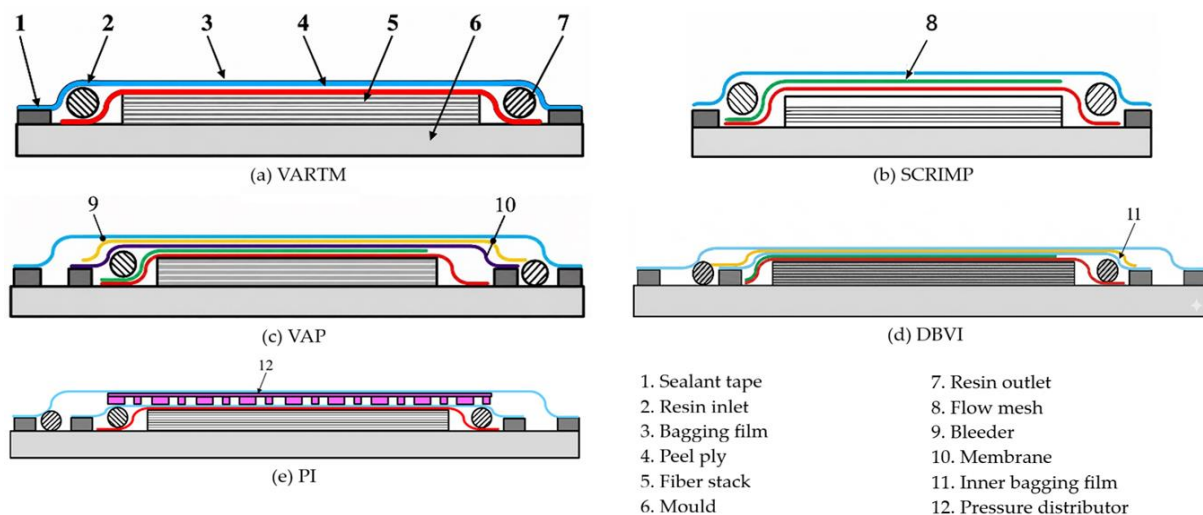
Prior to application, the epoxy resin and hardener (2:1) were mechanically mixed using an IKA Microstar 15 stirrer at a rotational speed of 500 rpm for 2 min to ensure homogeneous mixing. For the HLU process, the resin mixture was applied within 30 min after mixing to avoid premature gelation at room temperature.

The hand lay-up process was initiated by arranging the carbon fiber layers on the mould surface, followed by the manual application of liquid resin onto each fiber ply using a brush to ensure uniform impregnation throughout the laminate. After lay-up of the final ply, the laminate is left to cure at ambient conditions for 24 hours. The vacuum bagging technique is an expansion of the HLU method, where a plastic vacuum bag, peel ply, and breather are used to seal the laminated region and are attached to a vacuum pump. The applied vacuum pressure was set to -100 kPa, corresponding to the maximum capacity of the vacuum pump, and is maintained until resin gelation at room temperature and throughout the 24-hour curing duration.

For the VARI process, vacuum pressure was utilized to flow epoxy resin into the fiber plies. Vacuum pressure was generated using a Vacmobile PVR EM8/B vacuum pump (50 Hz, flow capacity of 8.5 m³/h; New Zealand), with a maximum attainable vacuum pressure of -100 kPa. The vacuum is maintained until resin gelation, followed by curing of the panels at ambient temperature for 24 hours. The vacuum pressure applied was identical to that used in the vacuum bagging process (-100 kPa).

The VARI setup employed in this study differs from several previously reported VARI configurations illustrated in Figure 1. In this study, the VARI setup is similar to the SCRIMP configuration, with the addition of a flow mesh and peel ply placed beneath the fiber stack, as shown in Figure 2. This configuration promotes deeper resin impregnation, as the presence of flow meshes on both the bottom and top faces enables resin flow and penetration from both directions into the fiber stack.

Figure 3 illustrates the three CFRP manufacturing processes investigated in this study. After fabricating the carbon fiber reinforced composite plates, they were water jet cut into sets of five specimens that met the geo-

**Figure 1.** The variant of the VARI process [16] (permission No. 6196381062657)

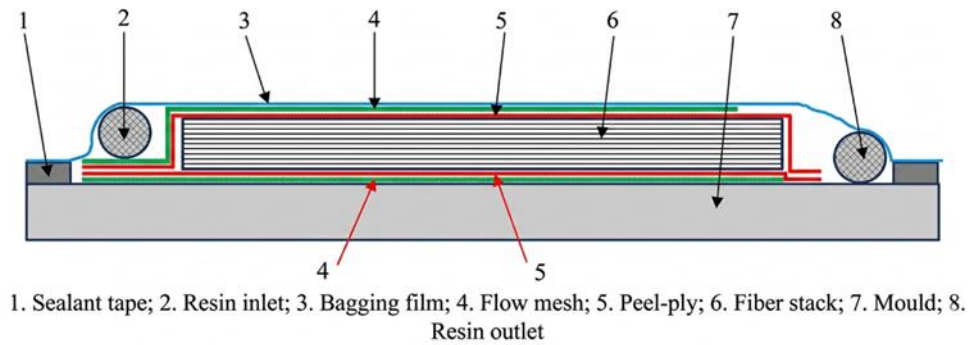


Figure 2. The VARI setup

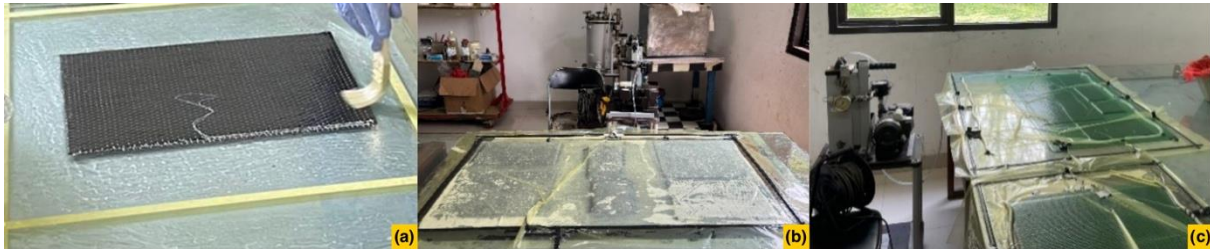


Figure 3. Manufacturing process of CFRP panels: (a) HLU, (b) VB, and (c) VARI

metric dimensions of the American Standard Testing Method (ASTM).

2.3. Characterization

2.3.1. X-ray computed tomography (CT)

X-ray computed tomography (CT) was employed to characterise the internal microstructural features of CFRP laminates manufactured using VARI, VB, and HLU. The CT-scan analysis was conducted to qualitatively and quantitatively evaluate manufacturing-induced defects without damaging the specimens. CT images were acquired using an X-ray CT system at PT. Nikon Indonesia. The scanned volume encompassed the full laminate thickness to enable through-thickness assessment of defect distribution. Reconstructed cross-sectional and three-dimensional images were analysed to compare the internal characteristics of CFRP panels produced by the different manufacturing methods.

CT-scan characterization was conducted only on CFRP laminates with a 0° fiber orientation for the HLU, VB, and VARI fabrication methods. The 0° orientation was selected as a representative configuration because it corresponds to the principal load-bearing direction in unidirectional CFRP composites and provides a suitable basis for evaluating manufacturing-induced defects, including void distribution and internal porosity. Since the objective of the CT analysis was to

compare the influence of manufacturing methods on laminate quality, a consistent fiber orientation was maintained across all specimens.

2.3.2. Mechanical test

The selection of fiber orientations and mechanical tests was based on the material property requirements commonly used in composite structural analysis [45] and engineering design [46]. Tensile properties at 0° and 90° fiber orientations were characterized according to ASTM D3039, while the $\pm 45^\circ$ orientation was employed to determine in-plane shear properties following ASTM D3518 through tensile loading. Compressive properties were evaluated at 0° and 90° orientations according to ASTM D6641 to characterize longitudinal and transverse compressive behavior. For the V-notched beam test (ASTM D5379), only unidirectional laminates with a 0° fiber orientation were tested to determine the shear strength and shear modulus required for anisotropic material characterization. In addition, interlaminar shear properties was determined using ASTM D2344 with a 0° fiber orientation. This testing matrix was selected to provide the essential directional material properties required for anisotropic composite structural evaluation. Accordingly, comparisons in this study were performed among different manufacturing methods under identical fiber orientations and

testing configurations rather than between different fiber orientations.

2.3.2.1. Tensile test

Tensile testing was performed in this study using the ASTM D3039 standard as a guide. For 0° specimens, the size was 250 x 15 x 1 mm, while for 90° specimens, it was 175 x 25 x 2.5 mm. Tensile testing was also performed on specimens with a fiber orientation of ±45° (ASTM D3518) to specify the in-plane shear response of CFRP with specimen dimensions of 250 x 25 x 2.5 mm. The thickness of the specimen refers to the thickness of the composite specimen from the VARI, whereas the specimen thickness from the HLU and VB processes is thicker, as explained in the subsection on materials and fabrication process. The Tensilon RTF 2410 universal testing machine (UTM) was utilised to conduct the test. The test was performed under laboratory environmental conditions of 24.3 °C and 49.2% relative humidity (RH). Each carbon fiber/epoxy composite has five specimens, and the tensile characteristics were examined. The setup for composite tensile testing with fiber direction variations can be seen in Figure 4a.

Stress calculations according to ASTM D3039 utilise Eq. (1), where σ is tensile stress (MPa), P is load (N), and A is area (mm²). Meanwhile, stress calculations for ±45° specimens based on ASTM D3518 utilise Eq. (2), where τ is the in-plane shear stress (MPa), P is the load (N), and A is the area (mm²). Eq. (1) was used to calculate the tensile stress and strength of CFRP composites with 0° and 90° fiber orientations, whereas Eq. (2) was employed to determine the in-plane shear stress and strength of composites with a ±45° fiber orientation for the Discussion section.

$$\sigma = P/A \quad [47] \quad (1)$$

$$\tau = P/2A \quad [48] \quad (2)$$

2.3.2.2. Compressive test

Compressive testing was conducted in this manner according to the ASTM D6641 standard, utilising an appropriate test fixture. The size was 140x13x3 mm for 0° and 90° specimens. The Tensilon RTF 2410 UTM was used to perform the test. The test was performed under laboratory environmental conditions of 24.3 °C and 49.2% relative humidity (RH). Each carbon fiber/epoxy

composite has five specimens, and the compressive characteristics were investigated. The calculation of compressive stress is similar to the calculation of tensile stress in Equation (1), where the area considered is the gage area. The composite compression test setup with fiber direction variations can be seen in Figure 4b.

2.3.2.3. V-notched beam test

The V-notched beam test was performed to determine the shear properties of CFRP with unidirectional fibers. V-notched beam testing was performed in this study according to the ASTM D5379 standard, utilising an appropriate test fixture. The sample dimensions and test setup are as shown in Figure 5, where L is 76 mm, d_1 is 20 mm, w is 12 mm, and h is 4 mm for the VARI composite, while the HLU and VB composites are thicker. The Tensilon RTF 2410 UTM was used to perform the test. The test was performed under laboratory environmental conditions of 24.3 °C and 49.2% relative humidity (RH). Each carbon fiber/epoxy composite has five specimens, and the shear characteristics were evaluated.

The shear stress calculation based on ASTM D5379 follows Eq. (3). A in the v-notched specimen is $w \times h$ as shown in Figure 5b, where w is the distance between the v-ends (mm) and h is the thickness (mm). Eq. (3) was used to calculate the shear stress and strength of CFRP composites for the Discussion section.

$$\tau = P/A \quad [49] \quad (3)$$

2.3.2.4. Short beam test

A short beam test was conducted to determine the interlaminar shear strength of the specimens. Short beam testing was performed in this manner according to the ASTM D2344 standard, utilising three point bending test fixture. The size was 40 x 11 x 5 mm. The Tensilon RTF 2410 UTM was used

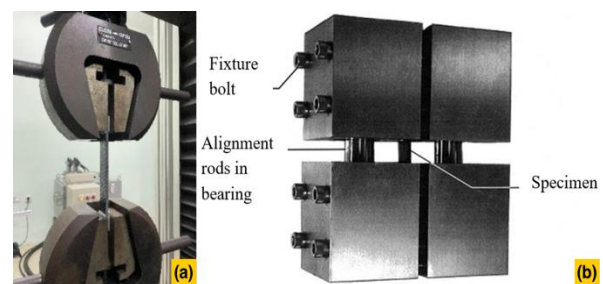


Figure 4. Tensile (a) and compressive (b) test set-up

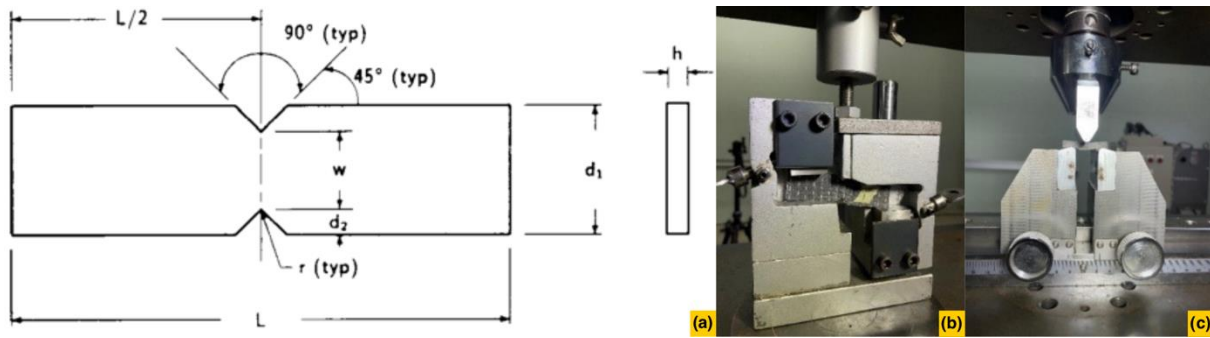


Figure 5. (a) V-notched beam specimen; (b) V-notched test set-up; (c) Short beam test set-up

to perform the test. The test was performed under laboratory environmental conditions of 24.3 °C and 49.2% relative humidity (RH). Each carbon fiber/epoxy composite has five specimens, and the interlaminar shear characteristics were observed. The short beam test set-up was illustrated in [Figure 5c](#). The interlaminar shear stress calculation based on ASTM D2344 follows Eq. (4), where F : interlaminar shear stress (MPa), P : the load (N), b : the specimen width (mm), and h : the thickness (mm). Eq. (4) was used to calculate the interlaminar shear stress and strength of CFRP composites for the Discussion section.

$$F = 0.75 \times P / (b \times h) \quad [50] \quad (4)$$

The specimen thicknesses used in this study were selected in accordance with the dimensional recommendations specified in the relevant ASTM standards for each mechanical test. Different ASTM standards prescribe different specimen geometries, including thickness, depending on the loading mode and test objective. For example, tensile testing (ASTM D3039), compression testing (ASTM D6641), v-notched shear testing (ASTM D5379), and short beam interlaminar shear testing (ASTM D2344) each recommend different specimen thicknesses to ensure reliable stress distribution and representative failure mechanisms.

2.3.3. Failure analysis

The failure mode of the specimen was analysed through macro photographic observation. To explore the interfacial behaviour of composite materials, specimens were subjected to fractographic investigation using scanning electron microscopy (SEM). SEM specimens were collected from post-tensile fracture samples and evaluated at the Energy Laboratories of the

National Research and Innovation Agency. SEM was utilized to examine the microstructural features of specimens produced by the VARI, VB, and HLU manufacturing processes.

2.3.4. Finite element analysis

This work utilised finite element analysis (FEA) to evaluate the tensile response and failure behaviour of UD CFRP laminates with different fiber orientations. The FEA employed shell elements with assigned orthotropic material properties, laminate thickness, and fiber orientation corresponding to the experimental specimens. In addition to comparing the numerical and experimental stress-strain responses, the FEA was used to evaluate the capability and limitations of the adopted material model and Hashin failure criterion in representing orientation-dependent tensile behaviour and failure mechanisms of the laminates. The Hashin failure criterion, which is commonly used for composite failure prediction, was adopted in this study to model fiber- and matrix-dominated damage initiation.

3. Results and Discussion

3.1. Fabrication Results

The manufacturing outcomes reveal distinct physical characteristics among the three processes, with fiber volume fractions of 50.44% with void content of 5.74% for VARI, 37.86% with void content of 7.97% for VB, and 26.93% with void content 9.12% for HLU. These results indicate that VARI produces the highest fiber volume fraction (i.e., the lowest resin content), followed by VB and HLU. The differences in fiber volume fraction among the HLU, VB, and VARI laminates are inherent to the respective manufacturing processes and were intentionally

preserved in this study to represent realistic fabrication outcomes. In the HLU process, the absence of vacuum pressure results in higher resin retention and lower laminate compaction, whereas the application of vacuum in VB reduces excess resin and improves fiber consolidation. The VARI process, in which vacuum is maintained throughout resin infusion, promotes enhanced laminate compaction and more effective resin distribution, resulting in a higher fiber volume fraction. Therefore, the comparison performed in this study aims to evaluate the practical influence of different manufacturing routes on the resulting composite characteristics and mechanical performance, rather than to compare laminates with artificially equalized fiber volume fractions.

Differences in density were also observed, with values of 1.25 g/cm³ for HLU, 1.31 g/cm³ for vacuum bagging, and 1.44 g/cm³ for VARI. The density of the composite laminates was measured using a density kit attached to a Precisa ES320A analytical balance following ASTM D792. The measurements were conducted using the water displacement method by determining the specimen weight in air and immersed in water. The density was calculated according to Eq. (4), $\rho = \rho_0 \left(\frac{A}{A-B} \right)$ [51], where ρ_0 denotes the density of water, A is the specimen weight measured in air, and B is the specimen weight measured in water. The higher density of the VARI composite is attributed to its increased fiber volume fraction compared with the VB and HLU composites.

Specimen thickness also varied among the three manufacturing methods, with the VARI process producing the thinnest CFRP laminates, while the vacuum bagging and hand lay-up specimens were approximately 22% and 111% thicker than those produced by VARI, respectively. The differences in laminate thickness observed among HLU, VB, and VARI specimens were considered an inherent consequence of the respective manufacturing routes and were intentionally retained to represent realistic fabrication outcomes. The absence of vacuum pressure in HLU resulted in greater resin retention and lower laminate compaction, leading to thicker laminates. In contrast, VB improved laminate consolidation through vacuum compaction, whereas the VARI process, with vacuum applied throughout resin infusion,

promoted enhanced fiber consolidation and produced thinner, more compact laminates. Therefore, laminate thickness was evaluated as an important manufacturing outcome of each process, enabling a practical comparison of the resulting composite characteristics and mechanical performance for structural applications.

These results indicate that the VARI process produces more compact composites due to the continuous application of vacuum pressure from impregnation through curing, followed by vacuum bagging and hand lay-up. Consequently, VARI is a suitable primary manufacturing route for liquid-resin composite systems where laminate thickness is a critical constraint.

3.2. CT-Scan

Figure 6 presents representative CT-scan images of composite specimens manufactured by HLU (Figure 6a), VB (Figure 6b), and VARI (Figure 6c). The carbon composite regions appear in dark contrast, whereas the lighter regions correspond to the glass-fiber composite tabs. The CT images reveal that manufacturing-induced defects are predominantly present as voids within the carbon composite for the HLU and VB specimens, with a representative void in the HLU specimen measuring approximately 0.71 mm in height and 1.75 mm in width, and a smaller void in the VB specimen measuring about 0.412 mm in height and 0.686 mm in width.

CT-scan observations revealed distinct differences in void morphology and spatial distribution among the HLU, VB, and VARI laminates. The HLU laminate exhibited a relatively high density of voids with larger apparent diameters, reaching several millimeters in length (approximately 0.7–5.6 mm based on CT annotations), and these defects were distributed throughout the laminate thickness and along the specimen length. The widespread distribution of relatively large voids indicates insufficient laminate compaction and incomplete air removal during the manual hand lay-up process, leading to air entrapment between fiber plies and non-uniform resin impregnation. Such distributed voids may act as stress concentrators and contribute to premature crack initiation, which is consistent with the lower tensile performance observed in the HLU specimens.

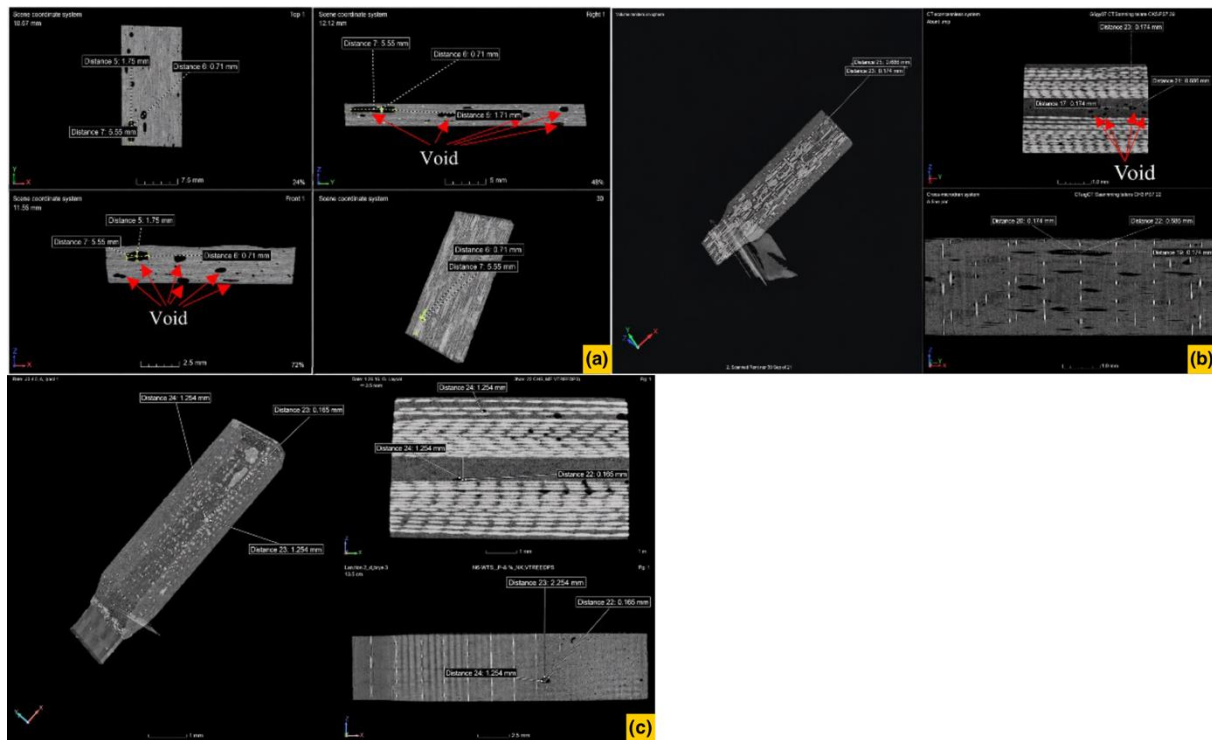


Figure 6. CT-Scan of (a) HLU; (b) VB; and (c) VARI specimens

In contrast, the VB laminate exhibited smaller void features with more localized distribution, generally confined to specific regions rather than uniformly dispersed throughout the specimen. The reduced void size and frequency in the VB laminate suggest that the applied vacuum pressure improved resin infiltration and facilitated partial evacuation of trapped air, thereby enhancing laminate consolidation compared with HLU. However, isolated voids were still observed, indicating that vacuum bagging reduced—but did not completely eliminate—defect formation. Meanwhile, no clearly observable voids were detected in the VARI laminate within the CT-scan resolution, indicating superior laminate quality and more effective impregnation. This behavior can be attributed to the continuous vacuum-assisted resin flow during fabrication, which promotes more homogeneous resin distribution and improved fiber wetting, resulting in a denser and more compact laminate structure.

The reduced void size in the VB specimens is attributed to the additional vacuum pressure applied during processing, which enhances laminate compaction and facilitates the removal of entrapped air and excess resin. This observation is consistent with previous studies reporting reduced void formation in vacuum-assisted

composite processing compared with conventional hand lay-up methods. Previous studies have reported that vacuum bagging improves laminate consolidation and significantly reduces void formation compared with conventional hand lay-up processing. Stringer [52] demonstrated that vacuum-assisted wet lay-up processing can achieve lower void content through improved laminate consolidation, while Boey *et al.* [53] reported that increasing vacuum pressure effectively reduces void content in thermoset composites by minimizing entrapped air within the laminate. A similar trend was observed in the present study [54], where the VB specimens exhibited smaller void features than the HLU specimens, indicating the beneficial role of vacuum-assisted processing in improving laminate quality. In contrast, no distinct voids were observed within the carbon fiber composite of the VARI specimens; the voids visible in Figure 6c are located in the adhesive layer, rather than within the laminate itself.

3.3. Tensile Properties of CFRP with Various Manufacturing Methods

Figure 7a to Figure 7c present the stress-strain responses obtained from tensile tests of CFRP specimens with a 0° orientation (longitudinal to the loading direction) manufactured by HLU, VB,

and VARI, respectively. The stress–strain curves clearly exhibit differences in slope among specimens produced by the three manufacturing methods. A gentler slope corresponds to lower stiffness, whereas a steeper slope indicates higher stiffness. Based on the stress–strain response shown in Figure 7a to Figure 7c, the VARI laminate exhibited the steepest elastic slope, followed by VB and HLU, indicating a higher tensile modulus and improved stiffness characteristics. The stress–strain curves show that specimens with lower stiffness exhibit a larger strain at failure than those with higher stiffness. A higher peak in the stress–strain curve corresponds to a greater ultimate tensile strength. Accordingly, CFRP specimens with a 0° fiber orientation manufactured by VARI exhibit the highest ultimate tensile strength, followed by those produced by VB and HLU, in agreement with previous findings for woven glass fiber composites [24].

As shown in Figure 7d, the ultimate tensile strengths of the CFRP composites are $507.72 \pm$

52.14 MPa for HLU, 685.69 ± 62.65 MPa for VB, and 774.31 ± 58.18 MPa for VARI. These results exhibit that the ultimate tensile strength of VB CFRP is 35.05% higher than that of HLU composites, while VARI composites exhibit increases of 52.51% over HLU and 12.92% over VB. Meanwhile, the tensile moduli of CFRP specimens with a 0° fiber orientation were 20.40 ± 0.97 GPa for HLU, 33.42 ± 1.25 GPa for VB, and 39.31 ± 4.58 GPa for VARI. Compared with HLU, the tensile modulus increased by 63.8% for VB specimens and by 92.7% for VARI specimens. The tensile modulus of the VARI specimens was also 17.64% higher than that of the VB specimens. In summary, CFRP with a 0° fiber orientation manufactured by the VARI method exhibits superior ultimate tensile strength and modulus compared with those produced by HLU and VB. This characteristic is primarily attributed to the higher fiber volume fraction achieved by VARI, indicating that for longitudinally oriented carbon fiber composites, tensile strength and modulus

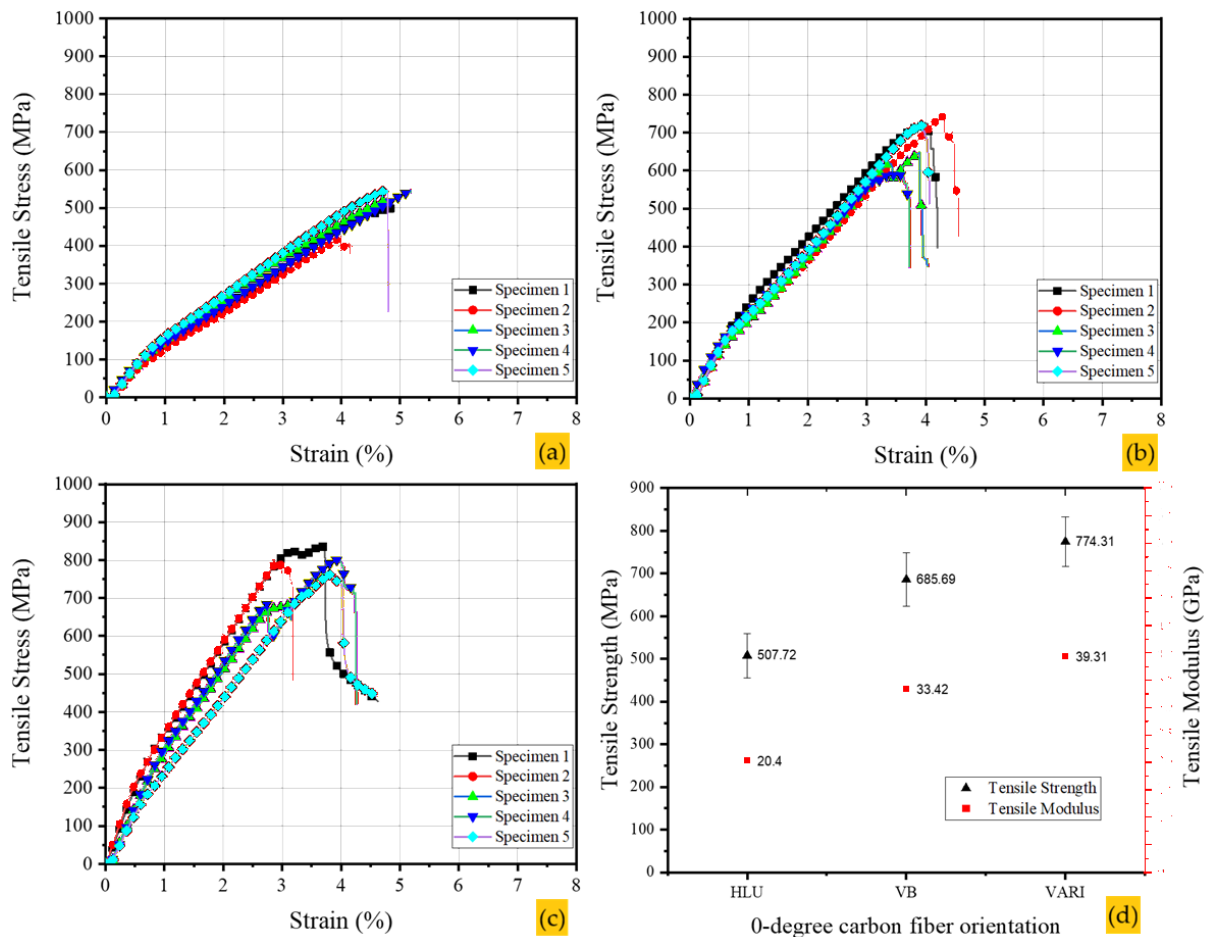


Figure 7. Tensile stress-strain curve of 0° CFRP: (a) hand lay-up, (b) vacuum bagging, (c) VARI, and (d) tensile properties comparison

strongly depend on fiber volume fraction, with higher values leading to enhanced strength. These findings are consistent with the study by Scalici *et al.* [43] on epoxy–basalt fiber composites, which reported that laminates with a 0° fiber orientation exhibited higher tensile modulus and strength than those manufactured by vacuum bagging. Scalici *et al.* reported tensile strengths of 619 ± 68.6 MPa and 553 ± 20.2 MPa for VARI and VB laminates, respectively [43]. Although a similar trend was observed, the tensile strengths obtained in the present study were comparatively 25% higher for VARI, which may be attributed to differences in material systems, fabrication parameters, or laminate quality. However, these results differ from those reported by Kubit *et al.* [37] for 0° carbon/epoxy composites, where comparable tensile strengths were obtained for vacuum-bagged and VARI-manufactured laminates. A previous study by Kubit *et al.* reported tensile strengths of 536 MPa for VARI and 599 MPa for VB laminates [37]. Compared with these findings, the VARI laminate fabricated

in the present study exhibited a tensile strength approximately 44% higher. The variation in tensile performance may be associated with differences in resin systems, fiber volume fraction, curing conditions, and laminate quality resulting from different fabrication parameters.

Figure 8 presents the stress–strain responses of 90° carbon fiber composites and compares the corresponding tensile modulus and strength for specimens manufactured by HLU, VB, and VARI. Figure 8a to Figure 8c illustrates the characteristic differences between the stress–strain responses of 90° and 0° carbon fiber composites. For the 90° carbon fiber composites, the stress–strain response is linear up to approximately 0.25% strain, after which the slope changes until the peak stress is reached. Unlike the 0° carbon fiber composites, the highest peak stress, corresponding to the ultimate tensile strength, is observed for HLU specimens in the 90° composites, followed by VARI and VB specimens, with the latter two exhibiting similar peak values. Meanwhile, the linear region slope, representing

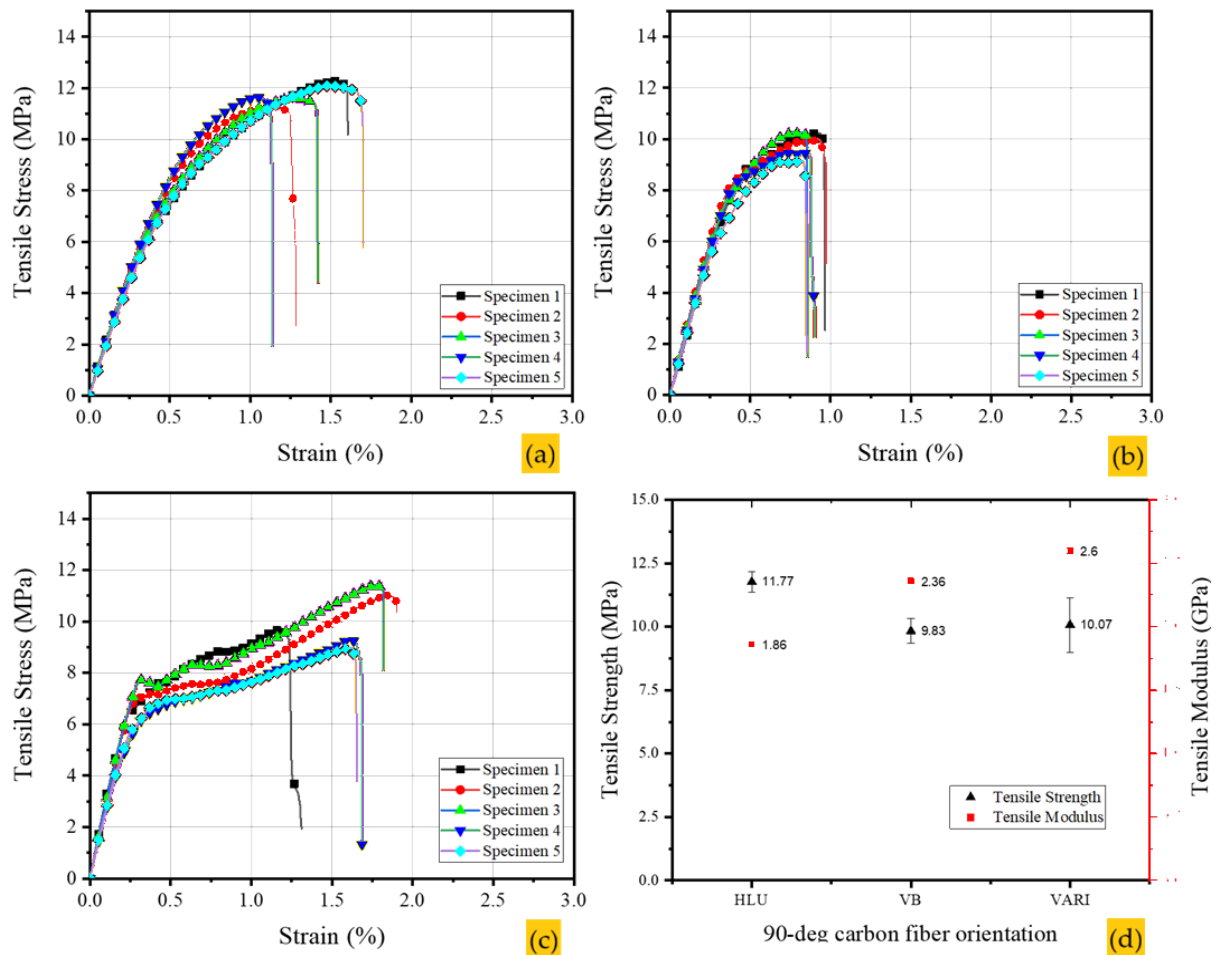


Figure 8. Tensile stress-strain curve of 90° CFRP: (a) HLU; (b) VB; (c) VARI; and (d) tensile properties comparison

composite stiffness, indicates that the VARI composites exhibit the highest stiffness, followed by VB and HLU specimens, a trend consistent with that observed for the 0° fiber orientation.

Figure 8d showed that the ultimate tensile strengths of the 90° composites are 11.77 ± 0.40 MPa for HLU, 9.83 ± 0.49 MPa for VB, and 10.07 ± 1.08 MPa for VARI specimens. The corresponding tensile moduli are 1.86 ± 0.06 GPa, 2.36 ± 0.09 GPa, and 2.60 ± 0.23 GPa, respectively. These results show that, for composites with transverse fiber orientation, the tensile strengths of the VB and VARI specimens are 16.51% and 14.41% lower, respectively, than that of the HLU specimens, while the VARI and vacuum-bagged specimens exhibit nearly identical tensile strength values. This behavior suggests that, for this fiber orientation, increases in fiber volume fraction have a limited influence on overall tensile strength, since transverse fibers do not effectively carry longitudinal tensile loads, unlike the case for 0°-oriented composites discussed earlier. In contrast to tensile strength, the modulus of composites with transverse carbon fiber orientation is highest for the VARI specimens, followed by VB and HLU specimens. This trend indicates consistent stiffness behavior for both longitudinal and transverse fiber orientations, with VARI producing stiffer laminates than VB and HLU, in agreement with the findings of Scalici *et al.* [43] comparing VARI- and VB composites. Scalici *et al.* reported tensile modulus values of 8.58 ± 0.74 GPa and 7.85 ± 0.52 GPa for VARI and VB laminates, respectively, indicating superior stiffness in VARI-fabricated composites [43]. A comparable trend was observed in the present study, where the tensile modulus of the VARI laminate was approximately 10% higher than that of the VB laminate, closely aligning with the 9% difference reported by Scalici *et al.* Although the absolute modulus values differed, the consistency in the relative performance between VARI and VB suggests a similar influence of the manufacturing process on composite stiffness. This behavior is attributed to the utilization of vacuum pressure during the VARI process, which produces a more compact composite structure.

Figure 9 exhibits the stress–strain responses of $\pm 45^\circ$ carbon fiber composites and compares the corresponding tensile (in-plane shear) modulus and strength for specimens manufactured by

HLU, VB, and VARI. Figure 9a to Figure 9c illustrates the stress–strain responses differences of $\pm 45^\circ$ carbon fiber composites compared to 0° and 90° specimens. For the $\pm 45^\circ$ carbon fiber composites, the stress–strain response is linear up to approximately 2.5% strain and changes thereafter up to 20% for HLU, 15% for VB, and 12.5% for VARI. This response is different from that of 0° and 90° composites. This is because the $\pm 45^\circ$ fibers in the composite specimens undergo shear when subjected to tensile loading, and the specimens elongate significantly, resulting in what is known as in-plane shear response. Unlike the 0° and 90° carbon fiber composites, the highest peak stress, corresponding to the ultimate tensile (in-plane shear) strength, is similar in all three specimens, indicating that the differences in the HLU, VB, and VARI manufacturing methods did not have a significant impact on the in-plane shear strength values. Meanwhile, the linear region slope, representing composite stiffness, indicates that the VARI composites exhibit the highest stiffness, followed by VB and HLU specimens, a trend consistent with that observed for the 0° and 90° fiber orientation.

As shown in Figure 9d, the ultimate tensile (in-plane shear) strengths of the $\pm 45^\circ$ CFRP composites are 20.85 ± 0.82 MPa for HLU, 21.2 ± 0.45 MPa for VB, and 22.18 ± 0.81 MPa for VARI specimens. The corresponding tensile (in-plane shear) moduli are 2.37 ± 0.13 GPa, 3.22 ± 0.19 GPa, and 3.71 ± 0.18 GPa, respectively. These results show that, for composites with $\pm 45^\circ$ fiber orientation, the tensile (in-plane shear) strengths of the three specimens are almost similar. However, the average values were slightly different, with VB and VARI specimens being 1.68% and 6.38% higher than HLU specimens, respectively. Similar to tensile strength, the modulus of $\pm 45^\circ$ composites is highest for the VARI specimens, followed by VB and HLU specimens. This trend indicates consistent stiffness behavior for longitudinal, transverse, and $\pm 45^\circ$ fiber orientations, with VARI producing stiffer laminates than VB and HLU, in agreement with the findings of Kubit *et al.* [37] comparing VARI and VB composites. Kubit *et al.* reported a modulus of 10 GPa for VARI and 9.2 GPa for VB laminates with a $\pm 45^\circ$ fiber orientation [37]. A similar trend was observed in the present study, where the VARI laminate exhibited a modulus

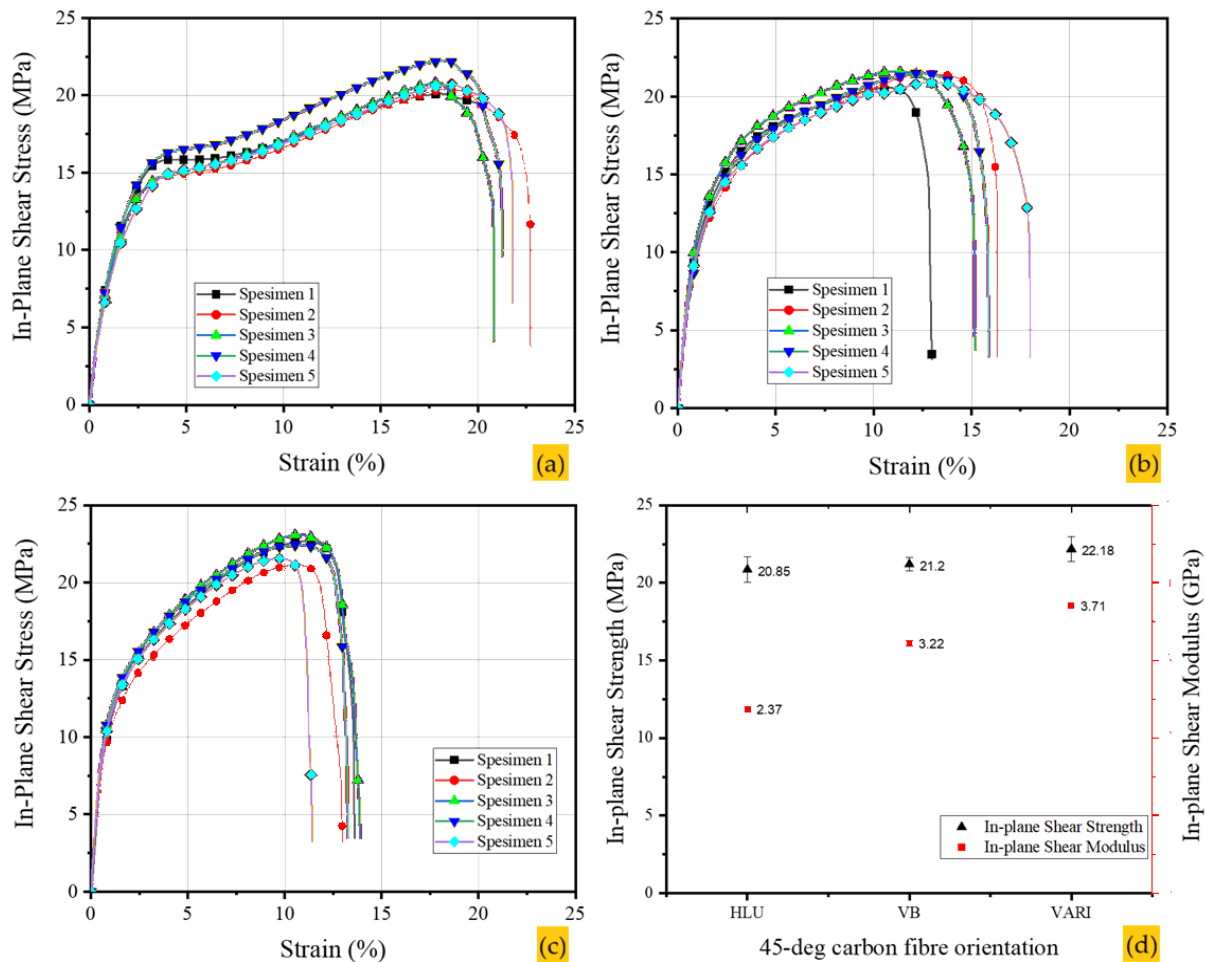


Figure 9. Tensile stress-strain curve of $\pm 45^\circ$ CFRP: (a) Hand lay-up; (b) Vacuum bagging; (c) VARI; and (d) Tensile properties comparison

approximately 15% higher than that of the VB laminate, compared with the 9% improvement reported by Kubit *et al.* This consistency in relative performance suggests that the VARI process provides more effective laminate consolidation, thereby enhancing the shear stiffness of CFRP composites. This behavior is attributed to the application of vacuum pressure during the VARI process, which produces a more compact composite structure.

3.4. Compressive Strength of CFRP with Various Manufacturing Methods

Figure 10 compares the compressive strength of composites manufactured by HLU, VB, and VARI for specimens with longitudinal (Figure 10a) and transverse (Figure 10b) fiber orientations relative to the compressive loading direction. For composites with a 0° carbon fiber orientation, the compressive strengths of specimens manufactured by HLU, VB, and VARI were 124.81 ± 13.12 MPa, 108.15 ± 28.53 MPa, and 97.22 ± 8.37

MPa, respectively. The HLU specimens exhibit the highest average compressive strength, while the VB and VARI specimens show reductions of 13.35% and 22.10%, respectively, relative to HLU. Interestingly, the HLU laminate with a 0° fiber orientation exhibited higher compressive strength despite showing lower tensile performance compared with VB and VARI laminates. This difference can be attributed to the distinct failure mechanisms under tensile and compressive loading in unidirectional CFRP composites [45]. Tensile strength in the 0° direction is primarily governed by the load-bearing capability of the carbon fibers and is therefore strongly influenced by fiber volume fraction, fiber alignment, and laminate consolidation quality [45]. Accordingly, the lower fiber volume fraction and higher void content in the HLU laminates contributed to reduced tensile strength. In contrast, compressive failure is often controlled by fiber microbuckling and kinking mechanisms, in which matrix support plays a critical role in stabilizing fibers

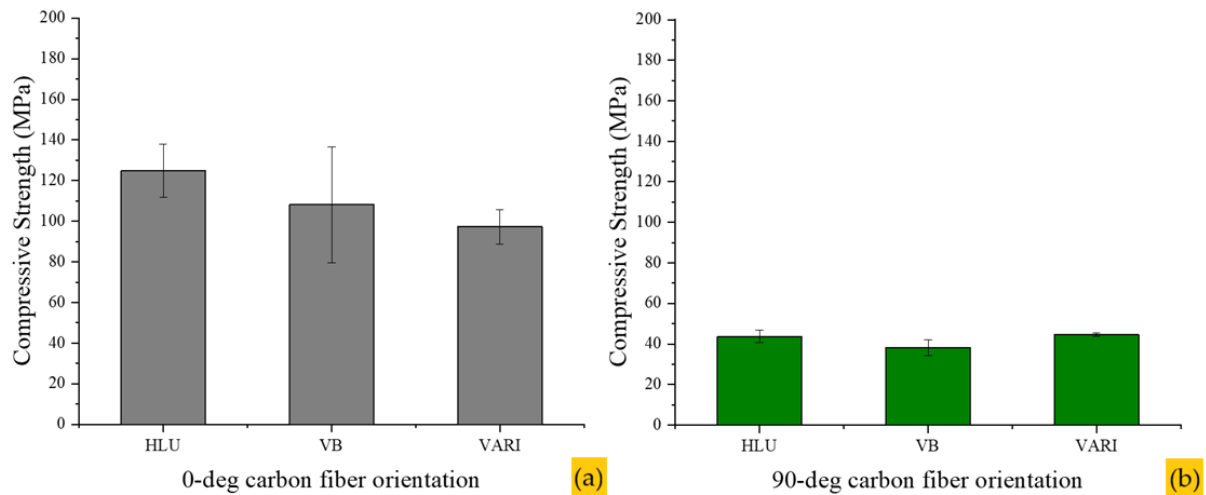


Figure 10. Compressive strength comparison of (a) 0° and (b) 90° carbon fiber composites

against local instability [46]. The relatively higher resin content and thicker laminate observed in the HLU specimens may have provided enhanced lateral support to the fibers, thereby contributing to improved compressive resistance despite lower tensile performance [55]. For the 90° fiber orientation, the compressive strengths of specimens manufactured by HLU, VB, and VARI were 43.75 ± 3.05 MPa, 38.12 ± 4.46 MPa, and 44.60 ± 0.82 MPa, respectively. These results indicate that the VARI specimens exhibit the highest compressive strength, exceeding those produced by HLU and VB by 2.47% and 12.78%, respectively.

3.5. V-Notched Shear Strength of CFRP with Various Manufacturing Methods

Figure 11a compares the shear strength and modulus of composites manufactured by HLU, VB, and the VARI process. The shear strengths of specimens manufactured by HLU, VB, and VARI were 18.14 ± 1.24 MPa, 18.71 ± 1.10 MPa, and 15.31 ± 1.01 MPa, respectively. The corresponding shear moduli are 0.65 ± 0.14 GPa, 0.93 ± 0.22 GPa, and 1.50 ± 0.15 GPa, respectively. The shear strength of hand lay-up and vacuum bagging specimens showed similar values, but the average values exhibited that the vacuum bagged specimens have the highest average shear strength, while the hand lay-up and VARI specimens show reductions of 3.05% and 18.17%, respectively, relative to vacuum bagging. This behavior suggests that, for the v-notched beam test, increases in fiber volume fraction have a limited impact on overall shear strength. In contrast to shear strength, the shear modulus of composites is highest for the VARI

specimens, followed by VB and HLU specimens. This trend indicates consistent stiffness behavior for the v-notched beam, with VARI producing stiffer laminates than VB and HLU. The relatively limited variation in shear strength among the manufacturing methods suggests that increases in fiber volume fraction may have a less pronounced influence on the overall shear strength measured using the v-notched beam method. This behavior may be attributed to the fact that shear failure in CFRP laminates is strongly governed by matrix deformation and fiber–matrix interfacial interactions, rather than by fiber-dominated load transfer mechanisms alone [45]. In contrast, the shear modulus exhibited a consistent increasing trend from HLU to VB and reached the highest value for the VARI laminates, indicating enhanced laminate stiffness with improved consolidation quality [45]. Previous studies have reported similar observations, where VARI-fabricated composites exhibited higher shear stiffness than vacuum-bagged laminates due to improved fiber packing and reduced void content [55]. For example, Scalici *et al.* [43] reported shear modulus values of 2.31 GPa for VARI and 2.08 GPa for VB laminates, demonstrating superior stiffness in VARI composites. A similar trend was observed in the present study, suggesting that enhanced laminate consolidation achieved through vacuum-assisted infusion contributes more significantly to stiffness enhancement than to improvements in shear strength. However, the shear strength values obtained in the present study differ from those reported by Scalici *et al.* for basalt fiber composites, where nearly identical shear strengths were observed for VB and VARI

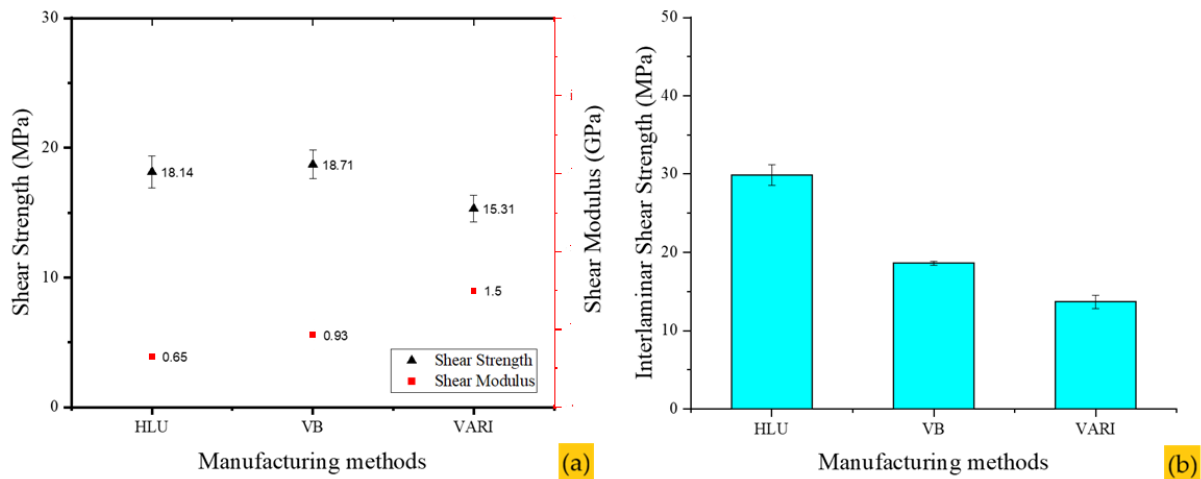


Figure 11. V-notched shear (a) and interlaminar shear (b) strength of CFRP

laminates, at 21.7 MPa and 21.8 MPa, respectively [43]. In contrast, a previous study on glass fiber composites reported shear strengths of 13.06 MPa, 11.88 MPa, and 16.88 MPa for HLU, VB, and VARI laminates, respectively [56]. Compared with these studies, the shear strengths obtained in the present work were lower than those reported for basalt fiber composites but higher than those observed in glass fiber composites. These variations suggest that fiber type plays a significant role in determining the shear performance of composite laminates, likely due to differences in intrinsic fiber properties, fiber-matrix interfacial bonding, and load transfer mechanisms across different manufacturing methods.

3.6. Interlaminar Shear Strength of CFRP with Various Manufacturing Methods

Figure 11b compares the interlaminar shear strength (ILSS) of composites manufactured by HLU, VB, and the VARI process. The interlaminar shear strengths of specimens manufactured by HLU, VB, and VARI were 29.85 ± 1.33 MPa, 18.61 ± 0.25 MPa, and 13.68 ± 0.85 MPa, respectively. The HLU specimens exhibit the highest average compressive strength, while the VB and VARI specimens show reductions of 37.65% and 54.17%, respectively, relative to HLU. This behavior indicates that, for interlaminar shear strength, increases in fiber volume fraction of VARI have a limited impact on interlaminar shear strength. The relatively limited improvement in interlaminar shear strength (ILSS) despite the higher fiber volume fraction of the VARI laminates suggests that fiber volume fraction alone does not govern

interlaminar performance. Unlike tensile properties, ILSS is predominantly influenced by matrix-dominated behavior [45], fiber-matrix interfacial bonding, and resistance to interlaminar crack propagation [55]. Consequently, a denser laminate with a higher fiber volume fraction does not necessarily exhibit superior ILSS. A similar trend was observed in the study by Scalici *et al.*, where the interlaminar shear strength (ILSS) of VB laminates exceeded that of VARI laminates, with reported values of 21.1 ± 0.87 MPa (VB) and 18.9 ± 0.29 MPa (VARI), respectively [43]. The relative improvement in ILSS of VB over VARI was approximately 12% in the study by Scalici *et al.*, whereas a larger difference of 36% was observed in the present study [43]. Although the magnitude of the improvement differed, the consistent trend suggests that the manufacturing process significantly influences the interlaminar shear performance of composite laminates, potentially through differences in resin distribution, fiber consolidation, and interfacial bonding quality.

A summary of the mechanical properties of CFRP composites with various fiber directions manufactured by HLU, VB, and VARI is presented in Table 2. These results indicate that, overall, carbon fiber reinforced composites produced by the VARI process exhibit superior mechanical properties when compared to those produced by hand lay-up or vacuum bagging processes. Therefore, this method is highly suitable for use in structural applications requiring high strength and stiffness. However, for structural applications that do not require high strength and stiffness, the HLU and VB methods can be considered. This mechanical property data

Table 2. Mechanical properties of CFRP

Properties	Hand Lay-up	Vacuum Bagging	VARI
Longitudinal (0°) tensile modulus (GPa)	20.40 ± 0.97	33.42 ± 1.25	39.31 ± 4.58
Transverse (90°) tensile modulus (GPa)	1.86 ± 0.06	2.36 ± 0.09	2.60 ± 0.23
±45° tensile (in-plane shear) modulus (GPa)	2.37 ± 0.13	3.22 ± 0.19	3.71 ± 0.18
V-notched (0°) shear modulus (GPa)	0.65 ± 0.14	0.93 ± 0.22	1.50 ± 0.15
Longitudinal (0°) tensile strength (MPa)	507.7 ± 52.1	685.7 ± 62.7	774.3 ± 58.2
Transverse (90°) tensile strength (MPa)	11.77 ± 0.40	9.83 ± 0.49	10.07 ± 1.08
±45° tensile (in-plane shear) strength (MPa)	20.85 ± 0.82	21.2 ± 0.45	22.18 ± 0.81
Longitudinal (0°) compressive strength (MPa)	124.8 ± 13.1	108.2 ± 28.5	97.2 ± 8.4
Transverse (90°) compressive strength (MPa)	43.75 ± 3.05	38.12 ± 4.46	44.60 ± 0.82
V-notched (0°) shear strength (MPa)	18.14 ± 1.24	18.71 ± 1.10	15.31 ± 1.01
Interlaminar (0°) shear strength (MPa)	29.85 ± 1.33	18.61 ± 0.25	13.68 ± 0.85

can be used as a basis for performing structural analysis in the design and analysis stages of automotive components based on the manufacturing method to be used. It should be noted that the comparison among HLU, VB, and VARI specimens is influenced not only by the manufacturing route itself but also by process-induced variations in fiber volume fraction and laminate thickness. As shown in sub-section 3.1, VARI specimens exhibited higher fiber volume fractions and lower thicknesses, whereas HLU specimens showed the opposite trend. These variations are intrinsically linked to the processing characteristics, where vacuum-assisted methods generally improve fiber compaction and resin distribution, reducing resin-rich regions and void content. Consequently, the superior mechanical performance observed in VARI specimens may partially originate from the increased fiber packing efficiency and reduced laminate thickness, in addition to the manufacturing method itself. Therefore, the present comparisons should be interpreted as the combined influence of manufacturing-induced laminate characteristics rather than as an isolated effect of fabrication technique alone.

The mechanical properties obtained for the VARI-fabricated CFRP laminate in the present study, including a tensile strength of 774.3 ± 58.2 MPa and tensile modulus of 39.31 ± 4.58 GPa, fall within the lower-to-intermediate range of carbon/epoxy composites reported for cost-effective automotive lightweight structures manufactured using non-autoclave processes. Compared with carbon sheet molding compound (SMC) composites employed in the body structure of the BMW i3 [57], which typically exhibit tensile strengths of approximately 150–350 MPa and

modulus values of 20–50 GPa, the present VARI laminate demonstrated substantially higher tensile strength while maintaining a comparable stiffness range, indicating improved load-bearing capability associated with the use of continuous unidirectional carbon fibers rather than discontinuous reinforcement. However, compared with higher-performance automotive CFRP systems fabricated using resin transfer molding (RTM) or resin infusion processes adopted in premium automotive applications such as Lamborghini structural components and other OEM lightweight composite structures [58], [59], where tensile strengths generally range from 400–900 MPa and tensile moduli from 35–80 GPa, the tensile response obtained in this study lies within the reported range, whereas the compressive strength (97.2 ± 8.4 MPa) and interlaminar shear strength (13.68 ± 0.85 MPa) remain comparatively lower. These differences may be attributed to variations in laminate architecture, fiber volume fraction, curing strategy, and manufacturing quality associated with non-autoclave composite fabrication routes. Nevertheless, the obtained results demonstrate the feasibility of the VARI process for producing lightweight CFRP laminates with promising mechanical performance for selected automotive body and semi-structural applications requiring cost-effective manufacturing routes.

To assess the reliability and repeatability of the experimental results, a statistical comparison based on standard deviation was conducted for all mechanical properties, with five specimens tested for each condition. In general, most mechanical responses exhibited relatively low standard deviations, indicating acceptable experimental consistency and good repeatability of the

manufacturing processes. For example, transverse tensile strength (90°), $\pm 45^\circ$ tensile strength, and transverse compressive strength demonstrated comparatively small deviations across all manufacturing routes, suggesting stable mechanical behavior under matrix-dominated loading conditions. Conversely, larger standard deviations were observed in several longitudinal (0°) tensile and compressive responses, particularly in HLU and VB specimens, which may be attributed to process-induced heterogeneity, such as uneven resin distribution, local fiber waviness, void formation, and variations in fiber alignment during manual processing. The lower variability generally observed in VARI-manufactured specimens further suggests improved process uniformity due to more controlled resin infusion and fiber impregnation. Overall, the standard deviation analysis confirms the repeatability of the

experimental measurements and supports the reliability of the comparative mechanical performance discussed in this study.

Considering the differences in CFRP density among the HLU, VB, and VARI manufacturing methods, the mechanical performance was additionally evaluated in terms of specific material properties to provide a density-normalized comparison. As presented in [Table 3](#), the specific properties were determined by dividing the mechanical properties reported in [Table 2](#) by the corresponding laminate density.

3.7. Failure Modes

[Figure 12a](#) to [Figure 12c](#) presents a comparison of tensile failure modes in CFRP composites with a 0° fiber orientation, while [Figure 12d](#) presents the tensile failure of $\pm 45^\circ$ specimens. The HLU specimens exhibited a lateral failure mode accompanied by longitudinal splitting along the

Table 3. Specific mechanical properties of CFRP

Specific Properties	HLU	VB	VARI
Longitudinal (0°) tensile modulus (GPa.cc/gr)	16.32 ± 0.78	25.51 ± 0.95	27.30 ± 3.18
Transverse (90°) tensile modulus (GPa.cc/gr)	1.49 ± 0.05	1.80 ± 0.07	1.81 ± 0.16
$\pm 45^\circ$ tensile (in-plane shear) modulus (GPa.cc/gr)	1.90 ± 0.10	2.46 ± 0.15	2.58 ± 0.13
V-notched (0°) shear modulus (GPa.cc/gr)	0.52 ± 0.11	0.71 ± 0.17	1.04 ± 0.10
Longitudinal (0°) tensile strength (MPa.cc/gr)	406.16 ± 41.68	523.44 ± 47.86	537.71 ± 40.42
Transverse (90°) tensile strength (MPa.cc/gr)	9.42 ± 0.32	7.50 ± 0.37	6.99 ± 0.75
$\pm 45^\circ$ tensile (in-plane shear) strength (MPa.cc/gr)	16.68 ± 0.66	16.18 ± 0.34	15.40 ± 0.56
Longitudinal (0°) compressive strength (MPa.cc/gr)	99.84 ± 10.48	82.60 ± 21.76	67.50 ± 5.83
Transverse (90°) compressive strength (MPa.cc/gr)	35.00 ± 2.44	29.10 ± 3.40	30.97 ± 0.57
V-notched (0°) shear strength (MPa.cc/gr)	14.51 ± 0.99	14.28 ± 0.84	10.63 ± 0.70
Interlaminar (0°) shear strength (MPa.cc/gr)	23.88 ± 1.06	14.21 ± 0.19	9.50 ± 0.59

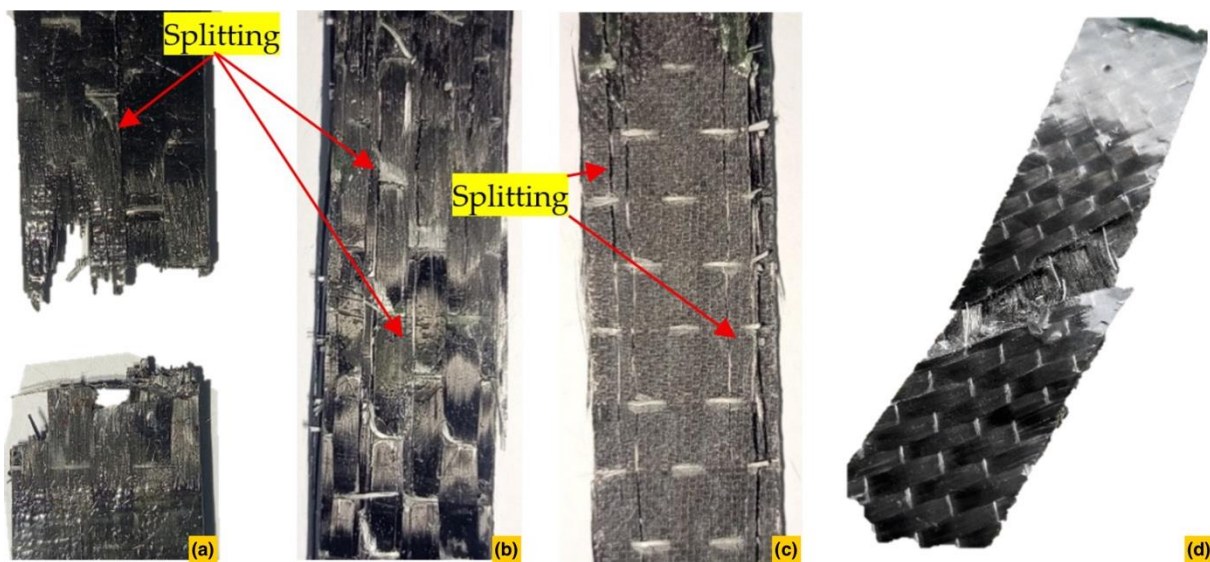


Figure 12. 0° specimens after tensile test of: (a) HLU; (b) VB; (c) VARI specimens; and (d) $\pm 45^\circ$ specimens after tensile test

surface fiber layers, as shown in [Figure 12a](#). This lateral failure mode causes the specimen to separate into two distinct parts, indicating the loss of load-carrying capability of the resin-bonded fiber network, which ultimately leads to catastrophic fracture. A similar lateral failure mode was observed in most composite specimens with a 90° fiber orientation, reflecting the inability of transversely aligned fibers to sustain longitudinal tensile loading. All specimens exhibited longitudinal splitting; however, the HLU specimen showed localized splitting limited to the central region, while more extensive and multiple splitting lines were observed in the VB and VARI specimens.

Unlike the 0° and 90° specimens, the failure mode of the $\pm 45^\circ$ specimens, as shown in [Figure 12d](#), is fracture at the composite surface layer. This is related to the fibers shifting during the loading process, which then causes delamination between layers. As loading continues, several layers on the specimen surface eventually fracture at a 45° angle, as seen in [Figure 12d](#).

[Figure 13a](#) to [Figure 13c](#) illustrates the various failure modes observed in specimens with longitudinal fiber orientation subjected to compressive loading, with shear failure mode observed in all specimens. In addition to shear failure, a kink band was observed in the HLU and VB specimens, whereas the VARI specimen exhibited a surface pop-out failure mode. Shear failure mode is characterized by cracks running parallel to the fiber direction, is induced by matrix breakdown, and is often associated with mild failure stress. It typically occurs when the loading direction makes a considerable angle with the surface fiber orientation [60]. As the stress increases, micro-buckling causes the creation of kink bands. Furthermore, sustained stress pushes the cracked composite with fiber breakage outward, resulting in surface pop-out.

[Figure 13d](#) to [Figure 13f](#) presents representative compressive failure modes observed in composite specimens with transversely aligned fibers. Only shear-dominated failure was observed in the HLU, VB, and VARI specimens, with no evidence of kink band formation, surface pop-out, or other secondary failure mechanisms. This behavior is attributed to the limited load-carrying capacity of composites with a 90° fiber orientation under longitudinal loading, leading to premature shear

failure without the development of kink bands or surface pop-out mechanisms.

Failure mode analysis was conducted not only for tensile and compression tests but also for the v-notched beam and short beam tests, as shown in [Figure 14](#). For the v-notched beam and short beam specimens, failure images were captured immediately after fracture while the specimens remained mounted in the testing fixture to preserve the visibility of characteristic failure features. This approach was adopted because these failure characteristics became less distinguishable after specimen removal from the fixture. [Figure 14](#) illustrates representative shear failure modes observed in composite specimens after the v-notched beam and short beam tests. The failure modes that occurred were fiber shear ([Figure 14a](#)) and interlaminar shear ([Figure 14b](#)). Fiber shear failure occurred in the v-notched beam specimen due to compressive loading with a special fixture that converted the compressive load into a shear load on the specimen. Fiber shear failure occurred precisely in the V area of the specimen. Interlaminar shear failure occurred in the short beam specimen after three-point bending loading. This failure mode occurred at one end of the specimen and is the typical primary failure mode after short beam testing according to ASTM D2344.

The observed failure mechanisms are closely associated with the fiber orientation and manufacturing-induced laminate quality, which together govern the load-transfer capability of the CFRP system. In the longitudinal (0°) tensile specimens, the more extensive longitudinal splitting observed in the VB and VARI laminates suggests more effective load transfer along the fiber direction prior to catastrophic failure, indicating stronger fiber-matrix interaction and higher stress accumulation before fracture initiation. This behavior is consistent with the superior tensile strength and stiffness exhibited by the VARI specimens, where improved laminate consolidation and reduced void content delayed premature crack initiation. In contrast, the localized splitting observed in the HLU specimens reflects less uniform stress distribution and earlier matrix cracking, which may be associated with resin-rich regions and manufacturing-induced defects identified in the CT-scan analysis. These observations indicate that improved laminate

compaction enhances tensile load-bearing efficiency but may also lead to a more brittle

catastrophic fracture once the ultimate load is exceeded.

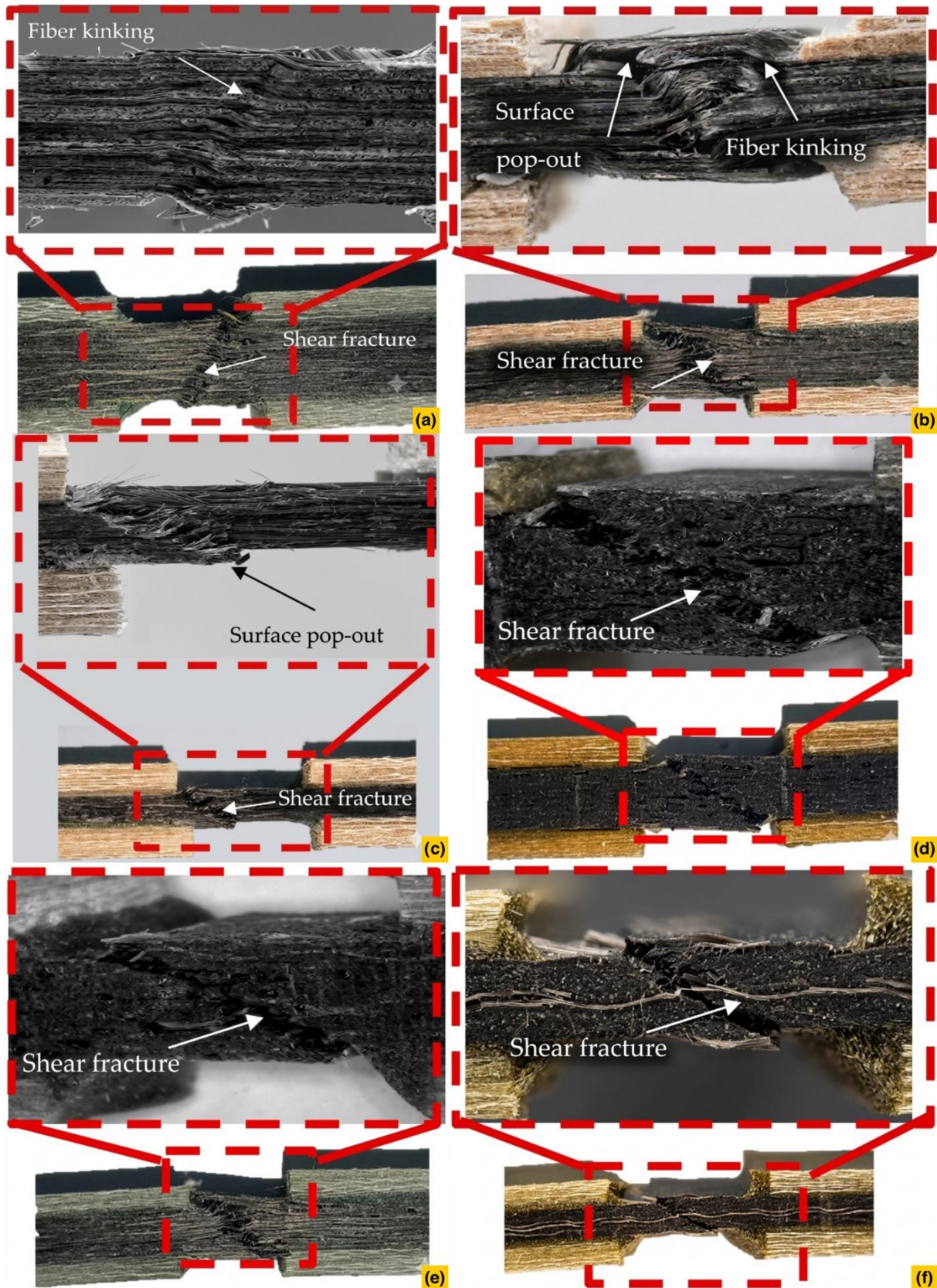


Figure 13. Specimens after compressive test: (a) 0° HLU; (b) 0° VB; (c) 0° VARI; (d) 90° HLU; (e) 90° VB; and (f) 90° VARI

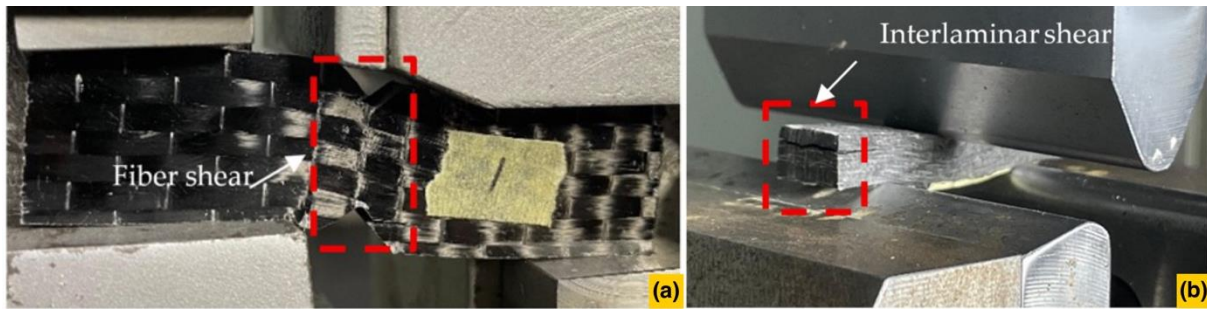


Figure 14. V-notched beam (a) and short beam (b) specimens after test

Under compressive and shear-dominated loading conditions, the failure mechanisms demonstrate the important role of matrix-dominated deformation and interfacial stability. The presence of kink bands in the HLU and VB laminates suggests localized fiber microbuckling promoted by relatively higher matrix content and lower laminate compaction, which may allow progressive stress redistribution before final collapse. Conversely, the surface pop-out failure observed in the VARI specimens indicates a more compact and constrained laminate structure, where accumulated compressive stresses are released through localized outward fracture. Similarly, the v-notched beam and short beam specimens revealed fiber shear and interlaminar shear failure modes, confirming that shear-dominated loading primarily activates matrix deformation and interfacial debonding mechanisms rather than fiber fracture. This finding supports the mechanical results, where the VARI laminates exhibited superior stiffness but comparatively lower shear and interlaminar shear strength, suggesting that increased fiber volume fraction alone does not necessarily improve matrix-dominated failure resistance.

3.8. SEM Observations

SEM observations were performed on the fracture surface of CFRP specimens with a 90° fiber orientation, as these specimens fractured completely into two separate sections during mechanical testing, thereby providing a clearly exposed fracture surface suitable for detailed microstructural observation. This configuration enabled better visualization of fracture characteristics, including fiber–matrix interfacial behavior, matrix cracking, and failure features.

Figure 15 presents SEM cross-sectional images of fractured composite specimens produced by HLU (**Figure 15a** and **Figure 15b**), VB (**Figure 15c** and

Figure 15d), and VARI (**Figure 15e** and **Figure 15f**). Images in **Figure 15a**, **Figure 15c**, and **Figure 15e** were obtained at 300× magnification, whereas those in **Figure 15b**, **Figure 15d**, and **Figure 15f** were captured at 3000× magnification. In the hand lay-up specimens, resin-rich regions are evident in the form of resin agglomerations (**Figure 15a**) and fractured resin within these regions (**Figure 15b**). Such resin-rich areas lead to non-uniform matrix-to-fiber load transfer, causing premature failure under sustained loading due to insufficient fiber reinforcement, and consequently resulting in inferior mechanical properties. The vacuum bagging specimens exhibit smaller resin-rich regions (**Figure 15c**) and dispersed resin fragments on the fracture surface, indicating intermediate mechanical performance. In contrast, the VARI specimens show no apparent resin-rich areas or resin fragments, suggesting a more uniform resin distribution and improved fiber–matrix interfacial bonding, which contributes to superior mechanical properties.

The SEM observations further validate the relationship between manufacturing route, microstructural integrity, and mechanical performance. The presence of resin agglomeration and fractured resin-rich regions in the HLU specimens indicates non-uniform resin impregnation and weak local stress transfer between the matrix and reinforcement phases.

These resin-rich areas may act as stress concentration sites that promote crack initiation under tensile loading, thereby explaining the lower tensile modulus and strength observed in the HLU laminates. The smaller resin-rich domains observed in the VB specimens indicate improved resin distribution due to vacuum-assisted consolidation, which partially enhanced fiber wetting and reduced local stress concentration compared with HLU. However, the persistence of some fractured resin fragments

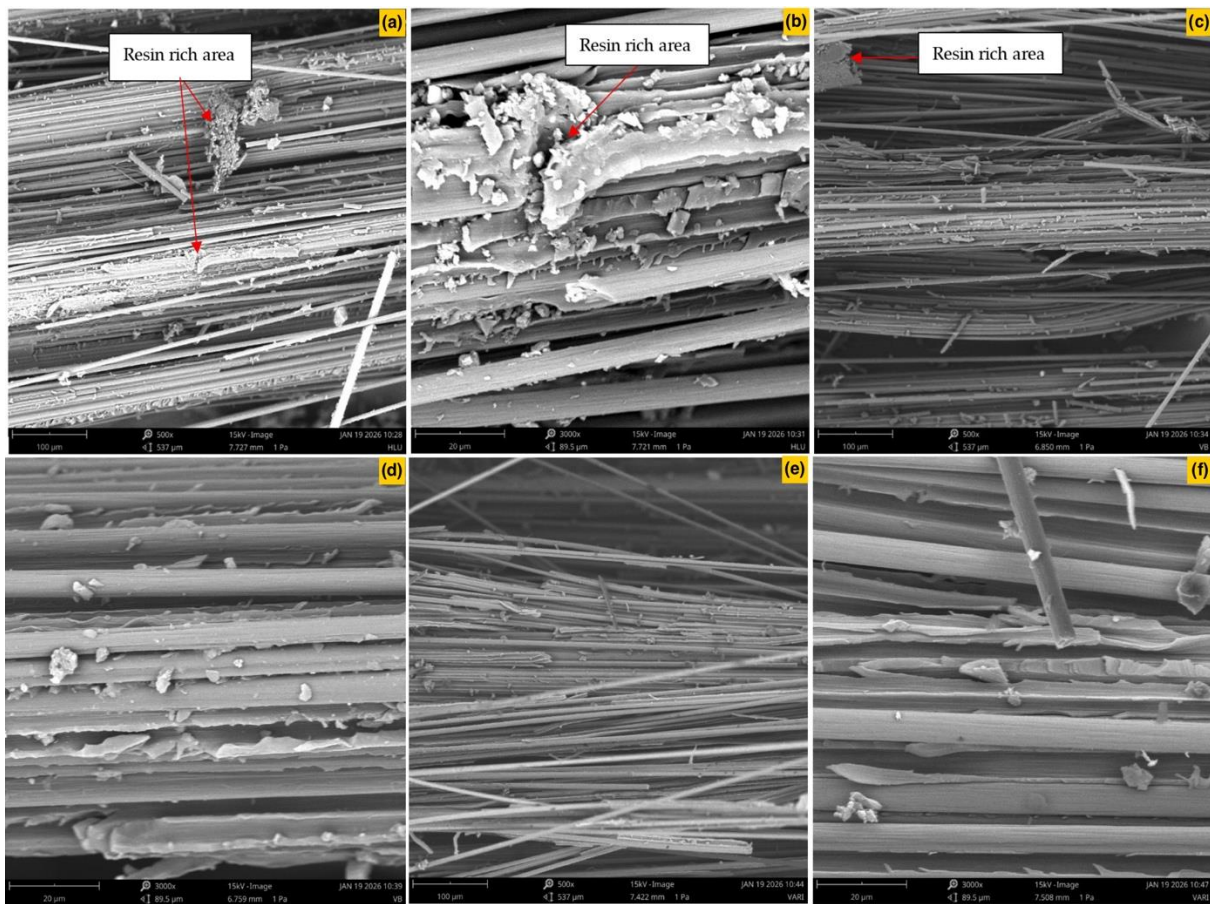


Figure 15. SEM micrograph of (a,b) HLU, (c,d) VB, and (e,f) VARI specimens

suggests that incomplete resin homogenization and localized interfacial discontinuities still occurred in the vacuum-bagged laminates.

In contrast, the absence of apparent resin-rich regions and the more uniform fracture morphology observed in the VARI laminates indicate improved impregnation quality and stronger fiber–matrix interfacial bonding. This microstructural condition enables more efficient stress transfer from the matrix to the carbon fibers, thereby contributing to the superior tensile and stiffness performance of the VARI specimens. Furthermore, the SEM findings are in good agreement with the CT-scan observations, where no distinct voids were detected within the VARI laminate, suggesting that continuous vacuum application during resin infusion effectively minimized manufacturing-induced defects. Nevertheless, despite the improved interfacial uniformity, the superior consolidation achieved in VARI did not proportionally improve shear and interlaminar shear strength, indicating that matrix-dominated failure mechanisms remain highly sensitive to local crack propagation and

interfacial fracture behavior rather than fiber packing density alone.

3.9. Finite Element Analysis

Finite element analysis was performed on CFRP specimens with a fiber orientation of 0° and 90° . Figure 16 shows a comparison of the stress-strain curves and ultimate tensile strength results from the experimental and FEA of 0° specimens. Figure 16a exhibits that the stress-strain curve from the FEA is similar to the experimental results. In other words, the maximum strain, the peak of the curve representing the ultimate tensile strength, and the slope representing the stiffness of the FEA are similar to the experimental. Figure 16b represents a comparison of the ultimate tensile strength of the FEA and the experiment. The histogram graph shows that the ultimate strength values from FEA and experiments are similar, with differences or errors of 1.81%, 3.31%, and 4.16% for HLU, VB, and VARI composites, respectively. These results indicated that the adopted material model and Hashin criterion were capable of representing fiber-dominated

tensile behavior. Since loading in the 0° direction was primarily carried by the carbon fibers, the numerical response was mainly governed by longitudinal elastic properties and fiber tensile failure, which were effectively captured by the Hashin formulation. These results suggested that the model was capable of representing the longitudinal tensile response of UD CFRP laminates and could provide a reliable basis for structural-level composite analysis.

Figure 17 shows a comparison of the stress-strain curves and ultimate tensile strength results from the experimental and FEA of 90° specimens. Figure 17a exhibits that the stress-strain curve from the FEA is similar to the experimental results for the linear region. Meanwhile, slight differences between the FEA and experimental curves occur beyond the linear elastic area, namely in the plastic (post-yield) area. The linear area of the FEA

results is longer than that observed experimentally, causing a difference between the peak of the FEA curve and the experimental curve, which represents the ultimate tensile strength. Nevertheless, Figure 17b shows the difference in ultimate tensile strength between FEA and experimental results, which is 0.24%, 0.23%, and 13% for the VARI, VB, and HLU specimens, respectively.

Although the FEA predicted the ultimate tensile strength of the 90° laminates with relatively small error, noticeable discrepancies were observed in the strain corresponding to the peak stress. The numerical model exhibited an extended linear elastic response compared to the experimental results, indicating that the adopted Hashin-based formulation was less capable of capturing the progressive matrix-dominated damage evolution occurring prior to final failure.

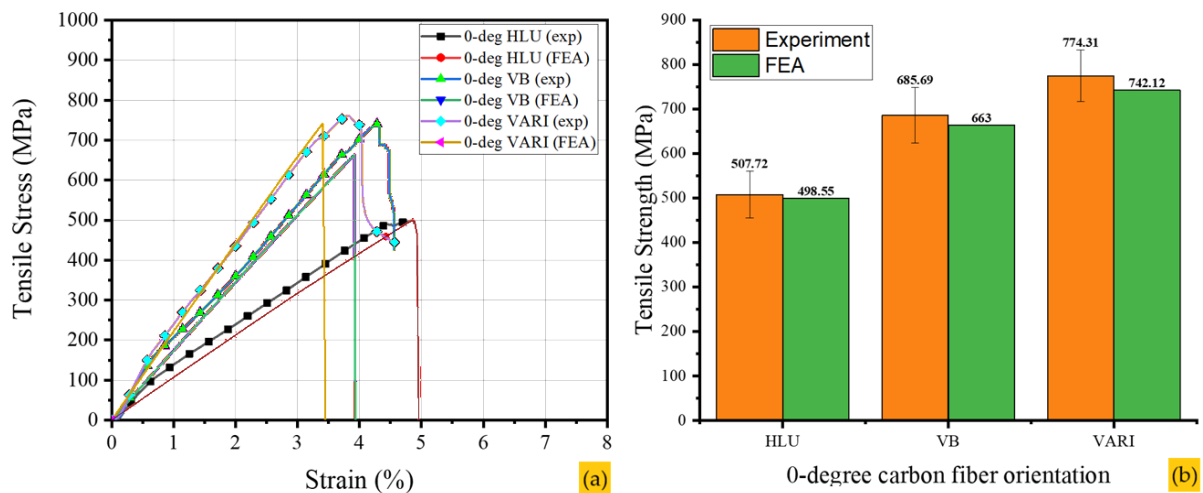


Figure 16. Experimental vs. FEA of 0° CFRP composites: (a) stress-strain curve and (b) tensile strength

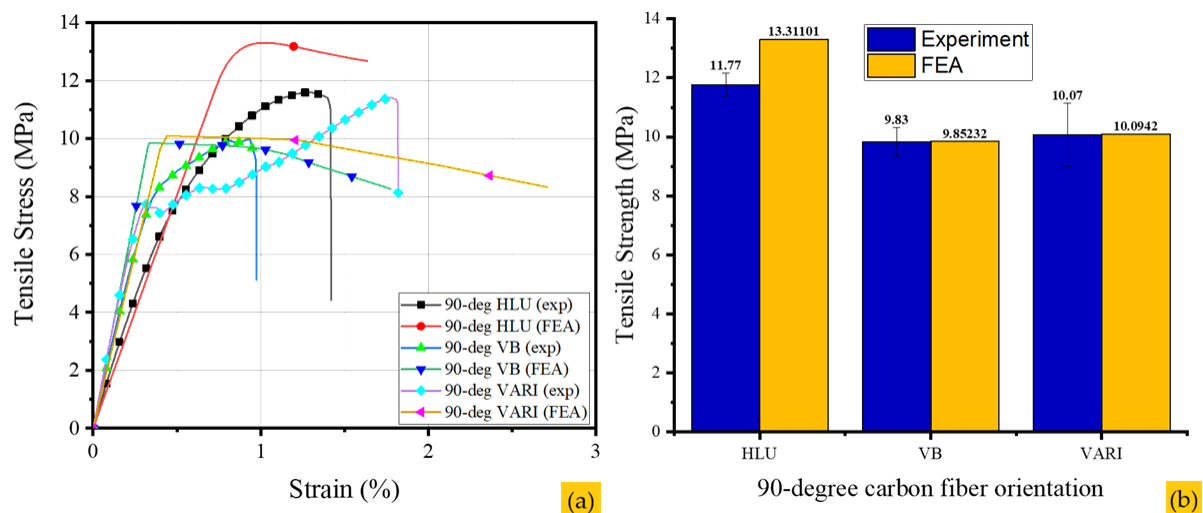


Figure 17. Experimental vs. FEA of 90° CFRP composites: (a) Stress-strain curve and (b) Tensile strength

In the experimental specimens, early matrix cracking and interfacial damage likely initiated stiffness degradation before ultimate fracture, resulting in nonlinear behavior that was not fully represented in the simulation. Nevertheless, the relatively accurate prediction of ultimate tensile strength suggests that the model remained effective in estimating failure initiation under transverse loading conditions.

Although experimental testing was conducted for the $\pm 45^\circ$ laminates, numerical validation was limited to the 0° and 90° configurations. The $\pm 45^\circ$ response is predominantly governed by in-plane shear deformation and progressive matrix shear damage, which would require dedicated shear-dominated material calibration and progressive damage evolution modeling beyond the intended scope of the present study. The numerical results demonstrated that the adopted Hashin-based formulation was effective for representing fiber-dominated tensile behavior, while limitations became more apparent under matrix-dominated transverse loading conditions. These findings provided insight into the applicability of the adopted material model and Hashin failure criterion for different laminate orientations.

The results presented across the preceding sub-sections collectively demonstrate that the mechanical performance of CFRP composites is governed by an interdependent relationship between manufacturing method, fiber orientation, and the resulting microstructural quality. The VARI process consistently produced laminates with the highest fiber volume fraction (50.44%), lowest void content (as confirmed by CT-scan), and most uniform resin distribution (evidenced by SEM), which directly translated into superior tensile stiffness and strength for 0° and $\pm 45^\circ$ orientations, where fibers effectively carry the applied load. However, these same microstructural attributes did not proportionally enhance transverse tensile strength (90°) or interlaminar shear strength, where matrix-dominated failure mechanisms prevail, and higher fiber content may even reduce performance due to restricted resin ductility and increased fiber-matrix constraint. Interestingly, despite exhibiting superior tensile stiffness and strength, the VARI specimens showed comparatively lower shear and interlaminar

shear strength (ILSS), indicating different governing failure mechanisms under fiber-dominated and matrix-dominated loading conditions. Shear and ILSS properties are more strongly governed by matrix integrity and interfacial bonding between adjacent plies. SEM observations revealed reduced resin-rich regions in VARI laminates due to higher compaction during infusion processing. Although this improved impregnation minimizes defects and enhances fiber-dominated behavior, the reduced resin-rich zones may decrease the matrix contribution to shear deformation and limit energy dissipation during interlaminar loading. Consequently, crack propagation under shear stress may occur more readily at the fiber-matrix interface or interlaminar region, contributing to the relatively lower shear and ILSS values observed in VARI specimens. Similar trends have been reported in previous studies, where higher fiber compaction improved tensile behavior but reduced matrix-dominated mechanical responses due to decreased resin availability in interfacial regions. Conversely, hand lay-up composites, despite exhibiting resin-rich regions and lower fiber content, showed the highest longitudinal compressive strength and interlaminar shear strength, suggesting that higher matrix volume and less compacted fiber architecture can better absorb compressive loads and resist delamination through enhanced interfacial energy dissipation. These trends confirm that optimizing CFRP for automotive applications requires a balanced consideration of manufacturing-induced fiber volume fraction, void reduction, and fiber orientation—where VARI excels for stiffness- and strength-driven components (e.g., body panels, roof structures), while HLU or VB may remain viable for shear- or compression-dominated parts where moderate performance is acceptable. The finite element analysis further validated that the experimentally observed differences are predictable when accurate directional properties are assigned, reinforcing the conclusion that the manufacturing route fundamentally alters not only defect content but also the anisotropic mechanical response of CFRP. Thus, the selection of the fabrication method must be aligned with the specific loading demands and failure criteria of the target automotive component.

4. Conclusion

This work investigates the impact of a combination of fabrication processes and fiber orientations on the mechanical properties of CFRP composites. The composite is composed of epoxy resin and unidirectional carbon fiber with variations in fiber direction of 0°, 90°, and $\pm 45^\circ$, and variations in manufacturing methods of VARI, VB, and HLU. Mechanical properties are characterised by tensile, compressive, v-notched beam, and short beam testing. Manufacturing results show that the most compact composites were produced by the VARI method, followed by VB and HLU, respectively. This is evidenced by the lowest thickness, the highest fiber volume fraction, and the absence of voids in the composites based on CT scan results. The VARI composites showed the highest tensile strength and modulus in the longitudinal and $\pm 45^\circ$ fiber orientation specimens, followed by VB and HLU composites. These superior tensile properties are related to the higher fiber volume fraction and better fiber/matrix bonding in the VARI composites. However, increasing the volume percentage of fiber did not significantly increase the tensile strength in specimens with transverse fiber orientation. Meanwhile, the tensile modulus in the transverse fiber orientation VARI specimens remained process dependent, resulting in consistently the highest stiffness. Under compressive loading, longitudinal fiber direction composites exhibited a reverse trend to tensile properties, with the highest tensile strength provided by hand-layup specimens. VARI composites demonstrated higher compressive strength than both vacuum bagging and hand layup specimens with transverse fiber direction. This indicates a complex interaction between fiber direction, matrix dominance, and laminate compaction under compressive loading. The shear modulus value of VARI composites is the highest, demonstrating the consistency of this method in producing composites with the highest stiffness under tensile, compressive, and shear loading. However, its shear strength and interlaminar shear strength values are lower than those of HLU and VB composites. Overall, the mechanical properties of VARI composites are superior to those of HLU and VB composites, except for shear strength and interlaminar shear strength. SEM analysis revealed resin-rich areas

and resin fractures in hand-layup specimens, which resulted in non-uniform load transfer and premature failure. Vacuum bagging specimens showed a decrease in resin-rich areas, while VARI specimens showed uniform resin distribution and increased fiber/matrix integrity, which are directly related to superior mechanical properties. The FEA results indicate that the stress-strain curve and ultimate tensile strength are similar to the experimental results. The results of this study are important in the design and analysis stages to determine the most suitable carbon fiber composite fabrication method for automotive component applications.

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Author’s Declaration

Authors’ contributions and responsibilities

Kosim Abdurrohman: Conceptualization, Investigation, Methodology, Formal analysis, Writing - original draft. Mohammad Adhitya: Supervision, Writing - review & editing. Jos Istiyanto: Supervision, Writing - review & editing. Farohaji Kurniawan: Supervision, Writing - review & editing. MOH. Habibullah: Data curation, Investigation. Rialdi Agustian: Data curation, Investigation. Mikhael Gilang P.P.P.: Simulation, Writing - original draft. Agus Bayu Utama: Investigation, Methodology. Rian Suari Aritonang: Data curation, Investigation.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Generative AI statement

During the preparation of this manuscript, the authors used ChatGPT and Quillbot to improve language clarity. All AI-assisted output was subsequently reviewed and, where necessary, edited by the authors, who take full responsibility for the final content of the manuscript.

Additional information

No additional information from the authors.

References

- [1] T. Ghosh, H. C. Kim, R. De Kleine, T. J. Wallington, and B. R. Bakshi, "Life cycle energy and greenhouse gas emissions implications of using carbon fiber reinforced polymers in automotive components: Front subframe case study," *Sustainable Materials and Technologies*, vol. 28, p. e00263, 2021, doi: 10.1016/j.susmat.2021.e00263.
- [2] S. Zhang, H. Song, L. Xu, and K. Cai, "Application Research on the Lightweight Design and Optimization of Carbon Fiber Reinforced Polymers (CFRP) Floor for Automobile," *Polymers*, vol. 14, no. 21, 2022, doi: 10.3390/polym14214768.
- [3] K. B. Sim *et al.*, "Enhanced surface properties of carbon fiber reinforced plastic by epoxy modified primer with plasma for automotive applications," *Polymers*, vol. 12, no. 3, 2020, doi: 10.3390/polym12030556.
- [4] W. Pian, Y. Zhou, and T. Xiao, "A review of the feasibility of aluminum alloys, carbon fiber composites and glass fiber composites for vehicle weight reduction in the automotive industry," *Journal of Physics: Conference Series*, vol. 2608, no. 1, 2023, doi: 10.1088/1742-6596/2608/1/012005.
- [5] H. Ahmad, A. A. Markina, M. V. Porotnikov, and F. Ahmad, "A review of carbon fiber materials in automotive industry," *IOP Conference Series: Materials Science and Engineering*, vol. 971, no. 3, 2020, doi: 10.1088/1757-899X/971/3/032011.
- [6] E. Gardie, V. Paramasivam, H. Dubale, E. Tefera Chekol, and S. K. Selvaraj, "Numerical analysis of reinforced carbon fiber composite material for lightweight automotive wheel application," *Materials Today: Proceedings*, vol. 46, pp. 7369–7374, 2021, doi: 10.1016/j.matpr.2020.12.1047.
- [7] K. K. Verma, B. L. Dinesh, K. Singh, K. M. Gaddikeri, and R. Sundaram, "Challenges in Processing of a Cocured Wing Test Box Using Vacuum Enhanced Resin Infusion Technology (VERITy)," *Procedia Materials Science*, vol. 6, no. Icmpc, pp. 331–340, 2014, doi: 10.1016/j.mspro.2014.07.042.
- [8] V. A. Komarov, E. I. Kurkin, and V. O. Sadykova, "Static Structural Modeling of Large Size Thermostable Infusion Tool from Materials with Different Coefficient of Thermal Expansion," *Procedia Computer Science*, vol. 65, no. Iccmit, pp. 859–863, 2015, doi: 10.1016/j.procs.2015.09.042.
- [9] B. A. Bulgakov *et al.*, "Carbon fabric reinforced propargyl ether/phthalonitrile composites produced by vacuum infusion," *Mendeleev Communications*, vol. 28, no. 1, pp. 44–46, 2018, doi: 10.1016/j.mencom.2018.01.014.
- [10] T. Gajjar, D. B. Shah, S. J. Joshi, and K. M. Patel, "Analysis of process parameters for composites manufacturing using vacuum infusion process," *Materials Today: Proceedings*, vol. 21, pp. 1244–1249, 2020, doi: 10.1016/j.matpr.2020.01.112.
- [11] L. G. Aryaswara, G. N. C. Santos, and M. A. Muflikhun, "Defect characteristics of unidirectional glass fiber reinforced epoxy manufactured via vacuum assisted resin infusion," *Materials Today: Proceedings*, vol. 66, pp. 2796–2800, 2022, doi: 10.1016/j.matpr.2022.06.518.
- [12] S. J. Zhang, R. M. Wang, and Y. Q. Liao, "A comparative study of two kinds of T800 carbon fibers produced by different spinning methods for the production of filament-wound pressure vessels," *New Carbon Materials*, vol. 34, no. 6, pp. 578–586, 2019, doi: 10.1016/S1872-5805(19)60033-8.
- [13] Y. Wan and J. Takahashi, "Development of carbon fiber-reinforced thermoplastics for mass-produced automotive applications in japan," *Journal of Composites Science*, vol. 5, no. 3, 2021, doi: 10.3390/jcs5030086.
- [14] S. Y. Kim, C. S. Shim, C. Sturtevant, D. D. W. Kim, and H. C. Song, "Mechanical properties and production quality of hand-layup and vacuum infusion processed hybrid composite materials for GFRP marine structures," *International Journal of Naval Architecture and Ocean Engineering*, vol. 6, no. 3, pp. 723–736, 2014, doi: 10.2478/IJNAOE-2013-0208.
- [15] L. Xu, A. Jiang, Z. Yang, H. Guan, H. Jia, and M. Min, "Mechanical properties of CFF/MC/SF composite prepared using vacuum infusion impregnation method," *Results in Physics*, vol. 7, pp. 1016–1021, 2017, doi: 10.1016/j.rinp.2017.02.042.

- [16] S. van Oosterom, T. Allen, M. Battley, and S. Bickerton, "An objective comparison of common vacuum assisted resin infusion processes," *Composites Part A: Applied Science and Manufacturing*, vol. 125, no. March, p. 105528, 2019, doi: 10.1016/j.compositesa.2019.105528.
- [17] A. Zarei, S. Farahani, and S. Pilla, "An experimental study on the manufacturing of engineered defects in composite plates," *Composites Part C: Open Access*, vol. 9, no. November, p. 100327, 2022, doi: 10.1016/j.jcomc.2022.100327.
- [18] P. Mazzuca, J. P. Firmo, J. R. Correia, and E. Castilho, "Influence of elevated temperatures on the mechanical properties of glass fibre reinforced polymer laminates produced by vacuum infusion," *Construction and Building Materials*, vol. 345, no. February, 2022, doi: 10.1016/j.conbuildmat.2022.128340.
- [19] A. Kumar and D. Kumar, "Vacuum assisted resin transfer Moulding process review and variability analysis using Taguchi optimization technique," *Materials Today: Proceedings*, vol. 50, pp. 1472–1479, 2021, doi: 10.1016/j.matpr.2021.09.055.
- [20] X. Qiang, Y. Shu, X. Jiang, and S. Zhang, "Theoretical study and design recommendations on load-carrying capacity of Fe-SMA-to-steel bolted joints," *Journal of Constructional Steel Research*, vol. 217, no. April, p. 108665, 2024, doi: 10.1016/j.jcsr.2024.108665.
- [21] W. Obande, D. Mamalis, D. Ray, L. Yang, and C. M. Ó Brádaigh, "Mechanical and thermomechanical characterisation of vacuum-infused thermoplastic- and thermoset-based composites," *Materials and Design*, vol. 175, p. 107828, 2019, doi: 10.1016/j.matdes.2019.107828.
- [22] M. A. Sunilpete and R. M. Cadambi, "Development of cost effective out-of-autoclave technology - Vacuum infusion process with tailored fibre volume fraction," *Materials Today: Proceedings*, vol. 21, pp. 1293–1297, 2020, doi: 10.1016/j.matpr.2020.01.165.
- [23] A. Toldy, Á. Pomázi, and B. Szolnoki, "The effect of manufacturing technologies on the flame retardancy of carbon fibre reinforced epoxy resin composites," *Polymer Degradation and Stability*, vol. 174, 2020, doi: 10.1016/j.polymdegradstab.2020.109094.
- [24] K. Abdurrohman, T. Satrio, N. L. Muzayadah, and Teten, "A comparison process between hand lay-up, vacuum infusion and vacuum bagging method toward e-glass EW 185/lycal composites," *Journal of Physics: Conference Series*, vol. 1130, no. 1, 2018, doi: 10.1088/1742-6596/1130/1/012018.
- [25] N. Hiremath, S. Young, H. Ghossein, D. Penumadu, U. Vaidya, and M. Theodore, "Low cost textile-grade carbon-fiber epoxy composites for automotive and wind energy applications," *Composites Part B: Engineering*, vol. 198, no. May, p. 108156, 2020, doi: 10.1016/j.compositesb.2020.108156.
- [26] P. E. Caltagirone *et al.*, "Substitution of virgin carbon fiber with low-cost recycled fiber in automotive grade injection molding polyamide 66 for equivalent composite mechanical performance with improved sustainability," *Composites Part B: Engineering*, vol. 221, no. September 2020, p. 109007, 2021, doi: 10.1016/j.compositesb.2021.109007.
- [27] F. Meng, J. Mckechnie, T. Turner, K. H. Wong, and S. J. Pickering, "Environmental Aspects of Use of Recycled Carbon Fiber Composites in Automotive Applications," *Environmental Science & Technology*, vol. 51, pp. 12727–12736, 2017, doi: 10.1021/acs.est.7b04069.
- [28] A. B. Irez and H. Yakar, "Transformation of waste carbon fiber prepreg into sustainable composites: Application in the automotive industry components," *Polymer Composites*, no. February, pp. 9471–9486, 2024, doi: 10.1002/pc.28421.
- [29] K. R. Diptaseptian, Wijianto, and P. I. Purboputro, "The Role of Catalysts on Composites Properties: A Case Study on Motorcycle Body Cover," *Automotive Experiences*, vol. 2, no. 2, pp. 59–66, 2019, doi: 10.31603/ae.v2i2.2731.
- [30] M. Perkasa *et al.*, "Ramie-PLA Composite Hollow Sections for EV Chassis: Development and Static Bending Test," *Automotive Experiences*, vol. 8, no. 3, pp. 716–725, Dec. 2025, doi: 10.31603/ae.14960.
- [31] M. Khafidh *et al.*, "A Study on Characteristics

- of Brake Pad Composite Materials by Varying the Composition of Epoxy, Rice Husk, Al₂O₃, and Fe₂O₃,” *Automotive Experiences*, vol. 6, no. 2, pp. 303–319, 2023, doi: 10.31603/ae.9121.
- [32] M. Afiefudin, R. D. Widodo, and R. Rusiyanto, “Fabrication and Characterization of Asbestos Free Brake Pads Composite using Elaeocarpus Ganitrus as Reinforcement,” *Automotive Experiences*, vol. 6, no. 2, pp. 359–371, Aug. 2023, doi: 10.31603/ae.9367.
- [33] A. I. Imran *et al.*, “Comparative Mechanical and Thermal Properties of Epoxy Matrix Composite Reinforced with Coco Peat and Coconut Shell Charcoal Fillers for Automotive Brake Friction Applications,” *Automotive Experiences*, vol. 8, no. 3, pp. 563–572, Dec. 2025, doi: 10.31603/ae.14131.
- [34] F. B. Susetyo *et al.*, “Synthesis and Characterization of Hybrid Teak Wood/Water Hyacinth Reinforced Polyester Composites for Eco-Friendly Motorcycle-Brake Pad Application,” *Automotive Experiences*, vol. 8, no. 3, pp. 640–652, Dec. 2025, doi: 10.31603/ae.14627.
- [35] M. Bodaghi, R. Costa, R. Gomes, J. Silva, N. Correia, and F. Silva, “Experimental comparative study of the variants of high-temperature vacuum-assisted resin transfer moulding,” *Composites Part A: Applied Science and Manufacturing*, vol. 129, no. July 2019, p. 105708, 2020, doi: 10.1016/j.compositesa.2019.105708.
- [36] A. Hindersmann, “Confusion about infusion: An overview of infusion processes,” *Composites Part A: Applied Science and Manufacturing*, vol. 126, no. July, p. 105583, 2019, doi: 10.1016/j.compositesa.2019.105583.
- [37] A. Kubit *et al.*, “Analysis of the Influence of Manufacturing Technology on Selected Static, Fatigue and Morphological Properties of CFRP Composites,” *Materials*, vol. 18, no. 1, 2025, doi: 10.3390/ma18010102.
- [38] N. M. Ula, N. L. Muzayadah, Muksin, M. G. P. P. Pratama, Y. G. Wijaya, and A. Nugroho, “Natural Frequency and Damping Properties of Composite Sandwich Materials Manufactured using Vacuum-Assisted Resin Infusion, Vacuum Bagging, and Hand Lay-Up,” *Evergreen*, vol. 12, no. 2, pp. 628–634, 2025, doi: 10.5109/7363464.
- [39] A. A. Talabari, M. H. Alaei, and H. R. Shalian, “Experimental investigation of tensile properties in a glass/epoxy sample manufactured by vacuum infusion, vacuum bag and hand layup process,” *Revue des Composites et des Materiaux Avances*, vol. 29, no. 3, pp. 179–182, 2019, doi: 10.18280/rcma.290308.
- [40] J. El Bahaoui, I. Hanafi, M. Chairi, F. Favaloro, C. Borsellino, and G. Di Bella, “Effect of Manufacturing Processes on Basalt Fiber-Reinforced Composites for Marine Applications,” *Journal of Composites Science*, vol. 9, no. 5, 2025, doi: 10.3390/jcs9050233.
- [41] H. Rydarowski and M. Koziol, “Repeatability of glass fiber reinforced polymer laminate panels manufactured by hand lay-up and vacuum-assisted resin infusion,” *Journal of Composite Materials*, vol. 49, no. 5, pp. 573–586, 2015, doi: 10.1177/0021998314521259.
- [42] S. R. Abdullah, M. U. Wahit, S. A. Hassan, N. Othman, and N. I. S. M. Yusof, “Ramie reinforced ABS solution impregnation composites using hand lay-up and vacuum infusion techniques,” *Materials Today: Proceedings*, vol. 110, no. C, pp. 1–4, 2022, doi: 10.1016/j.matpr.2023.07.361.
- [43] T. Scalici, G. Pitarresi, D. Badagliacco, V. Fiore, and A. Valenza, “Mechanical properties of basalt fiber reinforced composites manufactured with different vacuum assisted impregnation techniques,” *Composites Part B: Engineering*, vol. 104, pp. 35–43, 2016, doi: 10.1016/j.compositesb.2016.08.021.
- [44] A. Esnaola, I. Tena, I. Saenz-Dominguez, J. Aurrekoetxea, I. Gallego, and I. Ulacia, “Effect of the manufacturing process on the energy absorption capability of GFRP crush structures,” *Composite Structures*, vol. 187, no. September 2016, pp. 316–324, 2018, doi: 10.1016/j.compstruct.2017.12.079.
- [45] I. M. Daniel and O. Ishai, *Engineering mechanics of composite materials*, no. 2. 2006. doi: 10.1016/s0261-3069(97)87195-6.
- [46] R. M. Jones, *Mechanics of Composite Materials*, no. January 2001. 1999.

- [47] American Society for Testing and Materials, "D3039 Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials," *ASTM International*, vol. 35, no. 2, pp. 36–38, 2000.
- [48] American Society for Testing and Materials, "D3518 Standard Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a $\pm 45^\circ$ Laminate," *ASTM International*, vol. 94, no. Reapproved, pp. 1–7, 2007, doi: 10.1520/D3518.
- [49] American Society for Testing and Materials, "D5379 Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method," *ASTM International*, vol. 15.03, pp. 1–13, 1998.
- [50] American Society for Testing and Materials, "D2344 Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates," *ASTM International*, vol. 3, no. 2, pp. 136–140, 2003.
- [51] American Society for Testing and Materials, "D792 Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics," *Annual Book of ASTM Standards*, vol. 14, pp. 1–5, 2007.
- [52] L. G. Stringer, "Optimization of the wet lay-up/vacuum bag process for the fabrication of carbon fibre epoxy composites with high fibre fraction and low void content," *Composites*, vol. 20, no. 5, pp. 441–452, Sep. 1989, doi: 10.1016/0010-4361(89)90213-9.
- [53] F. Y. C. Boey and S. W. Lye, "Effects of vacuum and pressure in an autoclave curing process for a thermosetting fibre-reinforced composite," *Journal of Materials Processing Technology*, vol. 23, no. 2, pp. 121–131, Oct. 1990, doi: 10.1016/0924-0136(90)90152-K.
- [54] M. Elkolali, L. P. Nogueira, P. O. Rønning, and A. Alcocer, "Void Content Determination of Carbon Fiber Reinforced Polymers: A Comparison between Destructive and Non-Destructive Methods," *Polymers*, vol. 14, no. 6, 2022, doi: 10.3390/polym14061212.
- [55] K. K. Chawla, *Composite Materials Science and Engineering*. 2019.
- [56] K. Abdurrohman *et al.*, "A Comparison of Vacuum Infusion, Vacuum Bagging, and Hand Lay-Up Process on The Compressive and Shear Properties of GFRP Materials," *Indonesian Journal of Aerospace*, vol. 21, no. 1, pp. 39–50, 2023, doi: 10.55981/ijoa.2023.286.
- [57] BMW, "The BMW i3," pp. 1–12, 2013.
- [58] T. Taylor, J. Zhang, and J. Yanagimoto, "Evaluation of a concept out-of-autoclave process for manufacturing carbon fibre reinforced polymer automotive parts," *Procedia CIRP*, vol. 86, no. March, pp. 162–166, 2020, doi: 10.1016/j.procir.2020.01.030.
- [59] O. A. Ekuase, N. Anjum, V. O. Eze, and O. I. Okoli, "A Review on the Out-of-Autoclave Process for Composite Manufacturing," *Journal of Composites Science*, vol. 6, no. 6, 2022, doi: 10.3390/jcs6060172.
- [60] Y. Su, G. Batra, and J. S. Colton, "Composite Laminate Design for Improved Open-Hole Compression Strength using Non-Standard Ply Angles and Customized Stacking Sequences Characterized by [D] Matrix," *Materials Today Communications*, vol. 24, no. November 2019, 2020, doi: 10.1016/j.mtcomm.2020.101172.