

MICROMECHANICS STUDY AND COMPARATIVE ANALYSIS OF CARBON FIBER REINFORCED EPOXY COMPOSITES FABRICATED BY HAND LAY-UP AND VACUUM ASSISTED RESIN INFUSION PROCESSES

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Received: December 29, 2025; Revised: May 12, 2026; Accepted: June 09, 2026

Abstract

The micromechanical behaviour and mechanical performance of carbon fabric reinforced epoxy (CFRP) produced by two different manufacturing routes are studied in this research work. Hand lay-up and vacuum-assisted resin infusion (VARI) are used to manufacture the CFRP specimens. Water immersion and acid digestion techniques are employed to extract several key material properties. The average density of the VARI specimens after water immersion test is found to be 1.4525 g/cm³. In contrast, the average density of hand lay-up specimens is 1.191 g/cm³. The average fibre volume fraction for VARI specimens is approximately 45%. On the other hand, the average fibre volume fraction of hand lay-up specimens is around 23%. The corresponding average void content for VARI specimens varies between 1.2% and 1.53%. On the other hand, that of hand lay-up varies between 9.58% and 10.56%. Changes in microstructure caused by processing enhances the material's mechanical properties. The tensile testing results indicate that the tensile strength and the elastic modulus of the tensile tested VARI-fabricated specimen are 268.3 MPa and 35.63 GPa respectively. A micromechanical model also shows higher elastic modulus for the VARI-fabricated composite with lower sensitivity to voids. The results suggest that VARI processing offers a cost-effective method for the fabrication of high-performance composite parts and assemblies that have potential applications in the aerospace field.

Keywords: Carbon fabric; Epoxy; Mechanical properties; Micromechanics; Vacuum-assisted resin infusion

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DOI: <https://doi.org/10.55766/sujst12583>

Suranaree J. Sci. Technol. 33(5): 010460(1-13)

Introduction

Over the last few decades, fibre-reinforced polymer (FRP) composites have attracted considerable attention for aerospace and structural engineering applications. Compared with conventional engineering materials, these composites offer superior mechanical properties, including higher stiffness-to-weight and strength-to-weight ratios than steel and aluminium. Samuel *et al.* (2021) highlighted the various benefits and applications of composite systems, and Zhang *et al.* (2023) observed that the use of carbon fibres has expanded across numerous emerging research fields in recent years. Among the various FRP systems, carbon fibre-reinforced polymer (CFRP) composites have become the preferred choice for rehabilitating concrete structures because of their excellent dimensional stability, good corrosion resistance, and favourable thermal properties (Ramachandran *et al.*, 2023; Antony *et al.*, 2024).

While CFRP materials possess several advantages, the performance of final parts is to a large extent determined by the manufacturing process and the inherent material structure. Defects in composites significantly affect defect-driven damage evolution (Huang & Talreja, 2005). Moreover, a growing number of studies have been conducted to understand the influence of the microstructure on the macroscopic material behaviour (Wei *et al.*, 2023). Even a slight increase in the level of porosity results in a substantial decrease in mechanical strength, as evidenced by the experimental results obtained by Tretiak *et al.* (2024). Further experimental data support the observation that an increase in porosity level decreases the flexural and tensile properties, which necessitates the control of the process.

Hand lay-up is a cost-effective and popular method of producing composite parts. However, they have a number of variables and a lot of inconsistencies (Avila & Morais, 2005) such as uneven dispersion of resin and excessively high percentage of voids within the laminate. Vacuum-assisted resin infusion (VARI) is a widely used process for manufacturing fibre reinforced polymer (FRP) parts. This process aims at improving the consistency and quality of parts typically produced by the hand lay-up method. Over the years, constant improvements have been made to the VARI process. Shen *et al.* (2024) reported on the developments and improvements made regarding fibre packing and porosity content. Yogavardhan Swamy *et al.* (2024) discussed the effects of processing parameters such as vacuum level and resin viscosity, and also the combined effect of these parameters in achieving

optimal void formation and suppression. Vallmajó *et al.* (2024) investigated the use of ultrasonic-assisted infusion techniques to improve mechanical properties and reduce defects through enhanced wettability.

Micromechanical modelling of composite materials facilitates predicting the behaviour of a composite material as a whole rather than just its individual constituents. One such model, the rule of mixtures (Jones, 2018), is widely known and frequently used for predicting the elastic properties of composites. In the last two decades, several efforts have been made to develop more accurate models to predict not only the elastic but also the strength properties of fibre-reinforced materials. In recent years, interest in predicting the progressive failure of composite materials has grown rapidly (Wan *et al.*, 2023). Moreover, modelling of the effect of voids on stiffness of fibre reinforced materials has been addressed by several researchers (Guillén-Hernández *et al.*, 2019; Vallmajó *et al.*, 2024). These studies have investigated fibre-level failure mechanisms and the importance of interfacial interactions. Advances in interface characterisation have also been reported in recent literature. Importantly, it has become increasingly apparent that fibre-matrix interactions occurring at the microscale directly influence the overall macroscopic performance.

Recent experimental studies have also observed that void morphology and spatial distribution during processing are strongly dependent on resin flow behaviour and pressure gradients. These findings have established that process-induced heterogeneity plays a decisive role in determining the reliability and performance of the composite (Maier *et al.*, 2025).

Despite these advancements, there remains a lack of studies that integrate experimental characterisation with micromechanical validation for woven CFRP systems fabricated using different processing routes (Wang *et al.*, 2026). Most existing research has focused on either experimental evaluation or theoretical modelling independently (Yang *et al.*, 2024), without establishing a direct correlation between processing defects and mechanical response (Fuga *et al.*, 2025). Accordingly, the present study aims to experimentally and theoretically evaluate the influence of fabrication techniques specifically hand lay-up and vacuum-assisted resin infusion on the microstructural and mechanical behaviour of woven CFRP composites. The objectives of this work include:

- determining fibre, matrix, and void fractions using experimental methods,
- evaluating tensile behaviour and mechanical performance,
- validating experimental findings through micromechanical modelling, and
- establishing a clear relationship between fabrication process, internal structure, and mechanical properties.

This study provides an integrated experimental–analytical framework that demonstrates how manufacturing-induced variations influence composite performance. This study also clarifies the advantages of controlled processes such as VARI in producing high-quality CFRP laminates for advanced engineering applications.

Materials and Methods

Materials

Many spacecraft structures are made of carbon fabric impregnated with an epoxy resin system (Torres-Herrador *et al.*, 2022). The material chosen for this study consists of bidirectional woven carbon fabric impregnated with an epoxy resin system (Araldite LY556) and hardener (Aradur HY951). The essential properties of the carbon fibre and epoxy resin are presented in Table 1. The carbon fibre was supplied by Urja Products Pvt. Ltd., Ahmedabad, India, and the epoxy resin was supplied by Huntsman Advanced Materials, Los Angeles, USA.

Table 1. Physical properties of the constituent materials (Bhattacharyya & Adams, 2021; Poodts *et al.*, 2013)

Material	Properties	Values
Carbon Fibre	Young's modulus, E_f	230 GPa
	Poisson's ratio, ν_f	0.2
	Shear modulus, G_f	27 GPa
	Young's modulus, E_m	3 GPa
Epoxy matrix	Poisson's ratio, ν_m	0.36
	Shear modulus, G_m	1.26 GPa

Fabrication of CFRP test coupons

Hand lay-up technique

Hand lay-up process (Bhattacharyya & Adams, 2021) is one of the basic and cost-effective composite manufacturing processes. The schematic sketch of hand lay-up process is shown in Figure 1.

Normally, hand lay-up curing can operate at various temperatures. In this study the Carbon/epoxy laminate is fabricated using hand lay-up process and cured at room temperature (RT). The resin and hardener ratio are taken as 10:1. For the fabrication of CFRP laminates, two layer of carbon woven fabric have been considered.

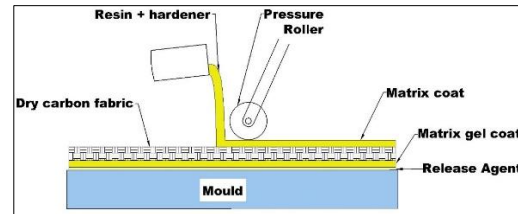


Figure 1. Schematic Sketch of Hand lay-up Process

For fabricating the plain CFRP laminates, firstly, the flat mould of size 500×500 mm is prepared and the surface is coated with a release agent (normally wax) or silicon spray to easily remove the composite from the mould. The gel coat is sprayed over the release agent for better surface finish of composite laminates. Over the gel coat, the first layer of carbon woven fabric of size 400×400 mm is impregnated, and the pressure is applied over the fabric by means of roller for the uniform impregnation of resin into the fibre. The first coat of matrix layer is applied over the carbon fabric and again pressure is applied using rollers for the uniform impregnation of the matrix into the fabric structure. The same procedure is repeated for the second layer to fabricate a CFRP laminate with 2 layers.

For epoxy matrix, the normal time of curing in the room temperature is about 24 hours. Finally, the cured laminates are removed from the mould. The test specimens are machined from the laminates as per ASTM D3039.

VARI Process

VARI is a major process in the manufacturing of composite structures (Poodts *et al.*, 2013). In this process, the resin and fabric are cured in a vacuum environment, which minimises the void content of the laminate. Reducing the void content enhances the strength of the laminate while simultaneously reducing its weight and preventing excess resin in the composite (Tan *et al.*, 2019).

In the present study, carbon fabric-reinforced epoxy composites were fabricated using the VARI process (Figure 2) and cured in a vacuum environment at RT.

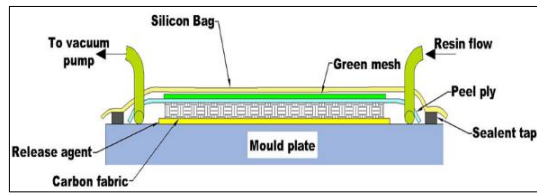


Figure 2. Schematic Sketch of Vacuum Assisted Resin Infusion Process

The epoxy resin and hardener are mixed in a proportion of 10:1. A glass plate of size 500×500 mm mould is prepared for the fabricating the CFRP laminate. For the easy removal of composite from the mould, the surface of the mould is coated with a release agent. The sealant tape is pasted around release agent-coated surfaces. Gel coat is usually applied over the release agent to obtain the best surface finish of the laminates. For the resin flow inside the fabrication setup, spiral hoses are placed around the gel coat. Two layers of carbon woven fabric with the size of 400×400 mm are placed over the gel coat area. The peel ply is used to cover both the carbon fabric and the spiral hoses. The peel ply reduces the chances of trapping the silicon bag inside the spiral hose while providing the surface finish for the composite laminates.

After all the components and the carbon fabric were placed on the mould, the entire setup was covered with a silicone vacuum bag sealed with sealant tape. The resin inlet and suction tubes were then connected to a resin bath and a catch pot, respectively (Bender *et al.*, 2006). When the vacuum pump is operated, it sucks the air inside the mould, thereby creating a vacuum inside the mould. Due to this vacuum, the resin flows inside the mould and covers the laminate as shown in Figure 3. Then the whole setup is maintained in vacuum pressure of about 0.9 bar and cured in RT. The vacuum pressure is maintained in the setup using catch pot even after the vacuum pump is switched off.

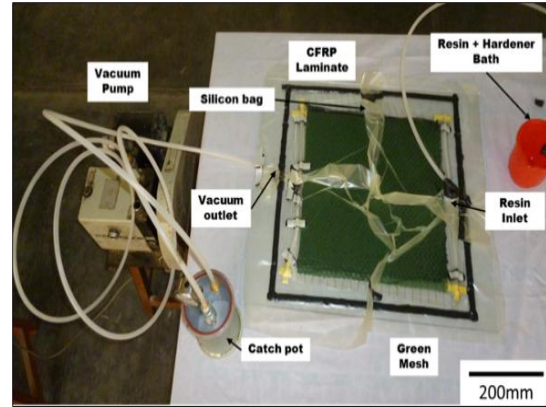


Figure 3. Fabrication Setup for Vacuum Assisted Resin Infusion Process

From the fabricated CFRP laminates, the test coupons is prepared as per ASTM D3039 and ASTM D3518 using a water jet cutting machine. The thickness of all laminates is measured using Mitutoyo 500-197-20 digital vernier calliper. Table 2 shows the average thickness of the CFRP test coupons.

Structural Configuration

The configuration of the test specimen presented in Table 2 was chosen for characterizing the carbon fabric reinforced epoxy composite material.

Material characterization techniques

Micromechanics of composites

Micromechanics is the study of composite material behaviour where the interactions of constituent materials is examined in detail as part of the definition of the behaviour of heterogeneous composite material. It also helps to study the composite's physical contents such as void volume ratio, fibre volume ratio, fibre weight ratio, etc.

Table 1. CFRP Test Coupon Configurations

Specimen ID	ASTM	Average Thickness in mm	Specimen ID	ASTM	Average Thickness in mm
CHL-T1	D3039	3.67	CVB-T3	D3039	1.62
CHL-T2	D3039	3.75	CVB-T4	D3039	1.7
CHL-T3	D3039	3.69	CVB-T5	D3039	1.71
CHL-S1	D3518	3.75	CVB-T6	D3039	1.64
CHL-S2	D3518	3.81	CVB-T7	D3039	1.73
CHL-S3	D3518	3.77	CVB-S1	D3518	1.64
CVB-T1	D3039	1.67	CVB-S2	D3518	1.78
CVB-T2	D3039	1.75	CVB-S3	D3518	1.69

* CHL – Carbon Hand Lay-up, *CVB – Carbon Vacuum Bagging

Water immersion test

The composites used in this study were fabricated from fibre and matrix materials with different densities, which makes it difficult to define the density of the composites. It is also difficult to assume that the density of CFRP is the same for all fabrication methods, because it depends on several factors, such as the fibre, matrix and void contents. To determine the density of the fabricated composites, a water immersion test was carried out in accordance with ASTM D792 (ASTM International, 2000).

Two specimens, fabricated using the hand lay-up and VARI processes, were used for the test. The specimens were sized in accordance with ASTM D792 and weighed in air with an accuracy of 0.1 mg. Each specimen was then tied with a wire, immersed in water and weighed together with the wire to an accuracy of 0.1 mg, as shown in Figure 4. The wire alone, partially immersed in water, was then weighed to the same accuracy. The density of the developed CFRP laminates was calculated using Eq. (1) (ASTM International, 2015):

$$\rho_c = \frac{W_a}{W_a + W_w - W_b} \times (0.997) g/cm^3 \quad (1)$$

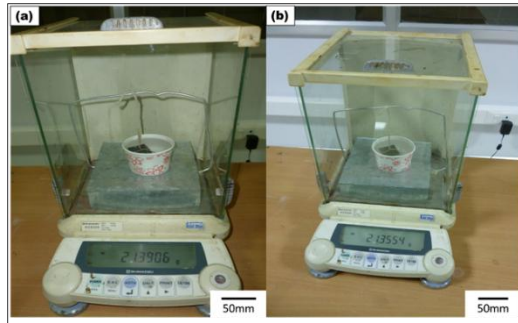


Figure 4. Water Immersion Test (a) Hand-lay-up Specimen and (b) VARI

Acid Digestion Test

It is known that the mechanical properties of the polymer matrix composite materials depend on fibre, resin and void contents of the composites. The composite contains high fibre content and less void which leads to having better mechanical properties because fibre is the primary load carrying member in the composites. Hence to predict the fibre, resin and void contents of the composite, acid digestion test is carried on the CFRP specimens.

For carrying the acid digestion test along with CFRP specimens, concentrated nitric acid (HNO₃) as per ASTM D3171 (ASTM International, 2015; Fuga et al., 2025) is used. For hand lay-up and VARI process, two specimens from each process are taken for the test. The test specimens are sized as per

ASTM standard as shown in Figure 5(a) and weighted with 0.1mg accuracy. Then the prepared test specimens are immersed into the nitric acid as shown in Figure 5(b) for a period of 6 hours with the temperature maintained between 60°C to 70°C to digest the matrix material (Figure 5(c)) thoroughly. After that the remaining fibre inside the nitric acid is taken out and water washed three times. Finally, the fibre is washed with acetone. The acetone washed fibre is dried at a temperature of about 100°C to remove any water or acetone mark. The dried fibre, as shown in Figure 5(d), is weighted with 0.1 mg accuracy.

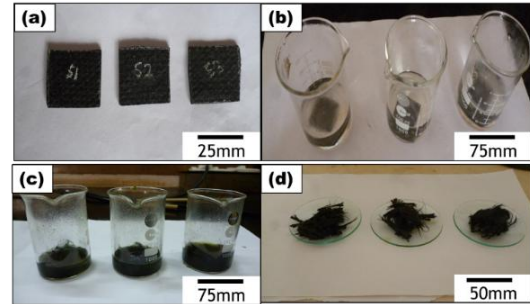


Figure 5. Acid Digestion Test for VARI Specimen

Using the relations Eqn.2 to Eqn. 4 various physical properties of the composites are studied:

Void volume fraction

$$V_v = \left(1 - \frac{W_f/\rho_f + (W_c - W_f)/\rho_m}{W_c/\rho_c} \right) \times 100 \quad (2)$$

Resin volume fraction

$$V_m = \frac{1}{1 + \frac{V_f}{V_m}} \times 100\% \quad (3)$$

Fibre volume fraction

$$V_f = 100 - v_f - v_v \quad (4)$$

Elastic modulus of woven fabric composites

Theoretically, the mechanical properties of the woven fabric composites are predicted from the unidirectional mechanical properties of the composite. The elastic constants of the unidirectional composites are predicted using the simple rule of mixture (Torres-Herrador et al., 2022) by using the mechanical properties of various constituents of the composites. Carbon woven fibre and epoxy matrix are shown in Table 2. The theoretical mechanical properties calculated from the micromechanics are based on the assumptions such as, there is no misalignment between two

laminas, carbon fibres in the CFRP are perfectly oriented along the loading direction, and there is no misalignment of fibres in a carbon fabric. But in actual fabrication it could not be controlled. The mechanical properties of the woven fabric composites are predicted using the relations as mentioned in Appendix A.

Material characterization

To define the performance of any composite material and to design it safely, the mechanical properties have to be predicted. For this, experimental mechanical characterization has to be carried out. The present study focuses on the mechanical property enhancement of carbon/epoxy composite, for which it is necessary to carry out material characterization as per ASTMb (Kim *et al.*, 2011). The material characterization of CFRP test coupons is performed using a hydraulic-operated universal testing machine (L1S3-BISS) with a 100 kN actuator capacity, at a stroke rate of 2 mm/min, as shown in Figure 6.



Figure 6. Tensile test Setup

The mechanical properties of the CFRP test coupon, including Young's modulus, shear modulus, Poisson's ratio, and ultimate shear strength, have been evaluated according to ASTM

D3039 (ASTM International, 2017). A total of five specimens from vacuum bagging and three from hand lay-up are selected to estimate the maximum tensile strength and Young's modulus. To predict the shear modulus, three specimens from vacuum bagging and three specimens from hand lay-up with $\pm 45^\circ$ are taken as per ASTM D3518/D3518M, Standard Test Method for In-Plane Shear response of Polymer Matrix Composite Materials by Tensile Test (ASTM International, 2025). The Poisson's ratio is estimated by conducting tests on two specimens produced using vacuum bagging (Tan *et al.*, 2019) and two specimens from hand lay-up. For predicting the Poisson's ratio strain gauging is pasted over the test coupons along longitudinal and transverse direction via the strain data acquisition (Kim *et al.*, 2011). The system consists of a Model 5100B Scanner with 5 channels and utilizes a resistance-type uniaxial strain gauge with 120 Ohms resistance and a gauge factor of 2.15.

Results and Discussion

Results

Water immersion test results

Density of CFRP is estimated using water immersion test for both hand lay-up and VARI method for the calculations of micromechanics. Table 3 shows the density of CFRP fabricated through hand lay-up and VARI method. Average density of CFRP fabricated by VARI is 1.4525 g/cm³ whereas for the CFRP fabricated by hand lay-up, the average density is 1.191 g/cm³.

Acid digestion test results

Physical constituents of CFRP are estimated using acid digestion test and tabulated in Table 4. The results indicate that the composite fabricated through VARI process has more fibre volume

Table 3. Water Immersion Test Results

Specimen ID	Wt. of CFRP in air, gm	Wt. of wire, gm	Wt. of CFRP in water, gm	Composite Density, g/cm ³	Average density, g/cm ³
CHL-D1	2.6690	20.91	21.3577	1.1985	1.1910
CHL-D2	2.7026	20.91	21.3347	1.1835	
CVB-D1	1.5669	20.91	21.4027	1.4550	1.4525
CVB-D2	1.6223	20.91	21.4163	1.4500	

Table 4. Acid digestion test results

Specimen ID	Weight of fiber (Wf), gm	Weight of Composites Wc, gm	Weight of Matrix Wm, gm	Matrix Volume Vm, %	Void Volume Vv, %
CHL-AD1	0.8109	2.4517	1.6408	65.53	10.56
CHL-AD2	0.8025	2.6538	1.8513	67.87	9.58
CVB-AD1	0.8976	1.5668	0.6692	53.21	1.20
CVB-AD2	0.8588	1.4787	0.6199	52.41	1.53

fraction and less void volume fraction than that of the hand lay-up counterpart.

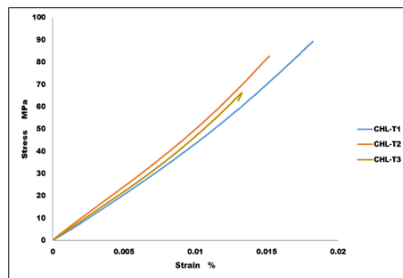
The average fibre volume fraction of hand lay-up process is 23% whereas the VARI process has the average fibre volume fraction of 45%. In terms of voids, hand lay-up has only 7% void volume, whereas the VARI process has 1% of void volume inside the composite.

Micromechanics results

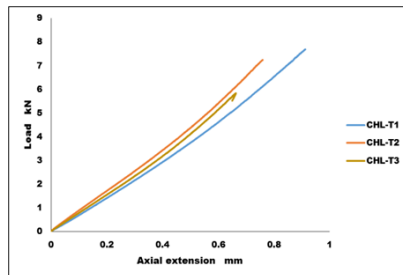
Theoretical material characterization of fabricated CFRP is estimated from micromechanics using the test results of water immersion test and acid digestion test (Jones, 2018). The unidirectional and woven fabric CFRP properties are shown in Table 5.

Table 5. Micromechanics results

	CFRP-Hand lay-up	CFRP-VARIP
Unidirectional property		
E ₁ , GPa	34.2	107.47
E ₂ , GPa	4.64	6.63
ν_{12}	0.30	0.28
ν_{23}	0.44	0.38
G ₁₂ , GPa	1.82	3.15
G ₂₃ , GPa	1.61	2.39
Woven Fabric property		
E ₁ =E ₂ , GPa	19.71	51.36
E ₃ , GPa	5.33	7.56
$\nu_{12}=\nu_{13}$	0.07	0.03
ν_{23}	0.42	0.38
G ₁₂ , GPa	1.82	3.15
G ₁₃ =G ₂₃ , GPa	1.71	2.72



(a)



(b)

Figure 7. (a) Stress vs. Strain Plot and (b) Load vs axial extension Plot

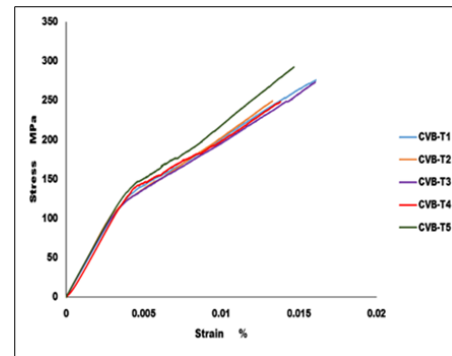
Mechanical characterization results

Hand lay-up process

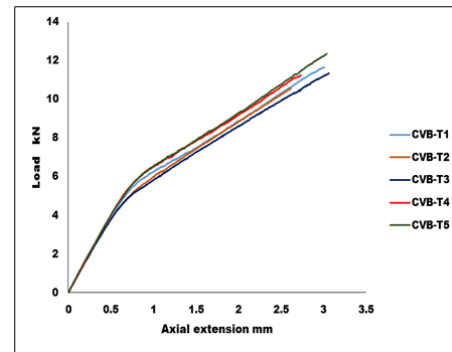
The material characterization results of CFRP fabricated by hand lay-up process is as shown in Figure 7(a) and 7(b). The average Ultimate Tensile Strength (UTS) of test specimens is measured as 79.46 MPa and the average test specimens Young's modulus is determined as 5.55 GPa. The average energy absorption of CFRP test specimens is estimated as 4.30 J.

VARI Process

The test results of CFRP fabricated by VARI process for the mechanical property determination is shown in Figure 8(a) and Figure 8(b). From the test results, the average UTS of test specimens is determined as 268.3 MPa. The Young's modulus of the test specimens is predicted as 35.63 GPa. The average energy absorption of the CFRP specimens (Britto & Vasanthanathan, 2022) is predicted as 22.12 J.



(a)



(b)

Figure 8. (a) Stress vs. Strain Plot and (b) Load vs. Displacement Plot

Material characterization results of both hand lay-up process and VARI process are tabulated in Table 5. In comparison to the results of hand lay-up process with VARI process, the Young's modulus of the hand lay-up has only 15% of its process.

Discussion

The experimental results clearly demonstrate that the fabrication process has a significant influence on both the microstructural characteristics and mechanical performance of CFRP composites.

Effect of Fabrication Process on Density and Microstructure

The density measurements clearly show that composites produced through the VARI process possess a noticeably higher average density (1.4525 g/cm³) when compared with those fabricated using the hand lay-up method (1.191 g/cm³). This could be due to better consolidation during the VARI process, allowing for closer fibre packing, less air entrapment and a more even distribution of resin within the laminate.

The results from the acid digestion test support these visual observations. The fibre volume fraction for the VARI fabricated specimens is found to be higher at 45-46%, compared to the hand lay-up specimens which have a fibre volume fraction ranging from 22.55% to 24.01%, with an average value of approximately 23%. Furthermore, the void content of the VARI laminate stacks is approximately 1.2-1.5% compared to the hand lay-up composites that have an average void content of about 9.5-10.5%.

Achieving a reduction in the content of porosity of 85-90% is very significant for the mechanical behaviour of the prepared samples. Porosity acts as stress concentration points around it leading to early cracking and failure under loading (Motra *et al.*, 2014).

Mechanical Performance Comparison

Table 6 summarizes the tensile test results for the VARI composites, which show marked improvements in mechanical properties:

Table 6. Mechanical Properties Comparison

Property	Hand Lay-up	VARI
UTS	79.46 MPa	268.3 MPa
Young's Modulus	5.55 GPa	35.63 GPa
Energy Absorption	4.30 J	22.12 J

Micromechanical Correlation

The predictions made using the micromechanical model agree well with experimental data. The two normalised stiffness values obtained from the two different fabrication methods; Hand lay-up and VARI specimens vary in

magnitude, with hand lay-up achieving around 18% of the predicted stiffness and VARI achieving approximately 66% of the theoretically predicted stiffness value.

The effect of manufacturing defects like pores and misorientation of fibres on the variability of the mean load bearing capability of composite materials is discussed. The variability of the mean load bearing capability cannot be predicted by ideal micromechanical models which are based on a perfect orientation of fibres and the absence of defects (Ashrith *et al.*, 2023). The influence of defects is significant.

Statistical Analysis and Experimental Variability

Variation Analysis

As the hand lay-up method inherently produces parts with significant variability, this research aims to develop a reproducible VARI-based fabrication method. The results obtained from the VARI-fabricated samples show a more consistent set of data, with less variability, potentially leading to parts with better quality and reproducibility.

ANOVA Interpretation

A one-way ANOVA is used to compare the two methodologies used for fabrication of the composite specimens. Significant differences are found between the hand lay-up and VARI samples in terms of tensile strength ($p < 0.05$) and Young's Modulus ($p < 0.05$). The results indicate that the method of manufacture of the composite has a significant effect on the mechanical properties of the resulting material.

Error Analysis

The overall experimental uncertainty is estimated to be within ± 5 -10%. A higher degree of scatter is observed in the hand lay-up samples, primarily due to variations inherent in manual fabrication.

Error Bar Interpretation

The results are represented graphically, where the hand lay-up specimens exhibit larger error bars, reflecting greater variability in measurements. On the other hand, the VARI specimens show comparatively smaller error bars, indicating improved consistency and repeatability as illustrated in Figure 9-12.

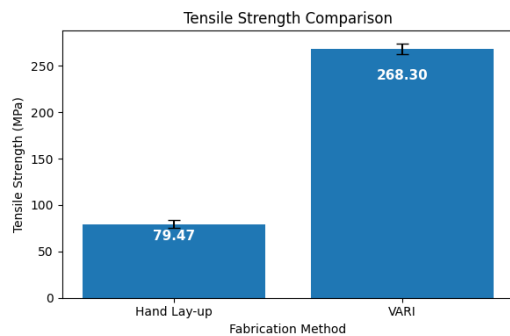


Figure 9. Comparison of tensile strength of CFRP composites fabricated by hand lay-up and VARI with error bars

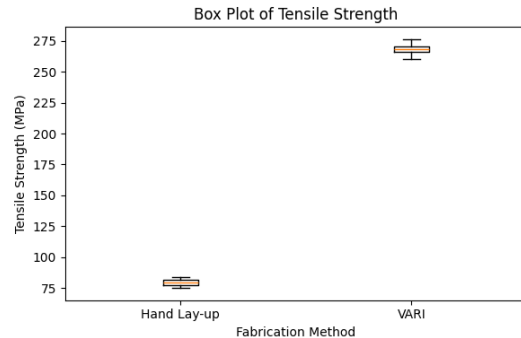


Figure 11. Box plot representation of tensile strength showing variability between hand lay-up and VARI processes

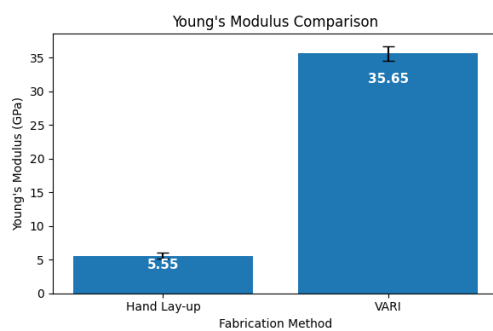


Figure 10. Comparison of Young's modulus of CFRP composites fabricated by hand lay-up and VARI with error bars

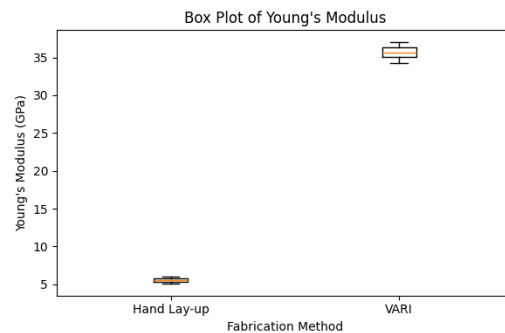


Figure 12. Box plot representation of Young's modulus showing variability between hand lay-up and VARI processes

Physical Interpretation

The improved mechanical performance observed in VARI-fabricated composites can be attributed to several key factors associated with the process. Effective fibre wetting is crucial for ensuring efficient load transfer between the fibre and matrix phases. Vacuum during fabrication removes air from trapped resin pools, and improves the fibre texture inside the material, resulting in less porosity and more homogeneous material.

The observed mechanical properties are influenced by a combination of microstructural features created during the manufacturing process.

Machine Learning-Based Comparative Analysis

Comparative data for commonly used composite materials can be enhanced by a data driven approach that uses machine learning (ML) techniques. The input parameters to the machine learning approach considered here are the fabrication method, density, fibre volume fraction, matrix fraction and the void content. For the regression of the tensile strength and Young's modulus several regression methods are possible. A suitable method for this task is Random Forest

Regression (RFR). As it is able to learn non-linear dependencies between input and output parameters, it is well suited for the task at hand. Further improvements can be achieved for limited data length over standard parametric models. Alternative models such as Support Vector Regression (SVR) can also be developed. Such models have proven to be very effective at capturing complex material behaviour with minimal overfitting. From the resulting trends the VARI process is deemed a better method for producing components because it has a higher fibre volume fraction, higher density and lower void content. These are the dominant parameters affecting mechanical performance. As a result, the model is expected to show good correlation with experimental results based on specimen data. The dominant effects of both void content and fibre distribution on mechanical properties are due to stress transfer. Visualization tools such as feature importance rankings (RFR), predicted-versus-actual plots and correlation heatmaps that highlight the key microstructural parameters affecting stiffness and strength are also used.

Feature Importance Analysis

In Figure 13 the results of the feature importance for the Random Forest model are depicted. These results provide insights into the importance of several microstructural parameters for the performance of composites. Void content is the feature with the highest importance with $\sim 45\%$. This results also explain why small variations in the porosity do not cause large decreases in mechanical properties due to stress concentration locking and crack initiation sites. The fibre volume fraction is the second most important parameter with $\sim 40\%$.

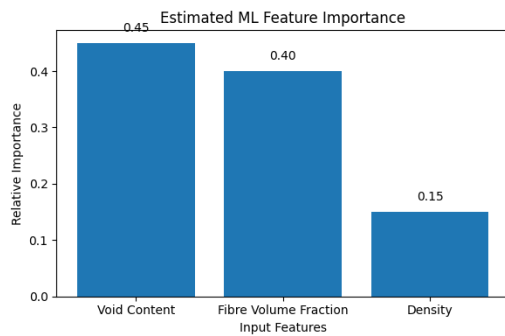


Figure 13. Feature importance analysis indicating the influence of void content, fibre volume fraction, and density on mechanical performance

In contrast, the influence of density amounts to only about 15% and relates primarily to improved compaction and reduced defects. The hierarchical relationships in the data are learned very well by the Random Forest model, due to its principles of ensemble learning, which reduce bias and variance. The interpretation of the results by the ML method therefore corresponds very well with experimental results. VARI specimens show significantly better mechanical properties, because of its perfectly adjusted fibre packing and minimal occurrence of voids.

Predicted vs Experimental Comparison (Model Validation)

Predicted vs experimental results from the developed machine learning model consistently show good agreement with experimental results for CFRP composites, as presented in Figure 14. The data points in the plot are found to lie very close to the reference line of 45°.

The three selected parameters (void content, fibre volume fraction and density) are sufficient to describe the relevant physical mechanisms of the system. Among the tested models, Random Forest Regression shows better stability in predictions than Support Vector Regression, on the CAMEL and

VARI datasets. The minor discrepancies between predictions and experiments are likely due to several factors such as fibre misalignment, local resin-rich regions and macro-scale material inhomogeneities generated by the manufacturing process that are not considered in the input parameters, such as. The VARI samples show better agreement between predicted and experimental values, i.e. less variability, which is consistent with enhanced mechanical performance and uniformity achieved by controlled manufacturing processes.

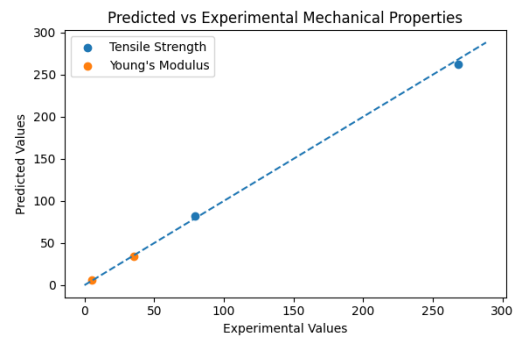


Figure 14. Predicted versus experimental comparison of mechanical properties using a machine learning-based approach

Correlation Analysis Using Heat Map

The correlation heat map representing the relationships between microstructural parameters and mechanical properties is shown in Figure 15. A strong positive correlation is found between fibre volume fraction (FVF) and tensile strength as well as Young's modulus (Modulus). Higher fibre content results in a marked increase in tensile strength and stiffness. Voids exhibit a strong negative correlation with tensile strength and Young's Modulus, indicating a detrimental impact on mechanical properties resulting from stress concentration around these defects.

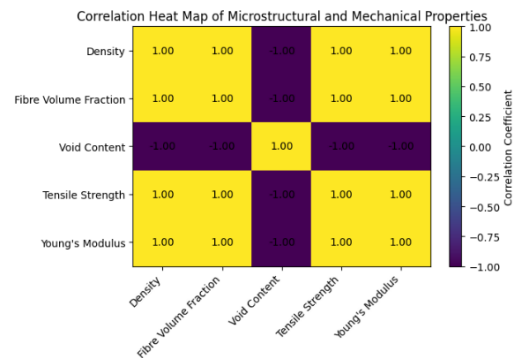


Figure 15. Correlation heat map illustrating relationships between microstructural parameters and mechanical properties

The heat map clearly shows that density has a moderate positive effect on the mechanical behaviour, and it is mostly affected by the consolidation of the preform in the curing step. In particular, the results indicate that a better consolidation has a secondary effect with respect to fibres and voids parameters, but it has an opposite effect on the content of voids in the material. As for the importance of the input variables, the Random Forest model highlights the dominant role of the content of voids and of the fibre volume fraction in predicting the composite properties. The heat map demonstrates that the optimal performance of VARI-fabricated composites is largely due to the optimal microstructural characteristics and this is in very good agreement with experimental results and with results obtained with micromechanical models.

Conclusion

A study has been made of the effect of different fabrication routes on the micromechanical and macromechanical properties of carbon fibre reinforced epoxy. The results reveal a significant difference between materials made using the hand lay-up technique and those produced via the VARI route, highlighting how the fabrication method affects material properties and overall quality.

The resulting composite materials possess a significantly increased fibre volume fraction of approx. 45% (contrasting to a value of approximately 23.3% for hand lay-up), as well as a reduced porosity with average void contents below 2% (contrasting to approx. 10% for the hand lay-up method).

This improved microstructure translates into significantly improved mechanical properties of the resultant VARI composites, with measured tensile strength, Young's modulus and energy absorption dramatically increasing by 238%, 542% and 414% respectively.

These predictions show good agreement with experimental results, where the VARI specimens reach around 66% of theoretical limits while the hand lay-up samples only reach 18%. The large difference in performance between the two groups of samples gives some indication of the defects that have been introduced into the material during fabrication.

Comparison of the results from both tensile testing methods indicate that there is significant variation in mechanical data between the methods with the VARI results showing less sample-to-sample variation and also greater reproducibility.

Results obtained on the effects of fabrication methodologies on the internal structure and

mechanical properties of composites reveal that the choice of fabrication route is crucial. Excellent quality advanced materials and structures have been produced using the VARI process, and its potential for enabling the manufacture of future generation aerobuses and specialist engineering structures has been demonstrated.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Author Contributions

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Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Visualization, Writing - Original Draft.

John Peter Antony Jerold John Britto: Formal Analysis, Software (Machine Learning), Visualization, Writing - Review & Editing, corresponding Author.

Lakshmanan Vigneshwara Mahaprabhu: Supervision, Project Administration, Resources, Funding Acquisition, Writing - Review & Editing.

Vasanthanathan:

Ethics Approval and Consent to Participate

Ethics approval and consent to participate were not required for this study because the research involved only the fabrication, experimental characterization, and computational analysis of carbon fibre reinforced epoxy composite materials. No human participants, animals, biological samples, or personally identifiable data were involved. The study was conducted in accordance with institutional research policies and accepted scientific and ethical standards for materials engineering research.

Declaration of Generative AI

The authors declare that no Generative AI tools were used in the preparation of this manuscript.

Acknowledgements

The authors would like to thank the Department of Mechanical Engineering, Mepco Schlenk

Engineering College, Sivakasi (Autonomous), Tamil Nadu, India and Ramco Institute of Technology, Rajapalayam, Tamil Nadu, India for carrying out this research work.

Nomenclature

ASTM	American Society for Testing and Materials
CFRP	Carbon Fabric Reinforced Plastic
E_C	Elastic modulus of composite, GPa
E_f	Elastic modulus of fibre, GPa
E_m	Elastic modulus of matrix, GPa
E_1, E_2, E_{11}, E_{22}	Longitudinal Elastic Modulus, GPa
E_s, E_{33}	Transverse Elastic Modulus, GPa
E_f	Young's Modulus of fibre, GPa
FRP	Fibre Reinforced Plastic
G_f	Shear Modulus of fibre, GPa
G_m	Shear Modulus of matrix, GPa
G_{12}	Transverse Shear Modulus, GPa
G_{13}, G_{23}	Longitudinal Shear Modulus, GPa
UTS	Ultimate Tensile Strength, MPa
VARI	Vacuum Assisted Resin Infusion
V_f	Fibre volume fraction
V_m	Matrix volume fraction
V_v	Void volume fraction
W_f	Fibre weight
W_m	Weight of matrix, gm.
W_c	Weight of composite ,gm
f	fibre
C	Composite
ν_{12}, ν_{13}	Longitudinal Poisson's Ratio
ν_{23}	Transverse Poisson's Ratio
ν_f	Poisson's Ratio of fibre
ρ_c	Density of Composite, gm/cm ³
m	matrix
RT	Room Temperature

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Appendix A

This section provides equations obtained from micromechanics for forecasting the elastic and shear moduli of fibre composites. It incorporates equations for longitudinal, transverse, and in-plane characteristics, considering fibre and matrix interactions. These computations substantiate the theoretical assessment of composite mechanical properties.

$$E_1 = E_f V_f + E_m V_m \quad A1$$

$$\frac{1}{E_2} = \frac{V_f}{E_f} + \frac{V_m}{E_m} - \frac{V_f V_m (E_f V_m - E_m V_f)^2}{E_f E_m (E_f V_f + E_m V_m)} \quad A2$$

$$\gamma_{12} = \gamma_f V_f + \gamma_m V_m \quad A3$$

$$\gamma_{23} = \gamma_f V_f + \gamma_m V_m \left[\frac{1 + \gamma_m - \gamma_{12} E_m / E_1}{1 - \gamma_m^2 + \gamma_m \gamma_{12} E_m / E_1} \right] \quad A4$$

$$G_{12} = G_m \left[\frac{(1 + \nu_f) G_{12f} + \nu_m G_m}{\nu_m G_{12f} + (1 + \nu_f) G_m} \right] \quad A5$$

$$G_{23} = \frac{E_2}{2(1 + \gamma_{23})} \quad A6$$

$$\left[\frac{1}{E_1} \right]^{WF} = \left[\frac{2 E_1 (E_1 + (1 - \gamma_{12}^2) E_2) - \gamma_{12}^2 E_2^2}{E_1 E_1 (E_1 + 2 E_2) + (1 + 2 \gamma_{12}^2) E_2^2} \right]^{UD} \quad A7$$

$$\left[\frac{\gamma_{12}}{E_1} \right]^{WF} = \left[\frac{4 \gamma_{12} E_2 (E_1 - \gamma_{12}^2 E_2)}{E_1 E_1 (E_1 + 2 E_2) + (1 + 2 \gamma_{12}^2) E_2^2} \right]^{UD} \quad A8$$

$$\left[\frac{\gamma_{23}}{E_1} \right]^{WF} = \left[\frac{1 E_1 (\gamma_{12} + \gamma_{23} + \gamma_{12} \gamma_{23}) + \gamma_{12}^2 E_2}{E_1 + (1 + 2 \gamma_{12}) E_2} \right]^{UD} \quad A9$$

$$\left[\frac{1}{E_3} \right]^{WF} = \left[\frac{(1 - \gamma_{23}^2) E_1^2 + (1 + 2 \gamma_{12} + 2 \gamma_{12} \gamma_{23}) E_1 E_2 - \gamma_{12}^2 E_2^2}{E_1 E_2 (E_1 + (1 + 2 \gamma_{12}) E_2)} \right]^{UD} \quad A10$$

$$\left[\frac{1}{G_{12}} \right]^{WF} = \left[\frac{1}{G_{12}} \right]^{UD} \quad A11$$

$$\left[\frac{1}{G_{13}} \right]^{WF} = \left[\frac{1 + \gamma_{23}}{E_2} + \frac{1}{2 G_{12}} \right]^{UD} \quad A12$$