engineering proceedings

Proceeding Paper

Performance Evaluation of Three-Ply Multi-Oriented Laminate Composite Fabricated via Vacuum Assisted Resin Transfer Molding Method under Tensile Loading †

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† Presented at the 4th International Conference on Advances in Mechanical Engineering (ICAME-24), Islamabad, Pakistan, 8 August 2024.

Abstract: Laminated composites are a key area of research due to their cost-effectiveness and productivity. Fiber-reinforced laminated composite structures are widely used for their excellent strength-to-weight ratio. These composites are typically manufactured using the Vacuum Assisted Resin Transfer Molding (VARTM) method. In laminated composites, properties are highly dependent on the orientation of the laminates and their proper adhesion with the epoxy matrix. This study focuses on the application of VARTM in fabricating fiberglass laminated composites using three glass fiber laminates oriented at 0°, 45°, and 90°, impregnated with epoxy resin under vacuum assistance. The features of these composites are compared with those of composite with laminates parallel to one other at 0° and 45°. The manufacturing process involved curing the composite sheets for 24 h, followed by cutting tensile specimens according to standard D3039. Results showed that specimens with all laminates oriented at 0° to the loading direction exhibited the highest strength of 253 MPa, while specimens with laminates oriented at 45° showed the lowest strength 69 MPa and highest elongation, i.e., strain of 0.22 mm/mm.

Keywords: VARTM; laminated composite; fiberglass laminates; tensile strength

Citation: Ullah, S.; Waseem, M.; Ashfaq, B.; Khan, M.B.; Shah, M.U. Performance Evaluation of Three-Ply Multi-Oriented Laminate Composite Fabricated via Vacuum Assisted Resin Transfer Molding Method under Tensile Loading. *Eng. Proc.* **2024**, *75*, 11. https://doi.org/10.3390/engproc2024075011

Academic Editors: Muhammad Mahabat Khan, Muhammad Irfan, Mohammad Javed Hyder and Manzar Masud

Published: 23 September 2024

1. Introduction

Composite materials, known for their high strength-to-weight ratio [1,2], are extensively used in various industries to construct complex structures such as aircraft [3], automobiles, marine vessels, and sports equipment [4]. Among these, polymer matrix composites, specifically Glass fiber-reinforced polymers (GFRPs) and Carbon fiber-reinforced polymers (CFRPs), are frequently used because of their outstanding qualities [5,6]. Different manufacturing processes are used to fabricate composite parts, such as hand layup, Vacuum Assisted Resin Transfer Molding (VARTM), and additive manufacturing (AM) [2,7].

The most common manufacturing technique used globally is the hand layup method. Various researchers [8–11] have studied different material properties manufactured via this method. Margabandu et al. [10] studied the flexural and impact characteristics of laminate jute/carbon composites with different fabric stacking arrangements, using four layers of hand-layup lamina. The impact and flexural responses of the ASTM standard samples were experimentally investigated and validated numerically with Ansys Workbench. Ramesh et al. [12] analyzed the morphological and mechanical characteristics of flax-glass fiber hybrid composites using FEA and hand lay-up methods per ASTM guidelines. They found that the zero-degree fiber orientation exhibited slightly higher tensile and flexural strengths, with FEA simulations closely matching the test results. Banakar et al. [13] studied the effect of fiber orientation on glass fiber composites under tensile loading, using both experimental and finite element analysis. Their results showed good agreement, indicating that maximum stress increases and load-bearing capacity improves with a decrease in lamina orientation. Noman et al. [14] used finite element analysis to study the mechanical strength of laminated carbon fiber composites with various fiber orientations in Ansys ACP. They analyzed 0°, 30°, 45°, 70°, and 90° orientations with a 0.5 mm lamina thickness. Static structural analysis measured von Mises stress, deformation, and strain, while modal analysis identified natural frequencies. Results showed that 0° orientation provided the highest mechanical strength and maximum natural frequency. Fiber orientation is a key factor that impacts the properties of fiberglass laminates. Fiber directions in glass fiber laminated materials determine their structure and characteristics [15]. Fiber orientation has a greater influence on these composites' physical qualities than fiber volume ratio [9]. In particular, hybrid composites' acoustic and mechanical qualities enhanced as the glass fiber percentage increased [11]. The research indicates that the mechanical characteristics of hybrid composites fabricated using the hand layup process are mostly influenced by the fiber processing and fiber orientation. Hand layup is the manual method of applying layers of fibers impregnated with resin to a mold [16]. It provides flexibility but is labor-intensive and prone to inconsistencies. In contrast, VARTM involves placing resin-infused fibers into a mold, covering them with a vacuum bag, and applying pressure to remove air and compact the layers during curing. VARTM utilizes vacuum pressure to infuse resin into fiber reinforcements, creating durable composite materials with uniform quality for diverse industrial applications [16].

This study aims to analyze three-ply laminates manufactured through the VARTM method, fabricating fiberglass laminated composites with laminates oriented at 0°, 45°, and 90°, considering their mechanical properties and performance, confirming their suitability for demanding industrial applications. The orientation of the laminates in laminated composites plays a crucial role in determining their mechanical properties. Composites with fibers oriented at 0° and 90° to the loading direction exhibit the highest tensile strength of 253 MPa and 228 MPa, respectively, because the load is primarily carried by the fibers which are aligned with the direction of the applied force. In contrast, fibers oriented at 45° to the loading direction show different mechanical behaviors. For instance, fibers at 45° typically exhibit higher elongation but lower tensile strength of 69 MPa due to the shear stresses developed within the matrix [17]. Further, we also found that our three-ply laminates manufactured through VARTM outperform higher-ply laminates produced via traditional hand lay-up methods [18]. This is due to smooth epoxy flow owing to uniform thickness with negligible air trap or defects. This makes VARTM fabricated three-ply laminates a viable alternative for applications requiring high performance with lower weight and cost, the method schematic is shown in Figure 1 [19]. This enhanced performance is attributed to the smooth epoxy flow, ensuring uniform thickness and minimal defects.

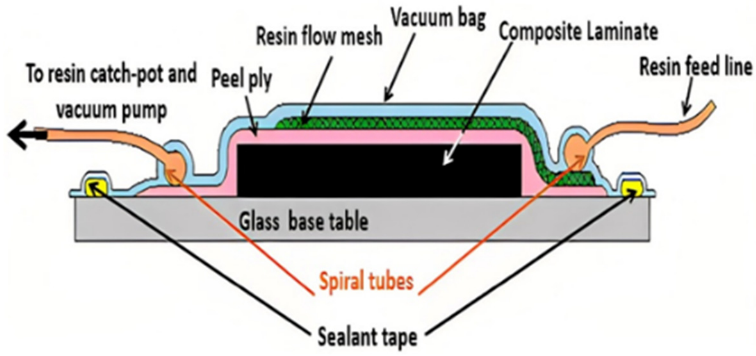


Figure 1. Schematic of VARTM.

2. Materials and Methods

This section discusses the materials utilized, which include glass fiber laminates, hardener, and epoxy, as well as the process and standard that were used.

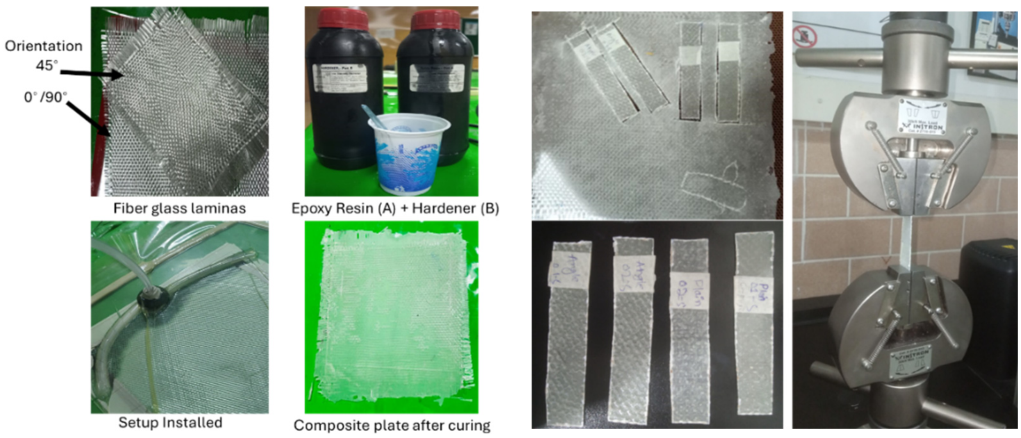
2.1. Materials

The materials employed in this study are three-ply glass fiber composite materials, with glass fibers serving as a reinforcement component and a low-viscosity hardener and resin combination constituting the matrix. The resin (part A) and hardener (part B) are combined to initiate a chemical reaction that solidifies the mixture [20]. Additional materials include peel ply, which helps shape the composite and evenly distribute the binding material, and spiral pipes, which transfer the resin mixture into the mold. A vacuum pump creates a vacuum inside the mold to facilitate the process, while sealing tape prevents air from entering the mold and a mesh provides a pathway for the resin to flow uniformly.

2.2. Methods

The fabrication process of fiberglass laminated composites begins with cleaning the glass slab thoroughly and applying wax to prevent epoxy adherence. All materials including glass fiber, ply, and mesh distribution pipes are weighed, with the resin calculated at 40% of the total weight. The epoxy and hardener are mixed in a 2:1 ratio for uniformity [21]; the details of materials used and their quantities are expressed in Table 1.

Three identical 22 × 22 cm glass fiber sheets are cut and positioned either at 0°, 90°, 0° or at 0°, 45°, 90° orientations within a mold on the glass slab. Fabric sheets and mesh are layered on top, with distribution pipes placed along the inlet and outlet sides. Sealing tape is applied around the perimeter, leaving a small gap, and the setup is covered with a plastic sheet and sealed under pressure. A vacuum pump is connected to the outlet side to form a vacuum, and resin is introduced into one end of the flow pipe while directing the other end to the sheet inlet. After allowing time for thorough resin coating, both ends are sealed, and the setup is left to cure in vacuum for 24 h. Finally, the plastic sheet is removed, and the setup is detached from the glass slab. The epoxy is mixed with hardener as per the ratio instructed by manufacturer as well as suggested by literature [21], resulting in 37.5 g of epoxy and 18.5 g of hardener. The setup overview been presented in Figure 2.



(**a**) (**b**)

Figure 2. Materials and methodology. (**a**) Stepwise materials processed, (**b**) tensile specimens' preparation and testing in UTM.

Table 1. Materials and their respective quantities utilized in the experimentation.

S/No	Item	Weight in (gm)
1	Glass fiber sheet	74
2	Mesh	5
3	Peel ply	8
4	Plastic covering sheet	2
5	Resin's inlet/outlet	37
6	Spiral pipe	14
	Total	140

2.3. Standard

The VARTM experiment adhered to the ASTM standard D3039 [22], employing sample sizes cut into rectangular cross sections with dimensions of 20 mm in width and 100 mm in length. Samples were prepared and evaluated for rectangular cross-section specimens with dimensions of 100 mm in length and 20 mm in width, following the ASTM D3039 standard protocol. According to ASTM D3039, specimens should be thin flat strips with a constant rectangular cross-section [23]. The requirements include ensuring the specimen's width and thickness promote failure in the gage section and contain enough fibers to be representative of the bulk material. The specimen length should be longer than the minimum requirement to reduce bending stresses caused by grip eccentricities, ensuring the gage section is far from the grips for reliable results. The gripping method must effectively introduce load into the specimen and prevent premature failure due to discontinuities. The standard specifies that the specimen's width and thickness tolerances are within ±1% and ±4% of the nominal dimensions, respectively. This standardization ensures consistency and facilitates comparisons in composite manufacturing. Mechanical testing under tensile loading was conducted using UTM Instron 5567 with maximum loading capacity of 30 kN. The results of the laminates' mechanical properties are illustrated in Figure 3a,b. Overall, the utilization of ASTM D3039 standards lays a robust foundation for optimizing composite manufacturing processes, underscoring the significance of standardized methodologies in materials science.

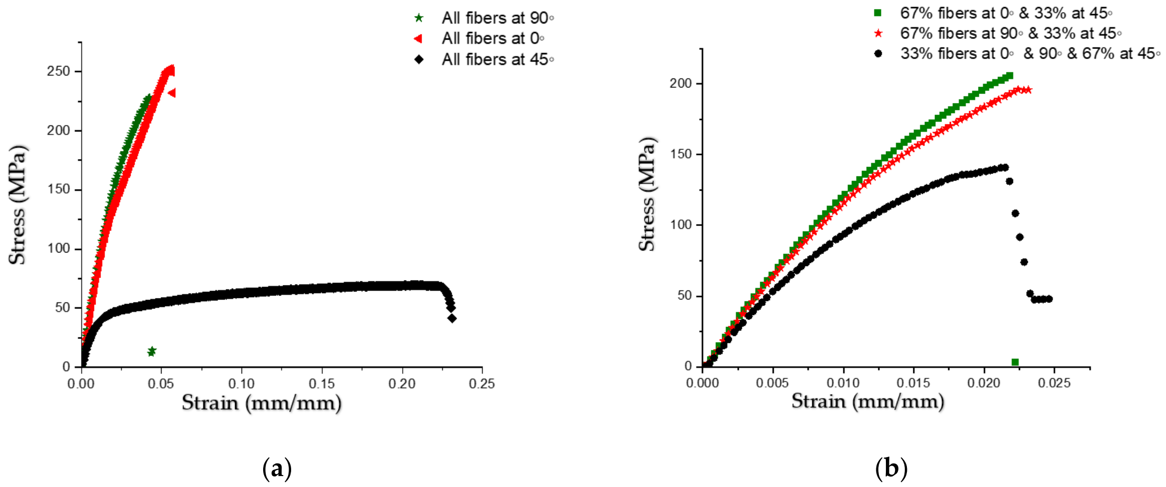


Figure 3. Tensile testing results. (**a**) Results of fibers oriented uniformly, (**b**) fibers oriented sequentially varying.

3. Results and Discussion

This section presents the results and analysis of tensile testing conducted on composite laminates prepared according to ASTM D3039 standards. The samples underwent mechanical testing under tensile loading using a UTM. Figure 3a,b illustrate the stress–strain curves for laminates with uniformed and sequentially varying fiber orientations, respectively, while Table 2 shows mean numerical results and uncertainty calculations.

Table 2. Tensile strength results, standard deviation, and uncertainty calculations.

S: No	Sample Type	Strength (MPa) (Mean)	S. D $S=\sqrt{\frac{\Sigma\left(x_i-\bar{x}\right)^2}{n-1}}$	Uncertainty $SE=\frac{\sigma}{\sqrt{n}}$
1	All fibers at 0°	253	5.96	3.44
2	All fibers at 45°	69	6.25	3.61
3	All fibers at 90°	228	4.95	2.86
4	67% fibers at 0° and 33% fibers at 45°	206	3.69	2.13
5	67% fibers at 90° and 33% fibers at 45°	195	3.65	2.11
6	67% fibers at 45° and 33% fibers at 0°/90°	141	5.25	3.03

3.1. Results

3.1.1. Uniformed Fiber Orientation (Laminate 1)

Figure 3a depicts the tensile test results for Laminate 1, where the samples were oriented at 0°, 45°, and 90° angles. The tensile strengths and strains are summarized as follows.

The 45° sample exhibits high strain but comparatively low strength due to transverse loading causing plastic deformation in the matrix. In contrast, the 0° and 90° samples demonstrate higher strength with lower ductility, as they primarily experience tensile loading aligned with the fibers.

3.1.2. Sequentially Varying Fiber Orientation (Laminate 2)

Figure 3b presents the stress–strain curves for Laminate 2 where two plies were oriented at 0° and 90° while one ply was oriented with a 45° angle. Samples were cut at 0°, 45°, and 90° angles.

Laminate 2 experiences complex loading conditions with laminates oriented at 90° and inner laminates at 45°. The 0° and 90° samples exhibit higher strength due to maximum fiber alignment with the loading direction, whereas the 45° sample shows reduced strength because a significant portion of its fibers (approximately 67%) are oriented at 45° to the loading direction, leading to plastic strain.

In Figure 3a, three samples from Laminate 1, with all fiber orientations uniform, i.e., at 0°, 45°, and 90° angles, show tensile strengths of 228, 69, and 253 MPa and strains of 0.043, 0.05, and 0.22, respectively, with a maximum of uncertainty of 3.6 in the strength value. The 45° sample exhibits high strain but low strength, while the 0° and 90° samples demonstrate high strength with low ductility. This disparity is due to fiber alignment: the 45° sample experiences transverse loading causing plastic deformation in the matrix, whereas the 0° and 90° samples have fibers primarily under tension, effectively bearing the load. Figure 3b shows the stress–strain curve for Laminate 2, three samples cut at 0°, 45°, and 90°, with tensile strengths of 206, 195, and 141 MPa and maximum strains of 0.022, 0.023, and 0.021, respectively. The maximum uncertainty recorded in samples of Laminate 2 was 3.03 in the strength value. These samples experience complex loading conditions, with two laminates oriented at 90° and inner laminates at 45°. The 0° and 90° samples exhibit greater strength due to maximum fiber alignment with the loading direction, whereas the 45° sample shows reduced strength because approximately 67% of its fibers are oriented at 45° to the loading direction, leading to some plastic strain. The fiber and laminate arrangements can be seen in the schematic given in Figure 4.

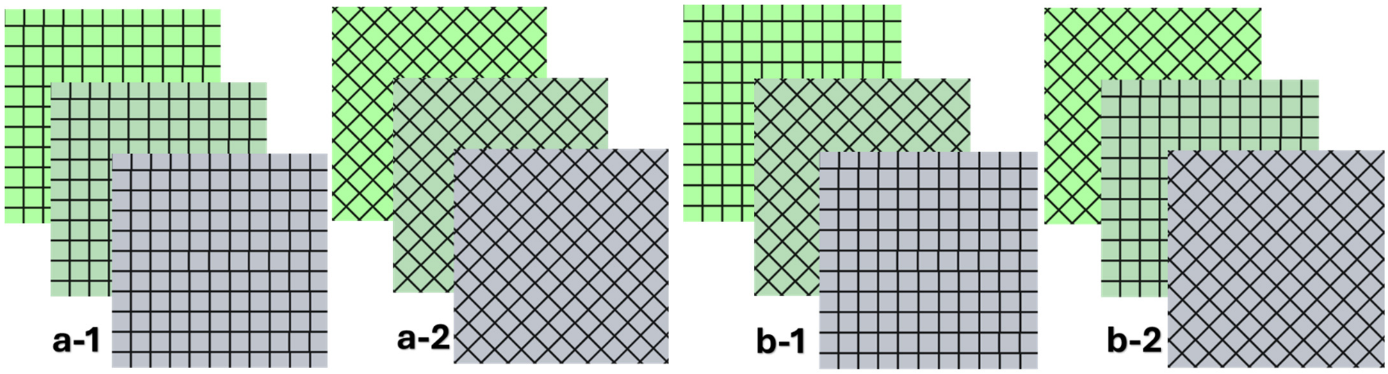


Figure 4. Schematic illustration of the fiber glass laminate orientations, i.e., (**a**) Laminate 1 with a-1, all laminates at 0°/90°; a-2, all laminates at 45°, (**b**) Laminate 2 with b-1, 2 laminates at 0°/90° and 1 laminate at 45°; b-2, 2 laminates at 45° and 1 laminate at 0°/90°.

3.2. Discussion

The results demonstrate the noteworthy influence of fiber orientation on the mechanical properties of composite laminates. Uniformed fiber orientations (Laminate 1) exhibit distinct behavior under tensile loading: orientations such as 0° and 90° offer high strength but limited ductility, while the 45° orientation shows higher strain but lower strength due to transverse loading effects. In contrast, Laminate 2 with sequentially varying fiber orientations illustrates trade-offs between strength and ductility. The 0° and 90° samples maintain higher strength due to optimal fiber alignment with the loading direction, whereas the 45° sample, despite its lower strength, achieves a balance between strength and strain due to mixed fiber orientations. These findings are crucial for engineering applications in aerospace and automotive industries, where composite materials are extensively used. Understanding how different fiber orientations influence mechanical properties allows for the design of laminates tailored to specific load conditions and performance requirements. For instance, laminates oriented at 0° and 90° may be preferred for applications requiring high strength, while those oriented at 45° could be suitable for applications needing flexibility and impact resistance.

3.3. Uncertainity Analysis

The experiments were repeated three times, showing minor variations with a maximum uncertainty of 3.6 in the results. The tensile strength of the composites was measured for different fiber orientations: all fibers were oriented at 0°, 45°, and 90°, as well as in combinations of 67% at 0° with 33% at 45°, 67% at 90° with 33% at 45°, and 67% at 45° with 33% at 0°/90°. The mean tensile strength values and their respective standard deviations and uncertainties are presented numerically in Table 2 and graphically in Figure 5.

The error bars on the graph represent uncertainties of the measurements, indicating the variability and precision of the data. Initially, inconsistencies in the calculation of error bars were noted and corrected to ensure they symmetrically extend above and below the mean values, accurately reflecting the experimental uncertainty. The mean tensile strength values and uncertainties for different fiber orientations are 228 MPa and 3.44 MPa, 69 MPa and 3.61 MPa, 253 MPa and 2.86 MPa, 206 MPa and 2.13 MPa, 195 MPa and 2.11 MPa, 141 MPa and 3.03 MPa, respectively. These results show that fiber orientation significantly impacts tensile strength, with fibers at 0° and 90° providing higher strengths compared to those at 45° and various combinations.

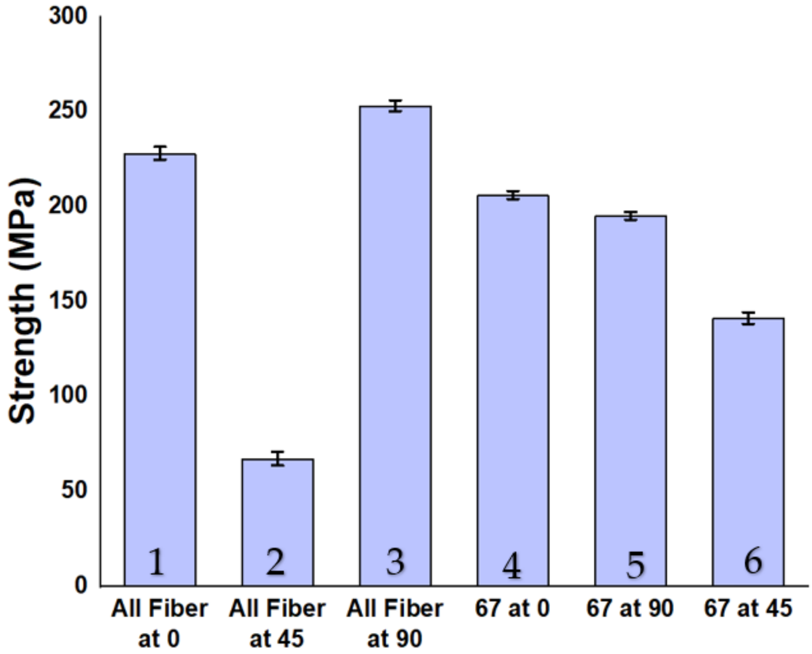


Figure 5. Error bars, (1,2,3) are from Laminate 1 while (4,5,6) are from Laminate 2.

4. Conclusions

The study explores Vacuum Assisted Resin Transfer Molding (VARTM) for producing three ply fiberglass laminated composites, evaluating mechanical properties, and discussing feasibility and performance for structural applications. Experiments conducted following ASTM D3039 standards offer insights into optimizing composite manufacturing through standardized methods. Some of the mentioned outcomes are detailed below.

- The highest strength of 253 MPa with minimum deformation having strain of 0.055 achieved in the sample with the maximum number of fibers aligned along the loading direction.
- The lowest strength of 69 MPa with maximum strain of 0.22 was observed in the sample with most fibers oriented at 45° to the loading direction.
- The sample with at least one fiber lamina at 45° to the loading direction shows 18.5% lower strength compared to those with all fibers aligned along the loading direction. Meanwhile, samples with two fiber laminates at 45° exhibit even lower strength but have 2.8 times better strain showing ductile behaviors.

The study underscores the importance of fiber alignment for enhancing the mechanical performance of composite materials, emphasizing the need to optimize fiber orientation. Challenges like mold design and resin viscosity are acknowledged, prompting future study.

Author Contributions: Conceptualization, S.U. and M.W.; methodology, S.U.; validation, M.U.S., S.U. and B.A.; formal analysis, M.B.K.; investigation, M.U.S.; resources, M.B.K.; writing—original draft preparation, M.W.; writing—review and editing, S.U.; visualization, B.A.; supervision, M.B.K.; project administration, M.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article material, further inquiries can be directed to the corresponding authors.

Acknowledgments: The authors acknowledge the composite's structure lab FME GIK Institute for providing the VARTM laminated composite manufacturing facility and materials for composite manufacturing.

Conflicts of Interest: The authors declare no conflicts of interest.

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