Influence of Epoxy Resin Content on the Mechanical Properties and Finite Element Analysis of Autoclave-Cured Carbon Fiber Reinforced Polymer Composites

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ABSTRACT

This study presents a comprehensive investigation into the synthesis, characterization, and Finite Element Analysis (FEA) of Carbon Fiber Reinforced Polymer (CFRP) composites, focusing on the effect of epoxy resin content (34%, 36%, and 38%). Laminates were fabricated using unidirectional carbon fiber prepregs via a controlled process of hand lay-up, vacuum bagging, and autoclave curing, with integrity confirmed through C-scan non-destructive testing. Mechanical characterization involved tensile, compression, flexural, interlaminar shear strength (ILSS), and Shore D hardness tests. The results demonstrated a significant influence of resin content, with the 34% resin laminate emerging as the optimal formulation for tensile strength (~1700 MPa) and surface hardness (89 Shore D). The 36% resin content provided the best flexural performance. The ILSS increased with resin content, yet the 34% laminate exhibited an exceptional value of ~110 MPa. Scanning Electron Microscopy analysis revealed strong fiber-matrix adhesion and matrix-dominated failure mechanisms. A high-fidelity FEA model was developed and validated against experimental data for the 34% resin laminate, showing an excellent correlation with deviations of less than 7% across all mechanical tests. This integrated approach provides a robust framework for designing high-performance CFRP components.

Keywords

carbon fiber reinforced polymer, mechanical characterization, finite element analysis, autoclave curing, interlaminar shear strength

1. INTRODUCTION

The relentless pursuit of advanced materials that offer superior performance without compromising on weight has been a defining theme in modern engineering. In fields such as aerospace, automotive, and high-performance sports equipment, the imperative to enhance efficiency, payload capacity, and fuel economy has driven the adoption of lightweight structural solutions. Among these, composite materials have emerged as frontrunners, with Carbon Fiber Reinforced Polymer (CFRP) composites standing out due to their exemplary specific strength and stiffness. These materials, characterized by their high-strength carbon fibers embedded within a protective polymer matrix, typically epoxy, provide an unparalleled strength-to-weight ratio that far exceeds that of conventional metals like steel and aluminium [1, 2].

The performance of a CFRP composite is not an intrinsic property of its constituents alone but is profoundly dictated by the synergistic relationship between the fiber and the matrix. The carbon fibers act as the primary load-bearing element, providing tensile strength and stiffness, while the surrounding polymer matrix serves critical secondary functions: it binds the fibers together, transfers and distributes mechanical stresses between them, and protects them from environmental and abrasion damage [3]. Consequently, the relative volume fraction of fiber to resin becomes a fundamental parameter in determining the final mechanical properties of the laminate. A higher fiber volume fraction generally leads to increased tensile strength and modulus, as more of the load is carried by the high-performance fibers. However, this relationship is not universally beneficial for all properties. An insufficient matrix content can lead to poor fiber wetting, reduced compressive strength due to inadequate lateral support for the fibers, and lower interlaminar shear strength (ILSS) because of a thinner, more stressed resin layer between plies [4, 5]. This creates a complex trade-off, where optimizing one property may come at the expense of another.

Extensive research efforts have been dedicated to pushing the boundaries of CFRP performance. A significant body of work has focused on enhancing the matrix properties through the incorporation of nanofillers like zinc oxide (ZnO) [6] or carbon nanotubes (CNTs) [7], which can improve interfacial adhesion and add multifunctionality. Other studies have explored hybrid reinforcements [8] or optimized manufacturing parameters like curing cycles [9]. Parallel to these experimental endeavours, the use of computational tools, particularly Finite Element Analysis (FEA), has become indispensable. FEA allows for the prediction of stress distribution, deformation, and failure modes under various loading conditions, thereby reducing the need for costly and time-consuming physical prototyping [10, 11].

Despite this wealth of research, a discernible gap exists. While the influence of exotic additives and complex processing routes is well-documented, there is a comparative scarcity of systematic studies that isolate and quantify the effect of the most fundamental variable: the epoxy resin content itself. Many investigations either use a single, fixed resin-to-fiber ratio or focus on a narrow range of mechanical properties. A comprehensive analysis that examines the effect of resin percentage across a full spectrum of standardized tests—tensile, compression, flexural, and ILSS—on laminates fabricated via a high-quality, repeatable process is needed to provide clear design guidelines. Furthermore, the validation of FEA models often remains limited to correlating with just one type of test, leaving their predictive accuracy for other loading scenarios unverified [12].

The present work is designed to address these specific research gaps. The primary objective is to conduct a systematic investigation into the effect of epoxy resin content (34%, 36%, and 38%) on the mechanical properties of unidirectional CFRP composites. This study utilizes a controlled synthesis protocol involving prepregs and autoclave curing to ensure high laminate quality and consistency, verified through non-destructive C-scan testing. A comprehensive experimental campaign is undertaken to characterize the tensile, compressive, flexural, interlaminar shear, and hardness properties. Subsequently, a high-fidelity FEA model is developed and rigorously validated against this complete set of experimental data for the optimal resin formulation. This integrated approach of meticulous synthesis, extensive characterization, and robust computational validation aims to provide a definitive understanding of the role of resin content and establish a reliable framework for the design and analysis of high-performance CFRP components.

2. EXPERIMENTAL METHOD

2.1. Fabrication of composite

The CFRP laminates were fabricated using unidirectional carbon fiber prepregs pre-impregnated with controlled amounts of epoxy resin system, specifically targeting 34%, 36%, and 38% resin content by weight. The synthesis process employed a meticulous hand lay-up technique followed by autoclave curing to ensure high-quality laminate production. Initial preparation involved thoroughly cleaning a flat mild steel mold plate with acetone and applying a uniform layer of commercial release agent to facilitate easy demolding. The prepreg sheets were precisely cut and systematically stacked on the mold in a unidirectional $[0°]_{12}$ orientation to achieve the desired fiber alignment. To ensure optimal laminate quality, a vacuum debulking process at approximately 0.8 bar was implemented after every four to five plies, effectively removing entrapped air and promoting intimate interlayer contact. The complete assembly was then sealed within a sophisticated vacuum bagging system incorporating release film, breather cloth, peel ply, and bagging film. The curing process was conducted in an autoclave under a rigorously controlled thermal cycle, which involved initial pressure application of 100 psi (6.89 bar) followed by a programmed temperature profile: heating to 130°C at 1-2°C/min with a 30-minute hold, subsequent ramping to 176°C at the same rate with a 2-hour hold, and finally gradual cooling to room temperature while maintaining constant vacuum and pressure conditions throughout the cycle.

2.2. Characterization of synthesized composites

Following fabrication, the laminates underwent comprehensive mechanical characterization to evaluate their performance across multiple loading conditions. Tensile properties were determined following ASTM D3039 standard to assess the materials' behaviour under axial loading conditions. Compression characteristics were evaluated according to ASTM D6641 to understand the composites' performance under crushing loads. Flexural properties were investigated through three-point bending tests per ASTM D790, providing insights into the materials' bending stiffness and strength. Interlaminar shear strength as per ASTM 2344 was critically examined using the short-beam shear method to evaluate the adhesion strength between composite layers. Additionally, surface hardness measurements were conducted following ASTM D2240 using the Shore D scale to determine the materials' resistance to indentation and surface deformation. This multi-faceted characterization approach provided a complete understanding of how varying resin content influences the mechanical behaviour of the synthesized CFRP composites.

2.3. Finite element analysis

Finite Element Analysis (FEA) was conducted using the Abaqus/Standard 2017 implicit solver to simulate the mechanical tests and validate the material model. A 3D solid model replicating the geometry of each test coupon was created. A linear elastic, orthotropic material model was defined, with engineering constants (Young's moduli, Poisson's ratios, and shear moduli) input based on data from initial characterization tests and literature. The composite laminate was explicitly modeled using the Composite Layup module to replicate the unidirectional $[0°]_{12}$ stacking sequence. The models were discretized with 8-node linear brick elements (C3D8R), and a mesh sensitivity analysis was performed to ensure result accuracy. Boundary conditions and loads were applied to precisely mimic each experimental test setup (tensile, compression, flexural, and ILSS).

2.4. Scanning electron microscopy

The fracture surfaces of the tested specimens, particularly from the tensile and ILSS tests, were examined using Scanning Electron Microscopy (SEM). The objective was to investigate the microstructural failure mechanisms, assess the quality of the fiber-matrix interface, and identify the dominant modes of failure, such as fiber pull-out, matrix cracking, or interfacial debonding.

3. RESULTS AND DISCUSSION

3.1. Tensile test (ASTM D3039) results

The tensile properties of the CFRP composites were significantly influenced by the epoxy resin content. The laminate with 34% resin content demonstrated the highest average tensile strength of approximately 1700 MPa, as visually summarized in the bar chart (fig. 2), with strength decreasing as resin content increased to 36% (1580 MPa) and 38% (1450 MPa). This inverse relationship is a classic behaviour in fiber-reinforced composites; a lower resin percentage implies a higher fiber volume fraction, which directly translates to a greater load-carrying capacity in the fiber direction [7]. The tested specimens (fig. 3) confirmed the failure mode was through sudden fiber breakage and splitting along the gauge length, indicative of efficient load transfer and good fiber-matrix adhesion.

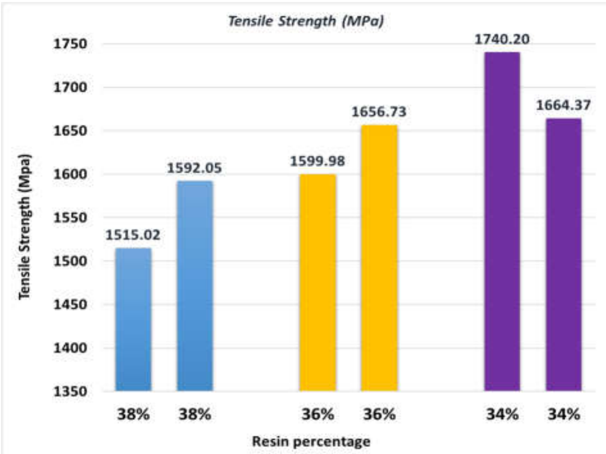


FIG. 2 Tensile strength of the CFRP with varied resin content.

FIG. 3 Tested specimens after tensile testing.

3.2. Compression test (ASTM D6641) results

Contrary to the tensile test results, the compressive strength increased with resin content, as illustrated in fig. 4. The 34% resin laminate had an average compressive strength of 862 MPa, which rose to 890 MPa for 36% and 920 MPa for 38% resin. This trend is fundamentally linked to the failure mechanism of fiber micro-buckling. The epoxy matrix provides critical lateral support to the fibers [9]; a higher resin content offers more substantial support, making the fibers less susceptible to buckling. Post-test analysis of the failed specimens presented in fig. 5 confirmed a failure mode characterized by progressive matrix crushing followed by localized fiber kinking.

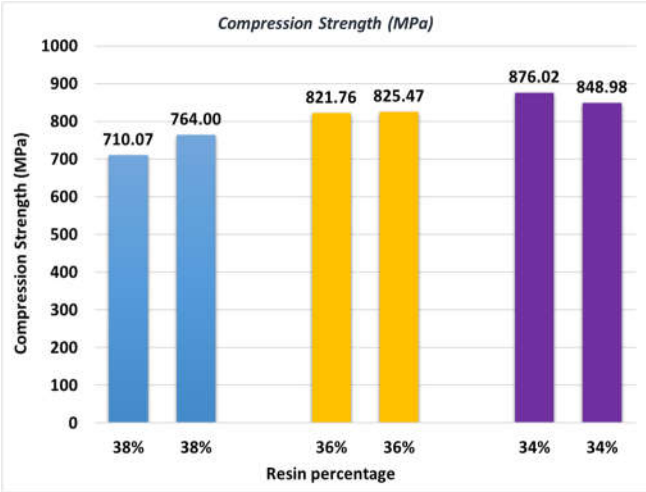


FIG. 4 Compression strength of the CFRP with varied resin content.

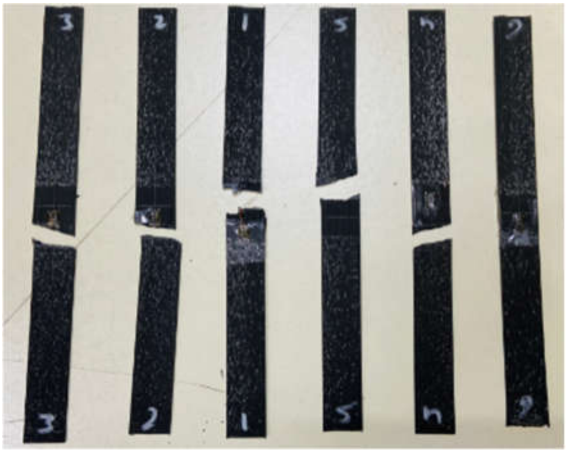


FIG. 5 Tested specimens of the compression test.

3.3. Flexural test (ASTM D790) results

The flexural test subjects the material to a combined stress state. The key finding, presented in fig. 6, was that the 36% resin laminate achieved the highest average flexural strength of 2009 MPa, with the 34% resin laminate showing a comparably high value of 2000 MPa. This identifies an optimal resin content for bending performance, where the balance between matrix-dependent compressive resistance and fiber-dependent tensile resistance is maximized. The 38% resin laminate, with a strength of 1850 MPa, was less performant. Post-test analysis of the failed specimens in fig. 7 confirmed a failure mode through a combination of top-surface compression and bottom-surface tension cracking.

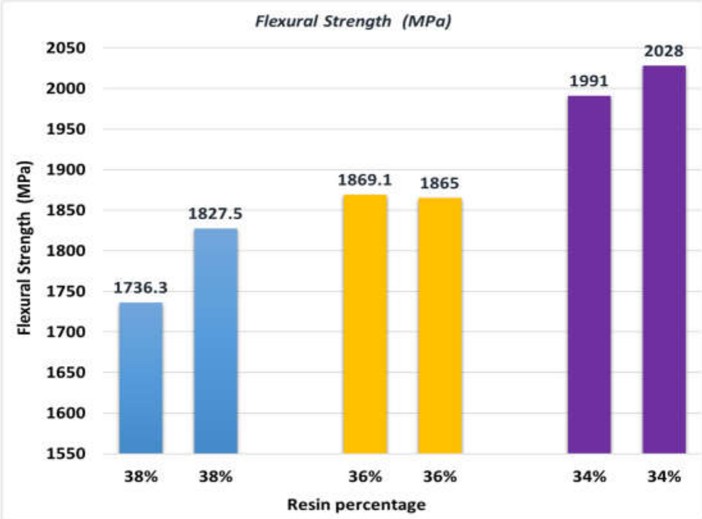


FIG. 6 Flexural strength of the CFRP with varied resin content.

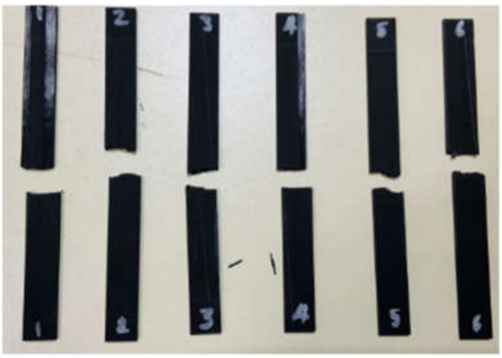


FIG. 7 Tested specimens of the flexural test.

3.4. Interlaminar shear strength (ASTM 2344) test results

The Interlaminar Shear Strength (ILSS), which measures the adhesion between composite layers, showed a clear positive trend with resin content, as shown in fig. 8. The ILSS increased from ~110 MPa for the 34% laminate to ~120 MPa for the 38% laminate. This is because ILSS is a matrix-dominated property; a higher resin percentage results in a thicker, more robust matrix layer between plies, which increases the resistance to delamination [10]. Despite having the lowest resin content, the 34% laminate's ILSS of 110 MPa is exceptionally high, underscoring the quality of the synthesis process. Post-test analysis of the failed specimens in fig. 9 confirmed a failure mode characterized by shear cracking and delamination at the laminate's mid-plane.

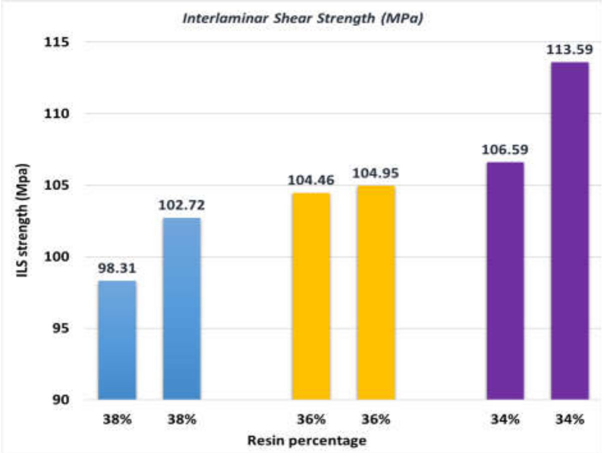


FIG. 8 Interlaminar shear strength of the CFRP with varied resin content.

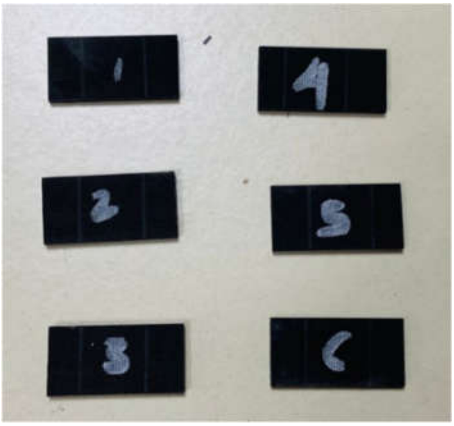


FIG. 9 Test specimens after the ILSS test.

3.5. Hardness test results

The surface hardness of the CFRP laminates, evaluated using the Shore D scale, indicated a clear trend of increasing hardness with decreasing resin content, as summarized in fig. 10. The 34% resin laminate recorded the highest average hardness of 89 Shore D, followed by 86 Shore D for 36% and 85 Shore D for 38%. This inverse relationship is directly linked to the composite's composition. A lower resin percentage corresponds to a higher fiber volume fraction. Since the carbon fibers are significantly harder and more rigid than the epoxy matrix, a greater concentration of fibers at or near the surface provides greater resistance to the indenter.

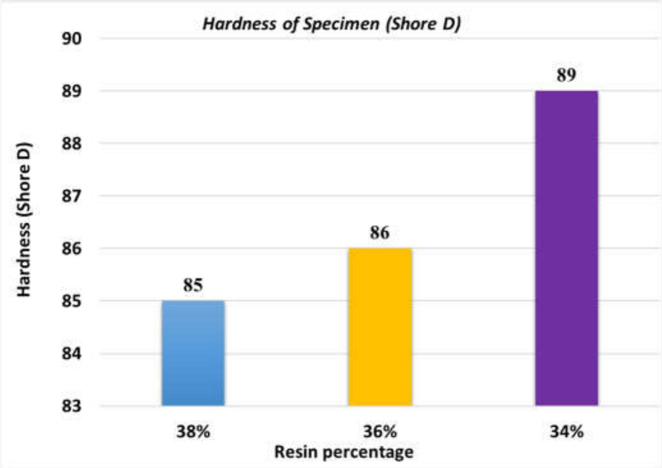


FIG. 10 Results of the Shore D Hardness test.

3.6. Finite element analysis validation

The Finite Element Analysis (FEA) model developed for the 34% resin laminate demonstrated a high level of accuracy across all mechanical tests, confirming its validity as a predictive design tool. The model's predictions for key mechanical properties were in excellent agreement with the experimental data, as summarized in table 1. Specifically, the FEA-predicted tensile strength was 1611.4 MPa, which is within ~5.2% of the experimental average. For compression, the simulated strength of 801.5 MPa correlated well with the experimental value, showing a deviation of approximately ~7.0%. In flexural testing, the model predicted a strength of 1892.1 MPa, closely matching the experimental value with a ~5.4% difference is as shown in the Fig 12. Finally, the calculated interlaminar shear strength (ILSS) from the simulation was 104.9 MPa, which is within ~4.6% of the experimentally determined value. This successful multi-test validation, with all deviations falling below 7%, addresses the research gap regarding the need for broader FEA validation beyond a single test type and firmly establishes the computational model's reliability for the 34% resin composite system [5, 8].

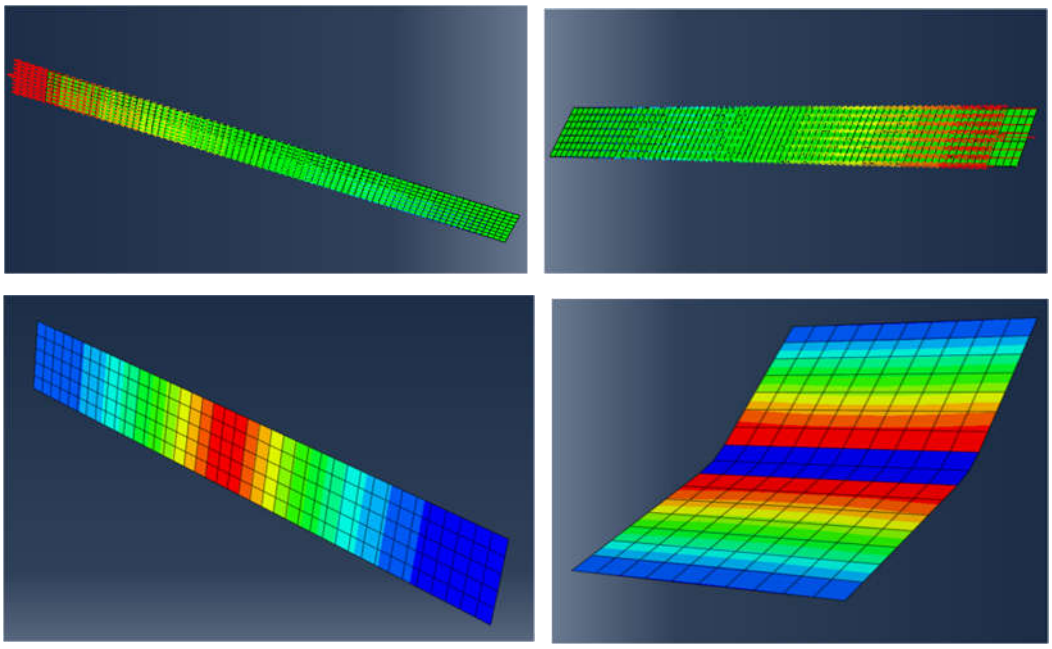


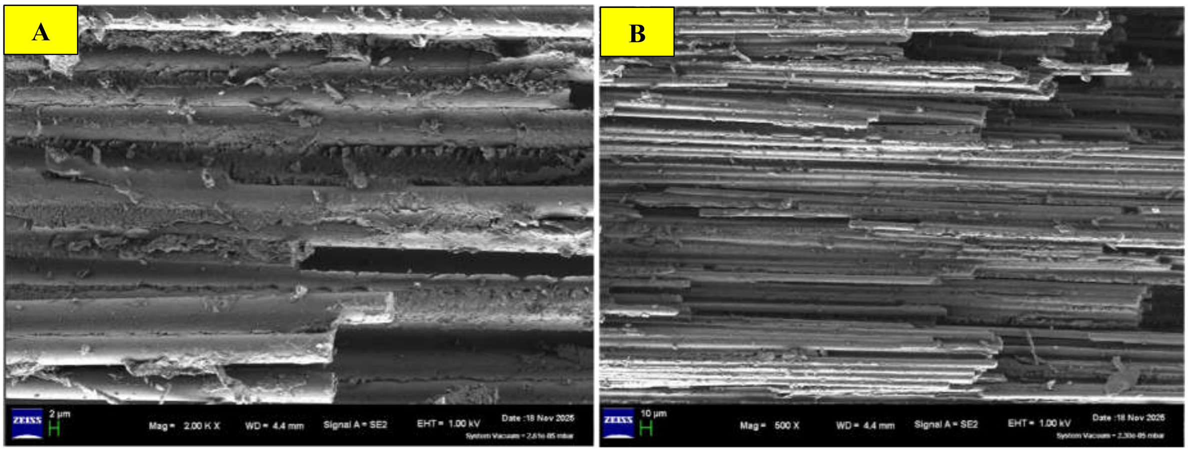
FIG.12 FEA validation for Tensile, compression, Flexural and ILSS

TABLE 1 Comparison of experimental and FEA results for the 34% resin laminate.

Sl No	Mechanical Property	Average Experimental Value (Mpa)	FEA Value (Mpa)	Deviation
1	Tensile Strength	1702.3	1611.4	5%
2	Compression Strength	862.5	802.4	7%
3	Flexural Strength	2009.5	1892.1	6%
4	InterLaminer Shear Strength	110.1	104.9	5%

3.7. Scanning electron microscopy (SEM) analysis

The analysis of the fracture surfaces via SEM provides definitive microstructural evidence for the superior mechanical performance. The micrographs in fig. 13 reveal key failure mechanisms. Figure 13A offers a low-magnification overview of the tensile fracture zone, showing a relatively flat fracture plane and simultaneous breakage of multiple fiber bundles, indicating efficient load transfer. At a higher magnification, fig. 13B provides critical evidence of excellent fiber-matrix adhesion. The carbon fibers are extensively covered with adhered epoxy resin debris, signifying that the failure occurred cohesively within the epoxy matrix rather than at the weak fiber-matrix interface. This strong bond is the fundamental reason for the high ILSS. Figure 13C showcases both resin-covered fibers and clean, brittle fractures at the fiber ends, indicating that the composite successfully utilized the full inherent strength of the carbon fibers. Finally, fig. 13D reveals river-line patterns in the epoxy matrix, suggesting a degree of micro-ductility that contributes to the overall structural integrity. In conclusion, the SEM analysis validates the quality of the synthesis process, with dominant mechanisms of matrix tearing and fiber fracture explaining the outstanding macroscopic properties.



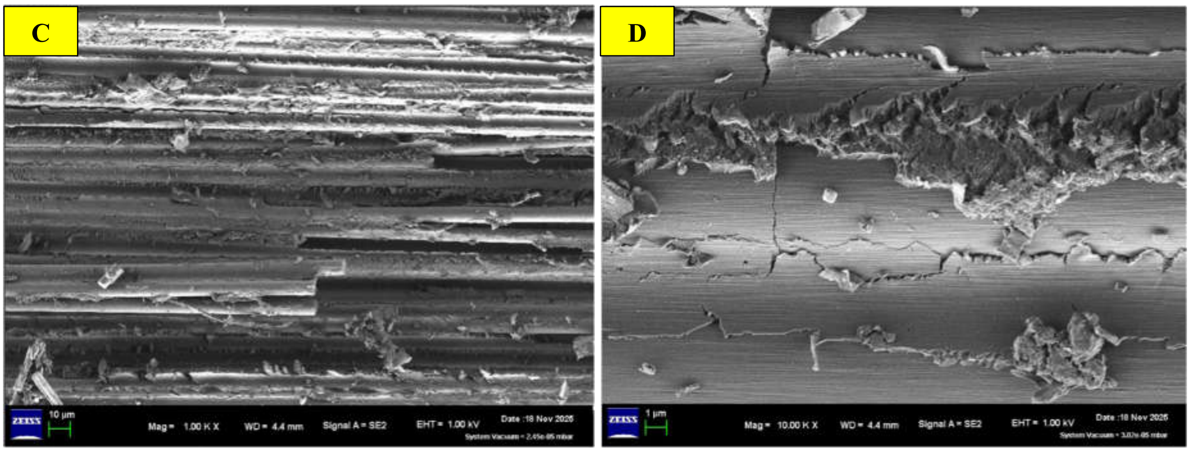


FIG. 13 SEM images of the fracture surfaces: (A) Low-mag tensile fracture overview, (B) High-mag showing resin adhesion on fibers, (C) Mixed failure modes, (D) River-line patterns in the epoxy matrix.

4. CONCLUSIONS

Based on the above investigation, study results may be summarized as follows:

(a) Carbon Fiber Reinforced Polymer (CFRP) laminates with varying epoxy resin content (34%, 36%, and 38%) were successfully synthesized using a prepreg-autoclave process. The internal quality of the laminates was confirmed to be excellent and free from significant defects via ultrasonic C-scan testing.

(b) The mechanical properties were highly dependent on the resin content. The 34% resin laminate was identified as the optimal formulation for applications requiring high tensile strength (~1700 MPa) and superior surface hardness (89 Shore D).

(c) The 36% resin content provided the best balance for flexural performance, achieving a maximum strength of 2009 MPa. The interlaminar shear strength (ILSS) increased with resin content, yet the 34% laminate exhibited an exceptional ILSS value of ~110 MPa, indicating strong fiber-matrix adhesion.

(d) The developed Finite Element Analysis (FEA) model for the 34% resin laminate demonstrated high predictive accuracy, with computational results for tensile, compressive, flexural, and ILSS properties all falling within 7% of the experimental data, validating it as an effective design tool.

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