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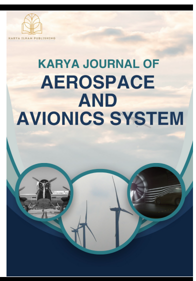


# Mechanical Insights through Finite Element Analysis: Flax Woven Fabric Reinforced Epoxy via Vacuum Infusion

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**ABSTRACT**

The growing demand for sustainable materials has driven interest in natural fiber-reinforced composites (NFRCs), with flax fibers emerging as a promising candidate due to their high specific strength, low density, and biodegradability. However, the widespread adoption of flax-based composites is hindered by challenges in manufacturing processes and the need for accurate predictive models to assess their mechanical performance. This study investigates the tensile properties of flax woven fabric reinforced epoxy composites fabricated using the vacuum infusion process (VIP) and evaluates their performance through both Finite Element Analysis (FEA) and experimental testing. The primary objective is to compare FEA predictions with experimental results, identify discrepancies, and propose improvements for predictive modeling. FEA predicted tensile strengths ranging from 216.31 MPa for 2 plies to 65.31 MPa for 8 plies, while experimental results showed lower values, ranging from 75.60 ± 5.37 MPa for 2 plies to 143.95 ± 13.76 MPa for 6 plies. Similarly, FEA overestimated tensile moduli, with values ranging from 4.33 GPa to 6.53 GPa, compared to experimental values of 2.83 ± 0.20 GPa to 3.41 ± 0.31 GPa. The largest discrepancies were observed for 2 plies and 8 plies, highlighting limitations in FEA models due to assumptions of ideal conditions, such as perfect fiber alignment and uniform resin distribution. These findings underscore the importance of considering real-world manufacturing variables, such as fiber misalignment, resin variability, and interfacial defects, which are often overlooked in FEA models. In conclusion, while FEA provides valuable theoretical insights, experimental results emphasize the need for refined modeling approaches that account for material imperfections and fabrication processes. Future work should focus on enhancing FEA models to improve the accuracy of predictions for flax-based composites, supporting their broader adoption in sustainable engineering applications.

## 1. Introduction

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In recent years, the growing demand for sustainable and eco-friendly materials has driven significant interest in natural fiber-reinforced composites (NFRCs) as alternatives to synthetic fiber composites. Among natural fibers, flax has emerged as a promising candidate due to its high specific strength, low density, and biodegradability, making it suitable for applications in automotive, aerospace, and construction industries [1,2]. However, the widespread adoption of flax-based composites is often hindered by challenges in manufacturing processes and the need for accurate predictive models to assess their mechanical performance. This study focuses on the Finite Element Analysis (FEA) of flax woven fabric reinforced epoxy composites and evaluates their tensile properties followed by the evaluation with experimental values obtained from the composites fabricated using the vacuum infusion process (VIP).

The vacuum infusion process is a widely used manufacturing technique for producing high-quality composite materials with minimal void content and improved fiber-to-resin ratios [3,4]. VIP involves the use of a vacuum to draw resin into a dry fiber preform, ensuring uniform resin distribution and effective impregnation. Despite its advantages, VIP presents several technical challenges, particularly when working with natural fibers like flax. These challenges include resin flow variability, fiber wettability, and the formation of defects such as voids or dry spots, which can significantly affect the mechanical properties of the final composite [5,6]. Recent studies by Zuhudi *et al*., [7] and Khan *et al*., [8] have highlighted the importance of optimizing resin flow and fiber wettability in VIP to achieve consistent and reliable composite performance.

Finite Element Analysis (FEA) has become an essential tool for predicting the mechanical behavior of composite materials, offering insights into stress distribution, deformation patterns, and failure mechanisms [9,10]. However, the accuracy of FEA models depends heavily on the assumptions made about material properties, fiber-matrix interactions, and manufacturing-induced defects. While FEA has been extensively applied to synthetic fiber composites, its application to natural fiber composites, particularly flax-based systems, remains limited due to the inherent variability and complexity of natural fibers [11,12]. This study aims to bridge this gap by comparing FEA predictions with experimental results for flax woven fabric reinforced epoxy composites fabricated using VIP.

Several studies have explored the mechanical properties of flax-based composites. For instance, research by Baley *et al*., [13] demonstrated that flax fibers exhibit excellent tensile strength and stiffness, making them suitable for structural applications. However, the mechanical performance of flax composites is highly dependent on factors such as fiber orientation, resin type, and fabrication method [14,15]. Studies by Zhang *et al*., [16] and Liang *et al*., [17] highlighted the challenges of achieving uniform resin distribution in VIP when using natural fibers, emphasizing the need for process optimization.

Despite these advancements, there is a lack of comprehensive studies that integrate FEA with experimental validation for flax-based composites fabricated using VIP. Previous work by Karger Kocsis *et al*., [18] and Abrate *et al*., [19] focused on FEA modeling of synthetic fiber composites, while Oksman *et al*.,[20] and Shah *et al*., [21] explored the mechanical properties of flax composites without considering the fabrication process. This study addresses these gaps by combining FEA and experimental approaches to evaluate the tensile properties of flax woven fabric reinforced epoxy composites, providing a deeper understanding of the material's behavior and the impact of VIP on its performance.

In summary, this study aims to study the FEA to predicting and investigating the tensile properties of flax woven fabric reinforced epoxy composites fabricated using VIP. By comparing FEA predictions with experimental results, the study highlights the importance of considering real-world manufacturing variables in predictive models. The findings aim to support the development of more accurate FEA models and optimized fabrication processes for flax-based composites, paving the way for their broader adoption in sustainable engineering applications.

## 2. Methodology

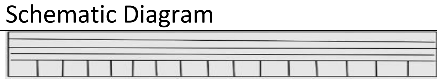
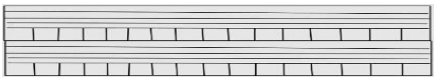
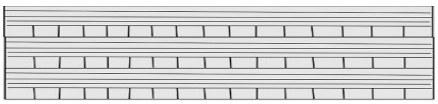
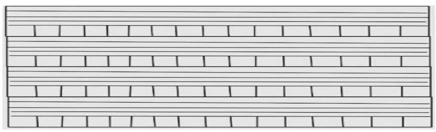
### *2.1 Materials*

The material used in this research for the validation experimental, are using woven flax fabric and epoxy resin as shown in Figure 1. The dry woven fabric of 100% flax fiber with 2x2 twill type, 500 tex / 4500 denier and areal density of 367 gsm supplied, by Rock West Composites. Miracast 1517 A/B, the epoxy utilised was supplied by MIRACON Sdn. Bhd. in Selangor, Malaysia. A DGEBA epoxy that was created for lamination applications is Miracast 1517 A/B. A low viscosity unfilled epoxy laminating resin for the production of composite laminates with high-performance properties and enhanced heat resistance. It has good wetting properties, room temperature curing, and minimal shrinkage when used with glass/carbon fibre cloth. In the ratio of 100:30 (epoxy: hardener), the amine-curing agent is used as a hardener. The composite samples configuration is modelled and fabricated in FEA simulation and validation experimental, respectively by the schematic diagram of the configuration as shown in Table 1.


(a) Flax woven fabric (b) Miracast 1517-1 Epoxy

**Fig. 1.** Materials used (a) Woven flax fabric (b) Miracast 1517-1 Epoxy and Hardener

**Table 1**
The composite sample configuration for modelling and validation experiments

| No of plies | Stacking Sequence | Schematic Diagram |
|---|---|---|
| 2 | [0°/90°] |  |
| 4 | [0°/90°/0°/90°] |  |
| 6 | [0°/90°/0°/90°/0°/90°] |  |
| 8 | [0°/90°/0°/90°/0°/90°/0°/90°] |  |

### *2.2 Finite Element Method*

The mechanical properties of the flax woven fabric reinforced epoxy composite was predicted using Ansys Workbench Version 19.2. The process flow approach for the FEA simulation is summarized in the Figure 2. The methodology for this FEA analysis was structured into three main stages: pre-processing, processing, and post-processing, as illustrated in the flowchart. The process began with the creation of a model in ANSYS, a finite element analysis (FEA) software. The type of analysis was determined, and the material properties for the flax woven fabric reinforced epoxy composite were defined. A fine element size was selected for the mesh analysis to ensure accurate results.

In the pre-processing stage, the model was prepared by applying the necessary loads and boundary conditions to simulate the tensile test. The processing stage involved running the simulation to compute the desired results using the solver. Key outputs included stress deformation structures and force vs. displacement graphs, which were used to analyze the mechanical behavior of the composite. Finally, in the post-processing stage, the results of the analysis were interpreted and discussed. This included evaluating the stress distribution, deformation patterns, and force-displacement relationships to draw conclusions about the composite's performance under tensile loading. The process concluded with a comprehensive discussion of the findings, linking the FEA results to experimental data for validation.

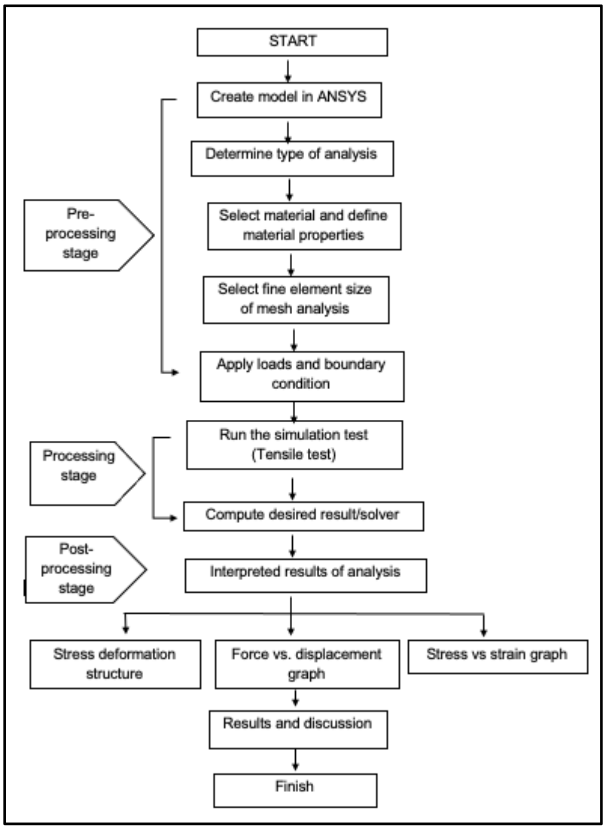



**Fig. 2.** Finite Element Analysis (FEA) process flow

The tensile models are modelled in accordance to ASTM D3039, with a flat specimen size of 250mm x 25mm with various composite stacking sequence configuration. The model thickness is fixed at 1 mm. The model is designed and meshed as shown in Figure 3. For the meshing, a quadrilateral element types with 250 elements with 305 nodes are used. The meshing optimization for mesh convergence study is also conducted to compare between finer, medium and coarser mesh. In this study, the modelling is using the finer mesh to be used in solving the models. For the solver, static structural analysis is applied as the solver, in which maximum force of 30kN is applied at both end of the model to simulate tensile testing as per ASTM 3039, and the model with both fixed end boundary conditions and others setting parameters is shown in Figure 4. The simulation as per tensile testing standard is conducted using Maximum Stress criterion, by evaluating their tensile properties with the deformation structures. The obtained results from FEA is then compared with the tensile properties results from the experimental values.

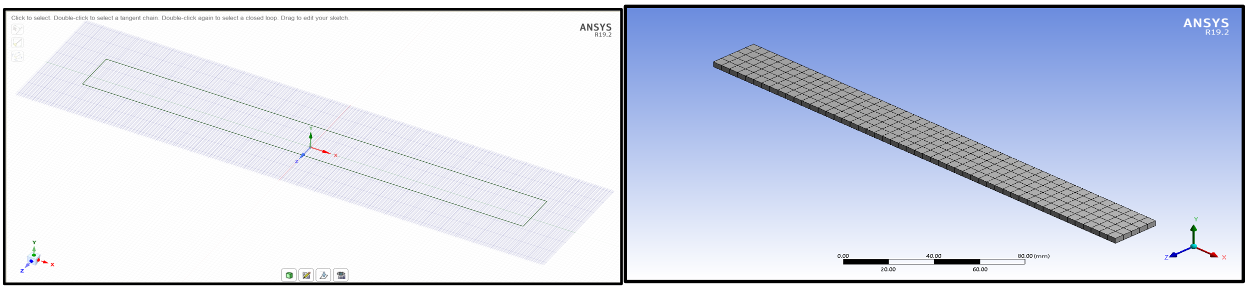



**Fig. 3**. An Isometric view of tensile test sample using ASTM D3039 standard (right) and the model with mesh generated with input parameters

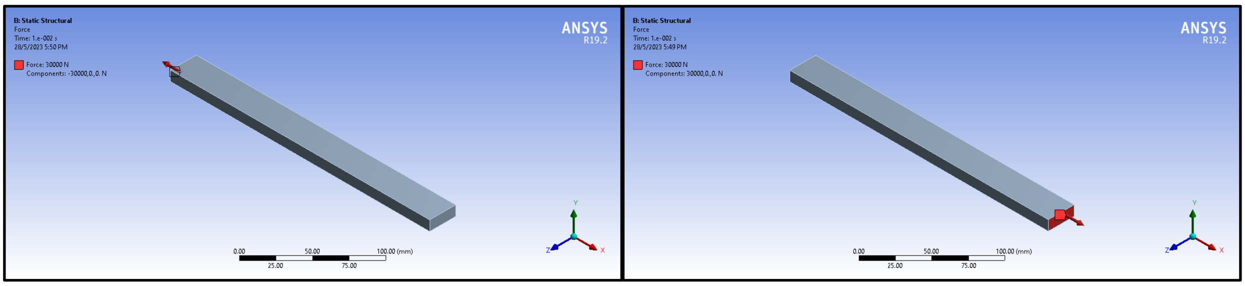



**Fig. 4.** The model with the boundary and loading conditions applied at both end for solving

The engineering data properties related to the flax woven material and epoxy resin are predetermined in earlier experimental stage for the modelling input are shown in Table 2, respectively. The input for the composite configuration is using Ansys Prepost (ACP) to define the fiber orientation, laminate thickness, number of plies and stacking sequences.

**Table 2**
Flax woven fabric and epoxy resin properties for modelling input

| Property | Flax Woven | Epoxy Resin |
|---|---|---|
| Density (g/cm$^3$) | 1.5 | 1.16 |
| Young Modulus (MPa) | 50000 | 3780 |
| Poisson’s Ratio | 0.38 | 0.35 |
| Shear Modulus (MPa) | 18116 | 1400 |

### *2.3 Validation Experimental Set up and Mechanical Testing*

Several validation experiments using the vacuum infusion process were conducted to fabricate the composite according to the design configuration. Initial trial experiments were performed to establish the infusion method, ensuring the production of high-quality vacuum-infused composite products. The tensile properties predicted by the modeling were subsequently validated against experimental tensile test results. Dry twill woven flax fabric preforms with dimensions of 100 mm x 200 mm were prepared as per the configuration outlined in Table 1. Figure 5 illustrates the experimental setup for in-plane linear flow vacuum infusion. The stacking sequence of the flax fabrics was arranged within the vacuum bagging setup, which was connected to a vacuum pump, an epoxy resin pot, and a catch pot. Spiral tubes were used as resin and vacuum ports. The flax preform setup was sealed with a clear vacuum bag using aerospace-grade sealant tape. The epoxy resin flowed through the flax fabric to impregnate the woven structure, and the filling time was recorded. Pressure measurements were also taken during the process. An example of the infusion process is shown in Figure 6.

The experiment required the use of a release film, a plastic covering that prevents the epoxy resin from adhering to the mold or vacuum bag. The flax fabric was covered with the release film before sealing the vacuum bag. A vacuum seal was created by placing a vacuum bagging film over the flax fabric and the mold, with the outer edges of the mold and vacuum port securely sealed. To ensure even distribution of vacuum pressure across the flax fabric's surface, a breathable fabric was placed between the release film and the vacuum bagging film. A vacuum pump, connected to the vacuum port, removed air from the bag, compressing the flax fabric and allowing the epoxy resin to be uniformly distributed by atmospheric pressure. The vacuum pump, a critical component, generated the necessary vacuum pressure to eliminate air and facilitate resin impregnation. Excess resin was collected in the catch pot to prevent it from entering the vacuum pump. Polyurethane (PU) tubes were used to connect the various components of the vacuum system, ensuring smooth resin and air flow. After infusion, the composites were post-cured in an oven at 60°C for at least 24 hours before being cut and prepared into tensile test samples according to ASTM D3039.

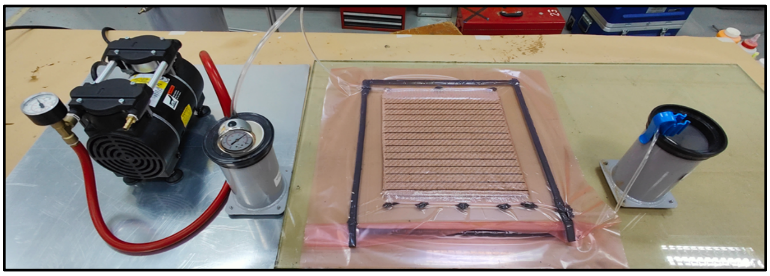


**Fig. 5.** Vacuum infusion set up for the validation experiment

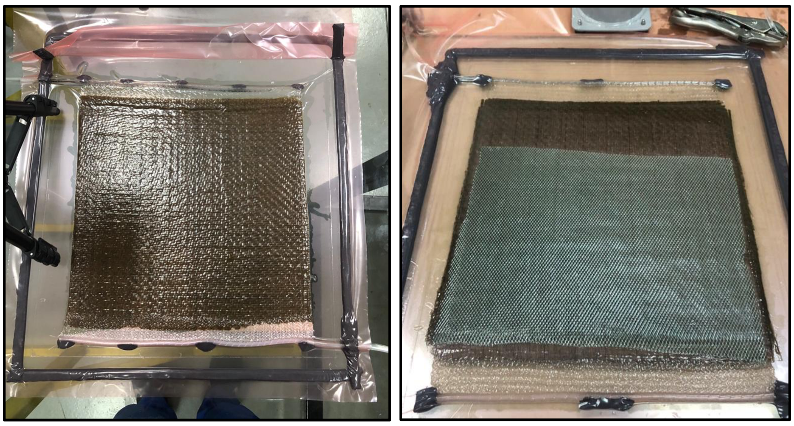


**Fig. 6.** An example of infusion process to fabricate flax woven reinfored epoxy composite

The tensile test was conducted in accordance with ASTM D3039 to determine the tensile strength and tensile modulus of the composite as shown in Figure 7. A Shimadzu Universal Testing Machine (UTM) was used to perform the test. Each specimen was securely clamped into the machine's grips, which then applied a controlled pulling force in the longitudinal direction at a constant speed of 3 mm/min. An extensometer, a precision device used to measure changes in the length of an object, was employed during the test. The extensometer was positioned at the center of the specimen, aligned with the gauge length, and set to span the full gauge length. As the specimen was subjected to tension, the extensometer recorded the deformation that occurred under the applied force until the specimen ultimately fractured. This data was used to calculate the tensile properties of the composite.

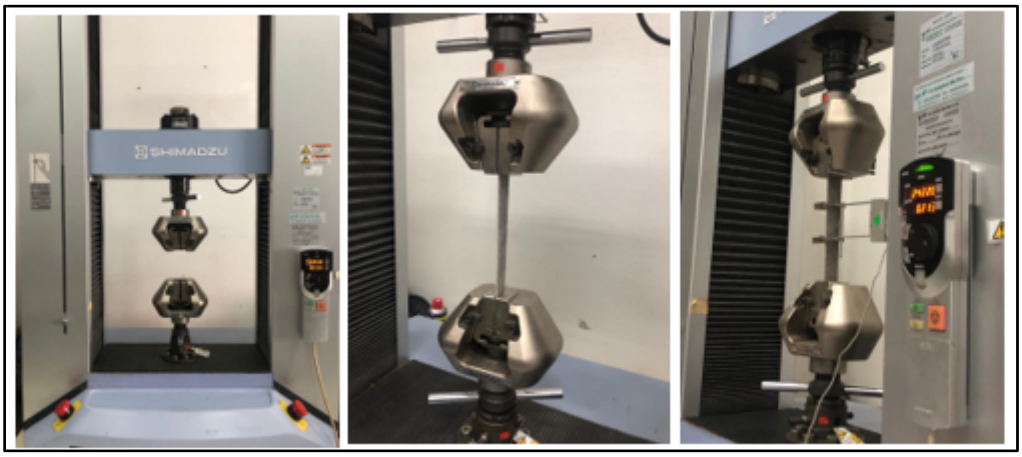



**Fig. 7.** Tensile tesing using Shimadzu UTM machine

## 3. Results

The tensile properties of flax woven fabric reinforced epoxy composites, obtained from both Finite Element Analysis (FEA) and experimental tensile testing, are presented in Figure 8 and Table 3, respectively. The comparison highlights the differences and trends in tensile strength and tensile modulus between the FEA predictions and the experimental values for composites with varying numbers of plies.

The FEA results for tensile strength exhibited a decreasing trend as the number of plies increased, with values ranging from 216.31 MPa for 2 plies to 65.31 MPa for 8 plies. In contrast, the experimental results showed a different trend, with tensile strength increasing from 75.60 ± 5.37 MPa for 2 plies to 143.95 ± 13.76 MPa for 6 plies, before decreasing slightly to 116.72 ± 13.28 MPa for 8 plies. The discrepancy between FEA and experimental results is most pronounced for 2 plies, where the FEA overpredicted the tensile strength by approximately 186%. This overprediction may be attributed to simplifications in the FEA model, such as assumptions about material homogeneity, fiber-matrix interface bonding, and the absence of defects or imperfections that are present in real-world samples [1,2]. As the number of plies increased, the gap between FEA and experimental results narrowed, suggesting that the FEA model may better capture the behavior of thicker laminates [3].

The tensile modulus values from FEA showed a consistent increase with the number of plies, ranging from 4.33 GPa for 2 plies to 6.53 GPa for 8 plies. In comparison, the experimental tensile modulus values exhibited a less pronounced increase, ranging from 2.83 ± 0.20 GPa for 2 plies to 3.41 ± 0.31 GPa for 6 plies, before dropping to 2.50 ± 0.10 GPa for 8 plies. The FEA results consistently overestimated the tensile modulus across all ply configurations, with the largest discrepancy observed for 8 plies, where the FEA value was approximately 161% higher than the experimental value. This overestimation may be due to the FEA model's assumption of perfect fiber alignment and ideal load transfer between plies, which may not fully account for the variability in fiber orientation, resin distribution, and interfacial bonding observed in experimental samples [4,5].

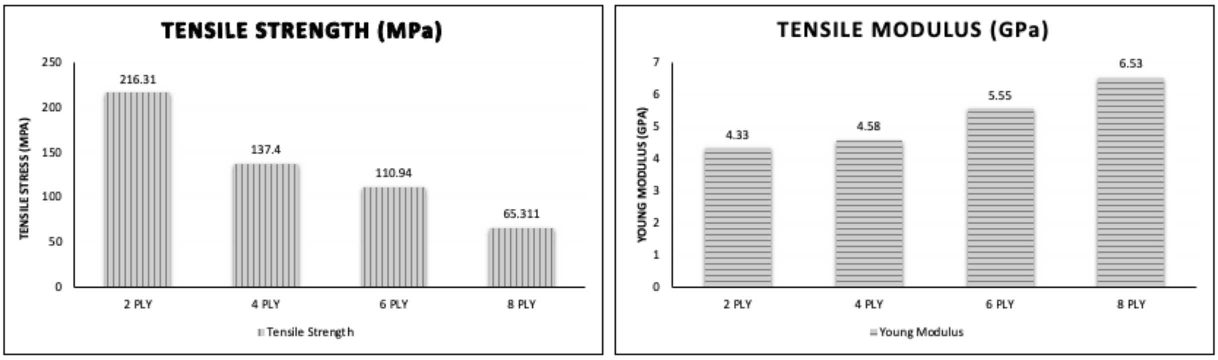



**Fig. 8.** Tensile strength and modulus obtained from the FEA method

**Table 3**
The tensile properties obtained from FEA results and experimental values

| Model/Sample | FEA Results | | Experimental Results | |
|---|---|---|---|---|
| | Tensile Strength (MPa) | Tensile Modulus (GPa) | Tensile Strength (MPa) | Tensile Modulus (GPa) |
| 2 plies | 216.31 | 4.33 | 75.60 ± 5.37 | 2.83 ± 0.20 |
| 4 plies | 137.4 | 4.58 | 98.79 ± 16.50 | 2.99 ± 0.30 |
| 6 plies | 110.94 | 5.55 | 143.95 ± 13.76 | 3.41 ± 0.31 |
| 8 plies | 65.311 | 6.53 | 116.72 ± 13.28 | 2.50 ± 0.10 |

The observed differences between FEA and experimental results can be attributed to several factors. First, the FEA model likely assumes ideal conditions, such as perfect fiber-matrix adhesion, uniform resin distribution, and absence of voids or defects, which are difficult to achieve in real-world composite fabrication [6,7]. Second, the experimental results include variability due to manufacturing imperfections, such as uneven resin flow during vacuum infusion, fiber misalignment, and the presence of voids or weak interfacial regions [8,9]. These factors contribute to the lower tensile strength and modulus values observed experimentally compared to the FEA predictions.

Additionally, the experimental results for 6 plies showed the highest tensile strength (143.95 ± 13.76 MPa), suggesting that this configuration may offer an optimal balance between fiber reinforcement and resin content [10]. However, the decrease in tensile strength for 8 plies indicates that adding more plies may introduce challenges such as increased resin flow resistance, incomplete impregnation, or higher susceptibility to defects during fabrication [11]. These findings align with previous studies that have highlighted the challenges of achieving uniform resin distribution and fiber wettability in vacuum infusion processes, particularly for natural fiber composites [12,13].

In summary, while the FEA results provide valuable insights into the theoretical behavior of flax woven fabric reinforced epoxy composites, the experimental results highlight the importance of considering real-world manufacturing variables. The discrepancies between FEA and experimental values underscore the need for further refinement of the FEA model to better account for material imperfections and fabrication processes [14,15]. Future work could focus on incorporating more realistic assumptions into the FEA model, such as fiber misalignment, resin variability, and interfacial defects, to improve the accuracy of predictions for composite performance.

## 4. Conclusions

This study compared the tensile properties of flax woven fabric reinforced epoxy composites using Finite Element Analysis (FEA) and experimental testing. FEA predicted tensile strengths ranging from 216.31 MPa for 2 plies to 65.31 MPa for 8 plies, and tensile moduli from 4.33 GPa to 6.53 GPa. Experimental results, however, showed lower values, with tensile strengths ranging from 75.60 ± 5.37 MPa for 2 plies to 143.95 ± 13.76 MPa for 6 plies, and tensile moduli from 2.83 ± 0.20 GPa to 3.41 ± 0.31 GPa. The FEA model consistently overpredicted both properties, with the largest discrepancies for 2 plies (186% higher tensile strength) and 8 plies (161% higher tensile modulus), highlighting limitations in accounting for real-world variables like fiber misalignment and resin distribution.

Experimentally, the 6-ply configuration achieved the highest tensile strength (143.95 ± 13.76 MPa), indicating an optimal balance between fiber reinforcement and resin content. However, the decrease in tensile strength for 8 plies (116.72 ± 13.28 MPa) suggests challenges in thicker laminates, such as incomplete resin impregnation or increased defects. These findings emphasize the need for FEA models to incorporate realistic assumptions about material imperfections and fabrication processes to improve accuracy.

In summary, while FEA provides valuable theoretical insights, experimental results underscore the importance of real-world manufacturing variables. The discrepancies between FEA and experimental values highlight the need for refined modeling approaches. Future work should focus on enhancing FEA models to better predict composite performance, contributing to the development of efficient and sustainable flax-based composites for engineering applications.

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