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Experimental Characterization of the Mechanical Properties of Composite Laminates

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Experimental Characterization of the Mechanical Properties of Composite Laminates

Abstract

Composite lamination is a method for fabricating polymer composites by stacking reinforcement layers within a polymer matrix to create controlled laminate architectures. Unlike filament-based additive manufacturing processes such as fused filament fabrication (FFF), laminate fabrication allows students to directly observe how layer orientation, fiber alignment, and matrix bonding influence mechanical behavior. This study investigated the tensile behavior of carbon fiber-reinforced epoxy laminates fabricated through a hands-on instructional module. Woven carbon fiber layers were stacked, impregnated with epoxy resin, cured, and prepared as dog-bone specimens in accordance with ASTM D638. Specimens were tested under uniaxial tension to evaluate elastic modulus, ultimate tensile strength, stress–strain response, and failure modes. The educational objective was to improve students' understanding of composite mechanics by connecting classical laminate theory with fabrication, testing, and data interpretation. Students compared specimens with fibers aligned along the loading direction and specimens with off-axis fiber orientations. Results showed that fiber orientation was a dominant factor affecting tensile performance. Aligned specimens exhibited higher stiffness and strength, whereas off-axis specimens showed reduced performance due to matrix-dominated and shear-driven deformation. Student learning was evaluated using surveys, laboratory reports, and performance-based assessment.

Introduction

Composite materials are widely used in modern engineering, yet many students find it difficult to visualize how fiber orientation governs load transfer, stiffness, and failure[1]. Concepts such as anisotropy, coupling between normal and shear deformation, and orientation-dependent failure modes are often introduced through tensor-based formulations and classical laminate theory, which can make laminate behavior appear mathematically rigorous but physically abstract. Consequently, students may follow the formal analysis of composites without fully understanding how changes in laminate architecture influence observable mechanical response[2].

This challenge is both technical and pedagogical. Instruction in composite mechanics often emphasizes analytical derivation and predictive models, which are essential for foundational understanding but less effective when presented without a clear physical counterpart[3]. In engineering education more broadly, there has been sustained emphasis on learning experiences that connect conceptual knowledge to application, performance, and reflection[4]. For the present study, that perspective provides an educational rationale for pairing composite theory with direct fabrication and testing.

Hands-on fabrication and testing create that connection by enabling students to compare theoretical expectations with the actual behavior of manufactured laminates. When students fabricate specimens themselves, they confront practical features that idealized assumptions often overlook, including process variability, imperfect bonding, and distinct failure mechanisms associated with fiber orientation[5,6]. Laminate manufacturing supported by accessible additive-manufacturing approaches is particularly valuable in this setting because stacking sequence and orientation can be modified rapidly, making the approach suitable for controlled classroom demonstrations and laboratory exercises focused on structure-property relationships.

Accordingly, this study presents an instructional framework in which laminate-manufactured polymer composites and tensile testing are used to examine how fiber orientation affects stiffness, strength, and failure. The module is organized around explicit learning objectives: students explain the influence of fiber orientation on tensile response, identify failure mechanisms in composite laminates, demonstrate safe and professional handling of composite materials, and estimate tensile properties using rule-of-mixtures reasoning. To evaluate learning within the scope of the study, the module incorporates a 5-question pre- and post-instruction concept test addressing stress-strain interpretation, shear-driven failure in off-axis laminates, and anisotropic stiffness, together with performance-based evaluations of prediction, fabrication, data analysis, and reporting. By integrating theory, manufacturing, testing, and interpretation within a single case study, the work is relevant not only to composite mechanics instruction but also to the broader materials, manufacturing, and engineering education communities.

Material and Laminate Manufacturing

As part of this instructional framework, students were introduced to the relationship between material selection, laminate fabrication, fiber orientation, and mechanical response. The laminate-manufactured composite investigated in this study was fabricated using woven carbon fiber reinforcement embedded in an epoxy resin matrix. Carbon fiber was selected because of its high stiffness-to-weight ratio and its widespread use in aerospace, automotive, and structural applications, while epoxy resin was used because of its strong adhesion to carbon fibers, effective load-transfer capability, and suitability for room-temperature curing in instructional laboratory settings .[3,7–10]. The module emphasized that fiber alignment along the loading direction

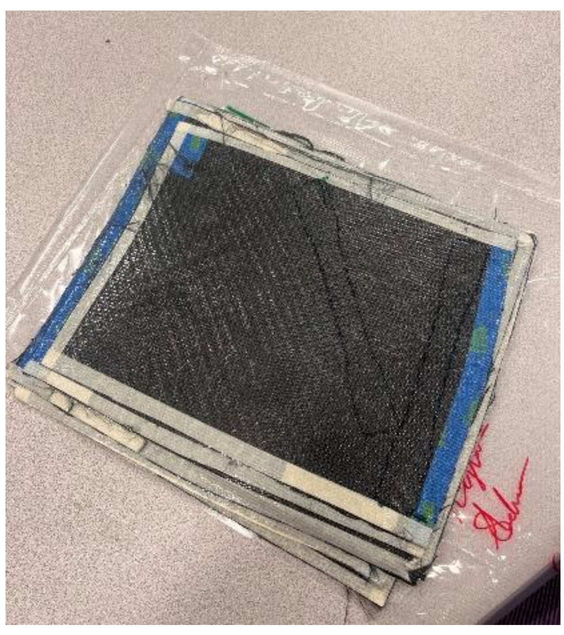

Figure 1. Prepared woven carbon fiber sheets cut to equal dimensions before laminate fabrication.

produces fiber-dominated mechanical behavior, whereas off-axis orientations promote matrix- and shear-dominated responses. Students also learned the basic fabrication process, in which equal-sized woven carbon fiber sheets were prepared before lamination, as shown in Fig. 1. Each layer was then impregnated with epoxy resin and stacked according to a specified orientation sequence to produce a laminate with uniform thickness and continuous fiber architecture [6,11–15]

Composite Fabrication

The composite laminate was fabricated using a stacking layup process similar to traditional wet layup[15–17]. Six equal-sized woven carbon fiber fabric sheets were prepared before lamination, as shown in Fig. 1. Each sheet was impregnated with a thermosetting resin–hardener mixture and stacked to form the composite laminate.

During fabrication, students were guided through the lamina concept by carefully positioning each layer to maintain consistent fiber alignment. Vacuum bagging was used to demonstrate how applied pressure can improve consolidation, reduce void formation, and enhance fiber–matrix bonding, as shown in Fig. 2. This process was connected to classical laminate theory assumptions, including ideal bonding between layers and uniform stress transfer between the fiber and matrix [7,18]

Figure 2. Laminated composite pressed in a vacuum bag to prevent voids during curing

After curing at room temperature for approximately two weeks, dog-bone tensile specimens were traced and cut from the laminate, as shown in Fig. 3. Specimens were prepared in two orientations relative to the loading axis: one with the primary fiber direction aligned with the tensile loading direction and another at 45° to the loading direction. The room-temperature curing period allowed students to observe the practical time required for resin hardening and to discuss how curing affects stiffness, strength, and dimensional stability.

Specimen cutting was performed using a band saw, which introduced realistic geometric imperfections. These imperfections were later discussed as possible sources of experimental variation and deviations from ideal theoretical predictions.[7,8,11,18,19]. Students also calculated the fiber volume fraction using measured material masses and known densities of carbon fiber and epoxy. For the fabricated specimens, the fiber volume fraction was approximately 8.5%, which was used in simplified rule-of-mixtures calculations to estimate theoretical tensile properties.

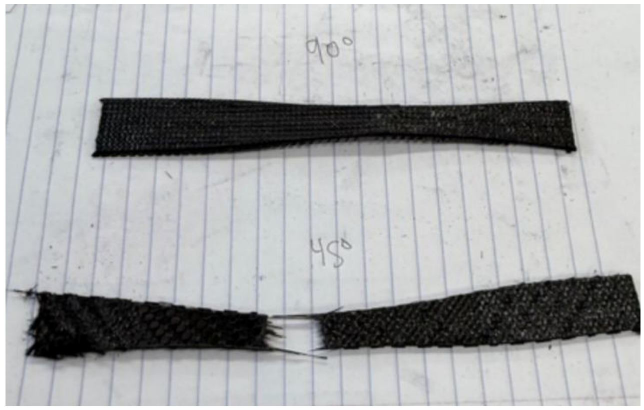

Figure 3. Specimen before and after failure.

Tensile testing was performed using an Instron Universal Testing Machine, as shown in Fig. 4. The specimens were clamped and subjected to uniaxial tension until failure while stress–strain data were recorded[17]. The experimental results were then compared with theoretical estimates obtained from a simplified rule-of-mixtures model for woven composite laminates.

Figure 4. Instron tensile setup for tensile testing.

Quality Control

Before tensile testing, dog-bone specimens were visually inspected for fabrication-related defects, including voids, delamination, and interlayer misalignment. Thickness measurements were taken at multiple locations along the gauge section to evaluate dimensional uniformity. After testing, fracture surfaces were examined to identify the dominant failure modes, including matrix cracking, fiber breakage, interlaminar delamination, and shear failure [7,16,20,21]

Results and Discussion

Two primary fiber orientations, 0° and 45°, were tested. Specimens with 0° fiber alignment exhibited significantly higher load capacity and stiffness than those with 45° fiber alignment (Table 1). The Instron test gave an ultimate tensile strength of 582 MPa for the 0-degree specimen, with strain and tensile modulus at UTS of 0.005 and 6.43 GPa, respectively (Fig. 5).

The 45-degree specimens had a much lower UTS of about 113 MPa, with a strain of 0.04 and an elastic modulus of 3.96 GPa.

Table 1. Tensile properties of laminate manufactured composite specimen

Fiber orientation	Ultimate tensile strength (Mpa)	Strain (UTS	Tensile Modulus (Gpa)
0^0	582	0.053	6.43
45^0	113	0.04	3.96

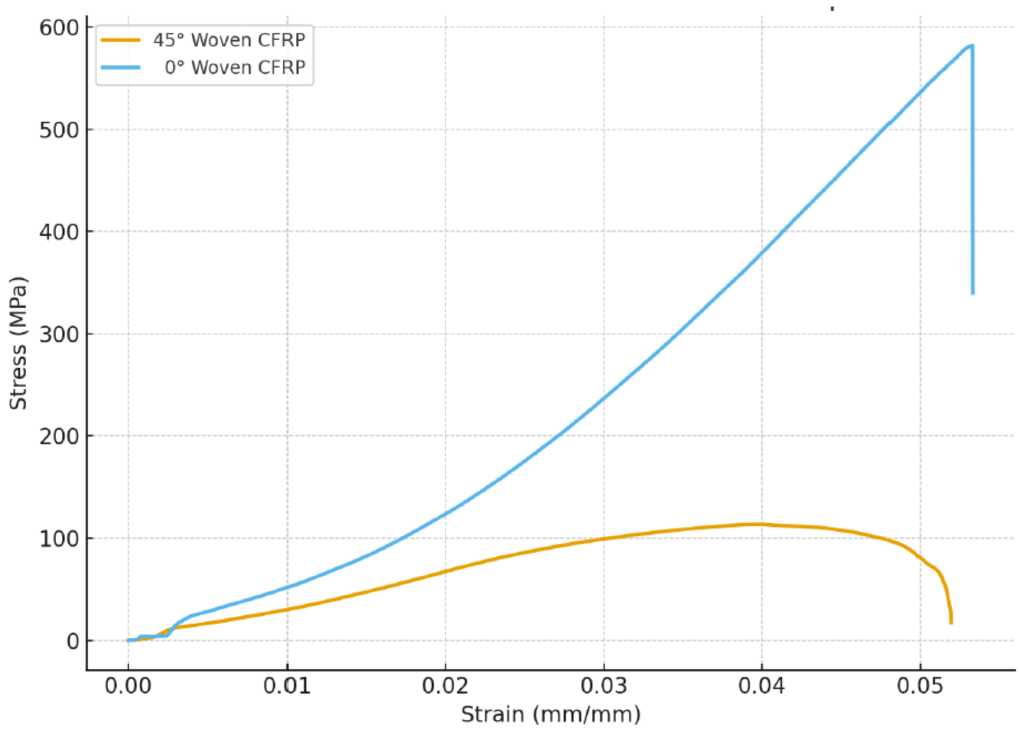

Figure 5. Effects of carbon fiber orientation on mechanical properties of specimens

These findings correspond with established knowledge that load transfer is most efficient when fibers are aligned with the applied stress (Table 1). The experimentally measured strengths were substantially lower than the ideal rule-of-mixtures predictions of 2128 MPa for 0° and 1505 MPa for 45°, which assume perfect fiber alignment and load transfer. The discrepancies are attributed to voids, fiber waviness, and matrix-rich regions [10,14,16]. The results indicate enhanced student comprehension, demonstrated by accurate predictions of directional stiffness, interpretation of nonlinear stress–strain behavior, and explanation of shear-driven failure in 45° laminates.

Learning Outcome and Educational Impact

This study on laminate-manufactured composites was developed to support explicit student learning objectives in composite fabrication, testing, and analysis. A guided laboratory module engaged students in material selection, laminate fabrication, specimen preparation, mechanical testing, and interpretation of stress–strain behavior. To address both student perception and measurable learning, educational impact was evaluated using three sources of evidence: student feedback surveys, pre- and post-module concept questions, and performance-based assessment from laboratory reports, homework/exam questions, and data-analysis activities. This multi-source assessment approach was used to reduce reliance on student self-reporting alone and to provide a stronger connection between the instructional activity and demonstrated learning outcomes.

Students' feedback regarding composite fundamentals is presented in Fig. 6. Results indicate improved understanding of fiber–matrix roles, load transfer mechanisms, and anisotropic stiffness behavior. Students reported greater confidence in explaining how fiber orientation influences mechanical performance. These survey results suggest that students perceived the activity as helpful.

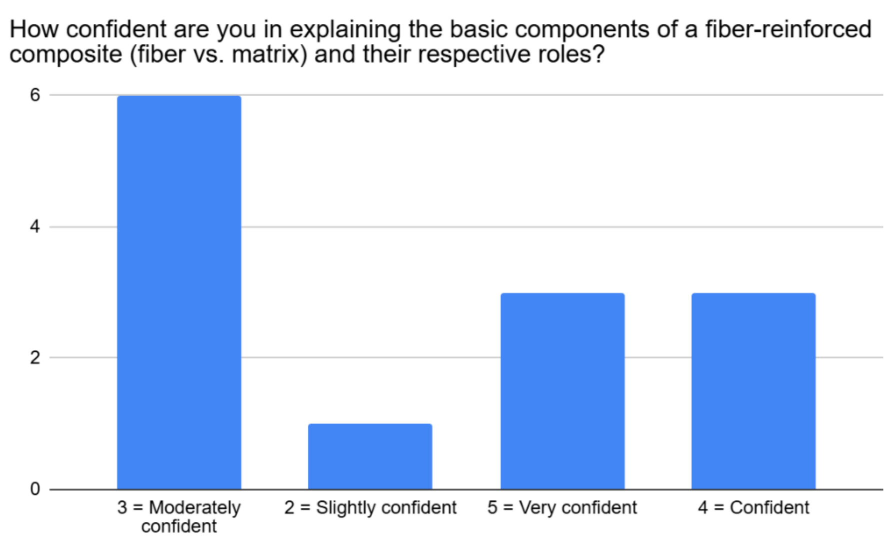

Figure 6. Students' feedback about composite fundamentals

Understanding of lamina fabrication procedures is summarized in Fig. 7. Students demonstrated improved comprehension of resin mixing, resin-to-fiber ratio control, laminate consolidation, and vacuum bagging. Reported challenges included managing resin viscosity, maintaining uniform layer thickness, and preventing fiber misalignment, reflecting realistic manufacturing constraints. These responses were consistent with observations from the laboratory activity, where students connected fabrication quality to mechanical behavior and experimental variability.

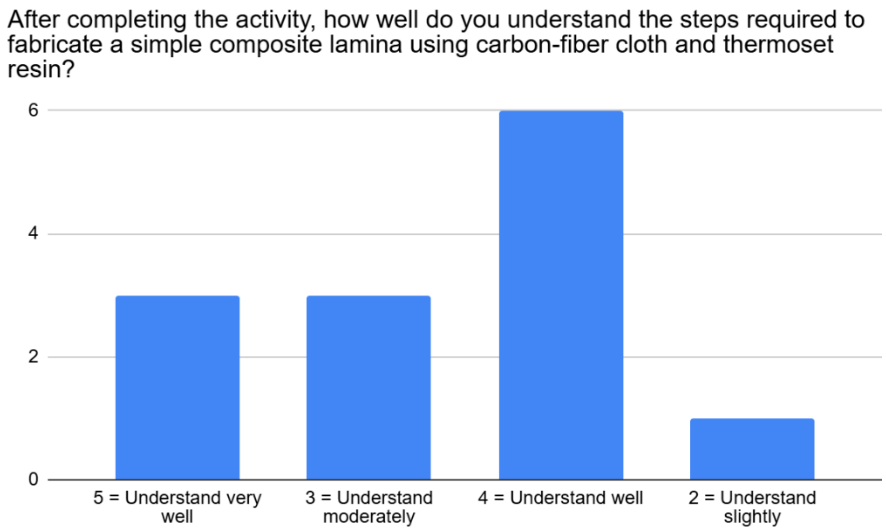

Figure 7. Students' feedback about lamina fabrication procedures

Feedback related to curing mechanics is shown in Fig. 8. Students indicated enhanced conceptual understanding of thermoset curing behavior, including resin hardening, polymerization, and the importance of proper consolidation during curing. Students also discussed how incomplete

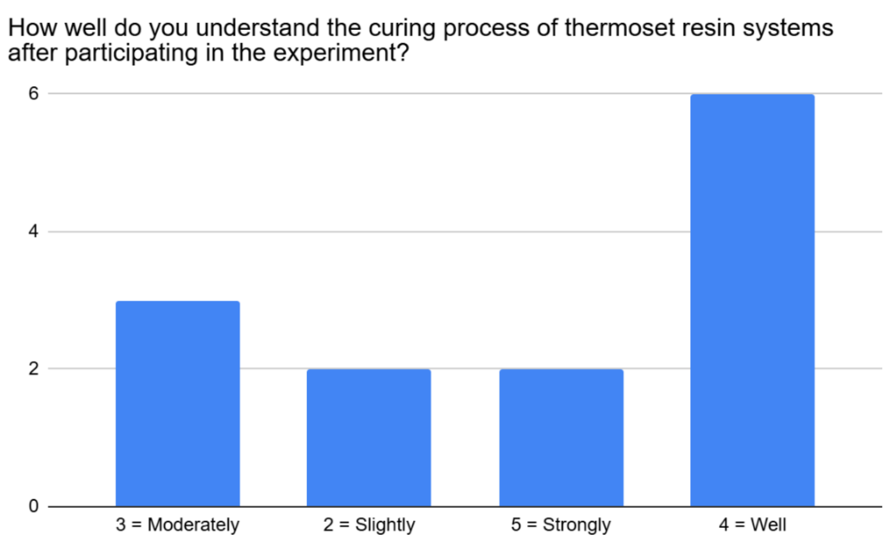

Figure 8. Students' feedback about understanding of curing mechanics

curing, voids, and poor bonding could influence stiffness, strength, and failure behavior, which helped connect processing conditions to composite performance.

Practical skill development outcomes are presented in Fig. 9. Most students reported moderate to significant improvement in their ability to work with composite materials compared with lecture-only instruction. The activity reinforced safe laboratory practices, quality control procedures, and professional material handling.

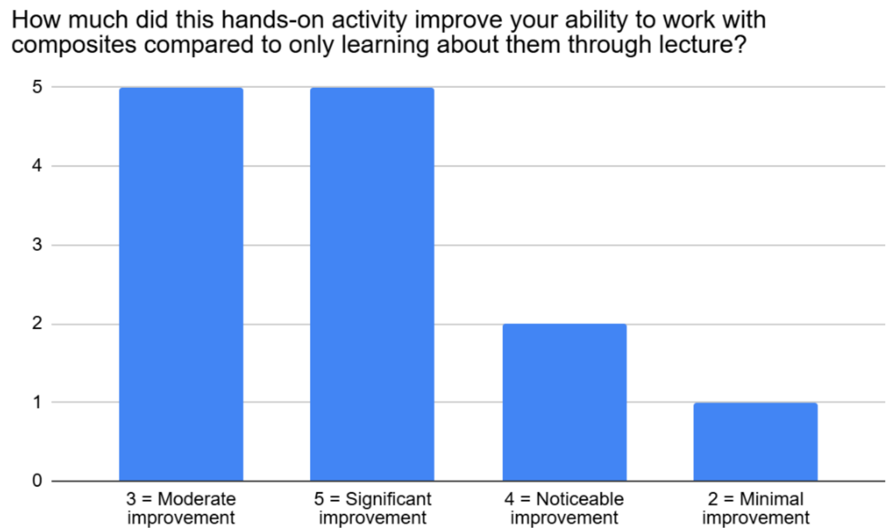

Figure 9. Students' feedback about practical skill development

Finally, Fig. 10 illustrates student confidence in applying composite materials to future engineering design projects. **Responses** indicate increased readiness to incorporate composite materials into structural and mechanical design contexts.

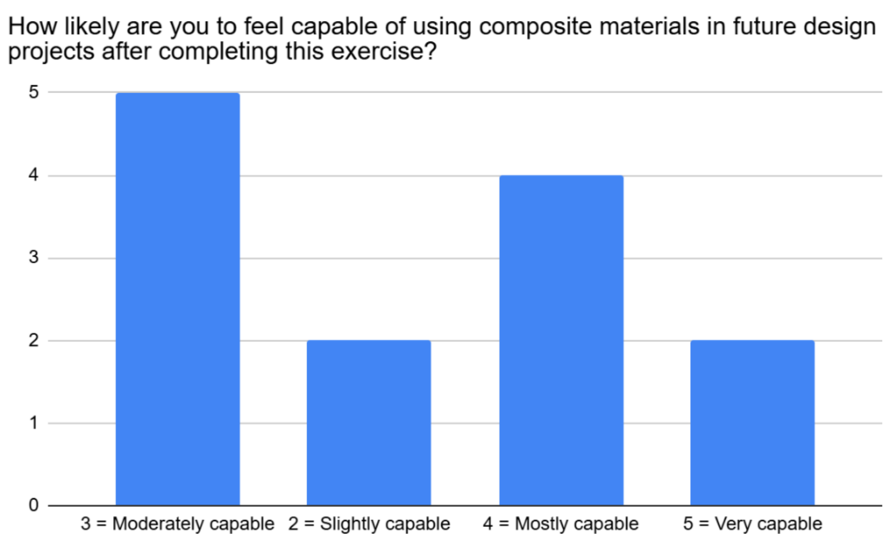

Figure 10. Students' feedback about application to engineering design

In addition to survey responses, student learning was evaluated using direct assessment of concept understanding. A 5-question concept test was administered before and after the instructional module. The questions addressed fiber–matrix load sharing, anisotropic stiffness, interpretation of stress–strain curves, and failure mechanisms. Student responses showed improvement after the module. It generally indicates that the hands-on activity helped students move beyond qualitative descriptions and toward more accurate explanations of composite behavior. Several students noted that the hands-on fabrication and testing helped them connect abstract laminate theory to physical behavior:

"Before this lab, I understood that fiber direction mattered, but I did not realize how much the loading direction changed the stiffness and failure mode."

"Making the laminate helped me understand why perfect bonding is an assumption. Small defects and uneven resin distribution can change the test results."

"The tensile test made the theory more clear because I could see the difference between fiber-dominated behavior and shear or matrix-dominated failure."

"This activity helped me understand that composite properties are not only based on the material, but also on the layup, curing, and fabrication quality."

These comments support quantitative and survey-based findings by showing that students recognized key concepts related to fiber orientation, fabrication quality, anisotropy, and failure behavior. Although the results are promising, the assessment remains limited by sample size and the exploratory nature of the instructional study. Future offerings will include a larger student population, consistent pre/post testing, and statistical analysis linking student confidence, concept-test performance, and exam/homework outcomes.

Conclusion

This study examined the tensile behavior of composite laminates and evaluated its role in improving student learning outcomes in composite materials education. The objective was to enhance students' understanding of the mechanical behavior of composites under uniaxial tensile loading. Surveys, pre/post learning assessment, laboratory reports, and performance-based evaluations were used to assess students' comprehension of standardized mechanical testing, stiffness, strength, deformation, and failure behavior in composite laminates. Laboratory reports demonstrated a significant improvement in analytical reasoning and understanding of composite laminate concepts compared to the previous cohort.

The results indicate that fiber orientation is a dominant factor influencing mechanical properties. Specimens with fibers aligned with the loading direction exhibited higher elastic modulus and strength, whereas off-axis laminates showed reduced stiffness and strength due to matrix-dominated and shear-driven failure modes. These findings reinforced the connection between laminate architecture, load transfer, and experimentally observed mechanical response. Laminate manufacturing also provided students with a practical method for controlling fiber orientation and stacking sequence, making it a valuable instructional and manufacturing approach for demonstrating structure–property relationships in composite materials.

This activity integrates materials science theory, manufacturing practice, and mechanical property analysis, supporting its application in undergraduate engineering education. Examination scores on composite anisotropy and stiffness improved by 22% relative to class averages, which suggests measurable gains in students' conceptual understanding beyond self-reported feedback. The study provided students with hands-on fabrication experience, data analysis, theory–experiment comparisons, and reflection on laminate-manufactured polymer composites.

Future research should incorporate finite-element model comparisons to improve predictive capabilities and foster advanced simulation skills. Additionally, microscopic analysis could provide further insight into failure mechanisms, fiber–matrix bonding, void formation, and microstructural differences between 0° and 45° fiber orientations. Future offerings should also include larger student cohorts and more formal statistical analysis of pre/post assessment data to further strengthen the evaluation of educational impact.

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