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Resin Type and Fiber Layer Effects on the Flexural Strength of Polymer-Jute Composites

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ABSTRACT

Natural fiber-reinforced composite materials are increasingly replacing plastics in engineering applications such as architecture, construction, and the automotive industry. Among them, jute fiber has shown potential to improve the mechanical properties of polymer composites. The advantages of natural fibers include biodegradability, renewability, and environmental friendliness. However, due to their anisotropic nature, further research is required to enhance the performance of natural fiber-reinforced composites. This study aims to evaluate the effect of fiber layer number and resin type on the flexural strength of jute fiber-reinforced polymer composites—with the goal of developing a potential replacement material for the motorcycle center body cover. Specimens were fabricated using the vacuum resin infusion process with variations of 1, 2, 3, and 4 fiber layers and two types of resin: polyester and epoxy. The flexural strength was evaluated using a three-point bending test according to the ASTM D7264 standard. The results indicated that the highest flexural strength of 96.88 MPa was obtained in jute fiber–polyester composites with a three-layer configuration, while the lowest value of 68.27 MPa was observed in jute fiber–epoxy composites with a single-layer configuration. The superior performance of the polyester matrix is attributed to its better compatibility and interfacial bonding with jute fibers.

Keywords: composites, jute fiber, polyester, epoxy, flexural strength

INTRODUCTION

Natural-fiber reinforced polymer composite materials have gained considerable attention in recent years due to increasing demands for sustainable, lightweight, and cost-effective engineering materials. In particular, such composites are being explored as alternatives to traditional plastics and synthetic-fiber composites in sectors such as construction, automotive and consumer goods (Iqbal et al., 2025; Sonali et al., 2023). Among natural fibers, jute fiber is promising because of its advantages such as renewability, low cost, relatively high strength-to-weight ratio, biodegradability and wide availability in tropical regions (Gogna et al., 2019; Ekundayo et al., 2024). Jute-reinforced polymer composites (JRPCs) have been the subject of many investigations focusing on their manufacturing processes, mechanical properties (tensile, flexural, impact) and potential applications (Iqbal et al., 2025; Omrani et al., 2016).

However, despite their promise, natural fiber composites (NFCs) still face significant challenges. The intrinsic anisotropy of natural fibers, variability in fiber quality, higher moisture absorption, weaker fiber-matrix interfacial bond and less predictable behaviour under load compare to glass or carbon fiber composites (Iqbal et al., 2025; Madueke et al., 2022). In the case of jute fiber composites, mechanical performance---particularly the flexural strength---depends sensitively on fiber architecture (orientation, layering, stacking), fiber volume fraction, surface treatment of the fiber, resin type and processing route (Pramanik et al., 2024;

Chandekar et al., 2020). For instance, studies have shown that the flexural strength of jute-based composites can be improved by optimising fiber placement, resin impregnation and matrix compatibility (Iqbal et al., 2025).

Another critical factor is the resin matrix type. Thermosetting resins such as epoxy and unsaturated polyester are widely used in natural fiber composites (Biswas et al., 2019). The choice between resin types affects not only the cost and processing, but also the mechanical performance of the composite, including flexural behaviour (Patel et al., 2023). Some literature reports that epoxy-matrix composites can provide superior flexural strength compared to polyester matrices due to better fiber--matrix adhesion and higher cross-link density (Iqbal et al., 2025). On the other hand, there are also findings that under certain conditions polyester matrices may show comparable or even higher flexural strength when optimised (Patil & Kalagi, 2015).

In addition, the number of fiber layers (or stacking number) within a laminate structure influences the composite's structural integrity under bending loads. More layers can increase stiffness and strength up to an optimal point, but beyond that may lead to resin rich zones, voids, poor fiber wetting, delamination risks and decreased performance (Asma et al., 2020).

Therefore, the current study aims to investigate the combined effect of two main variables—resin type (epoxy vs polyester) and fiber layer number (1, 2, 3, 4 sheets) — on the flexural strength of jute-reinforced polymer composites. The ultimate goal is to identify the optimum configuration for a lightweight, sustainable composite material suitable for replacing a motorcycle centre cover component. The composites were fabricated via vacuum resin infusion and tested using the three-point bending method in accordance with ASTM D7264 standard. The findings are expected to provide practical guidance for optimizing composite design, support the adoption of jute-based materials in industrial applications such as motorcycle body covers, and contribute to sustainable material development by enhancing the mechanical performance of eco-friendly composites.

METHOD

Materials

1. Jute Fiber

Jute is a lignocellulosic bast fiber whose performance in polymer composites is governed by its chemical composition (cellulose, hemicellulose, lignin), microfibrillar angle, and surface chemistry that controls matrix adhesion (Iqbal et al., 2025). The literature consistently reports cellulose as the dominant constituent, which underpins stiffness and load transfer in bending; hydrophilic surface groups, however, can reduce interfacial bonding with hydrophobic matrices unless treatments are used (Islam et al., 2022). For epoxy systems, recent open-access studies demonstrate improved flexural behavior after tailoring fiber--matrix interactions via photopolymerization chemistry or silane coupling routes (Acosta Ortiz et al., 2023), while in hybrid natural-fiber systems jute remains a robust reinforcement for flexural and impact properties (Daramola et al., 2021). Polyester-matrix laminates also benefit from architecture control and energy-assisted processing (for example, γ-radiation) that can enhance wet-out and bending response in jute fabrics (Azim et al., 2022). Nanomodification of jute/epoxy further improves interfacial shear and bending resistance by mitigating hydrophilicity and crack initiation at the fiber--matrix boundary (Amirabadi-Zadeh et al., 2022). A comprehensive 2023 review on natural-fiber/epoxy composites summarizes density, thermal, and mechanical ranges relevant to design in automotive and building components, supporting our material selection window for flexural testing (Patel et al., 2023).

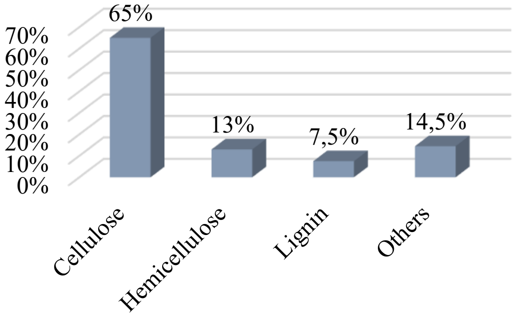

Figure 1 Typical chemical composition of jute fiber (wt%) [1]

The bar chart in Figure 1 illustrates the typical chemical composition of jute fiber, expressed in weight percentage (wt%). It shows that cellulose is the predominant component, accounting for approximately 65% of the fiber's composition, followed by hemicellulose (13%), lignin (7.5%), and other minor constituents (14.5%).

2. Polyester resin (unsaturated polyester, UP)

Unsaturated polyester is widely adopted in natural-fiber laminates due to its lower cost, room-temperature cure with Methyl Ethyl Ketone Peroxide (MEKP) as catalyst, and adequate flexural performance for moderate-load applications (Patel et al., 2023). For jute laminates, polyester's flexural response is highly sensitive to fiber architecture and impregnation quality; optimization of fabric weave and stacking can significantly shift bending strength, as shown in jute/polyester systems and hybrids reported in 2022--2024 literature (Pramanik et al., 2024; Azim et al., 2022; Islam et al., 2024). Process-dependent studies on natural-fiber polyester composites indicate that surface pretreatments (e.g., 5 % NaOH) can raise flexural strength compared to higher-concentration treatments by balancing lignin removal and fiber integrity (Pramanik et al., 2024).

3. Epoxy resin

Epoxy matrices are frequently selected for higher interfacial adhesion, stiffness, and damage tolerance, which translate into elevated flexural strength in many jute systems when processing is well-controlled (Patel et al., 2023). Open-access studies on woven-jute/epoxy composites prepared by vacuum infusion or related low-void routes show competitive flexural properties and moisture resistance enhancements, including strategies like eggshell-powder fillers to stabilize bending strength in wet conditions (Yildizhan et al., 2025). Reviews and experimental papers from 2021--2025 further document that epoxy often outperforms polyester in flexure for jute laminates (given similar fabric architecture and fiber volume fraction), although cost and cure schedules remain trade-offs for production (Patel et al., 2023; Islam et al., 2022; Negru et al., 2025; Owen et al., 2025).

Methods

1. Flowchart

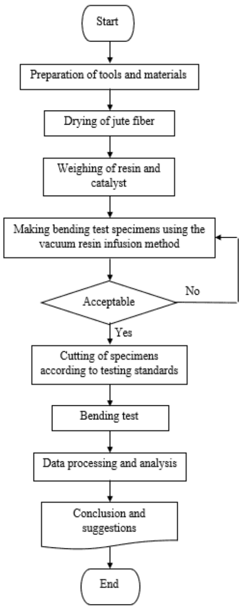

Figure 2. Flowchart

Source: Developed by the authors for this study (2025)

2. Preparation

The fabrication of jute fiber-reinforced polymer composites was carried out using the vacuum resin infusion process (VARI), a widely adopted technique for producing high-quality laminates with minimal voids and uniform fiber wet-out (Negru et al., 2025). Initially, the jute fiber mats were cut according to the mold dimensions of 160 mm × 160 mm × 3 mm. The fibers were then oven-dried at 90 °C for 30 minutes to remove residual moisture that could otherwise cause void formation and reduce interfacial adhesion between the fiber and polymer matrix (Akhyar et al., 2024).

Figure 3 Jute fiber arrangement

Source: Original photograph taken during the experiment (2025)

Following the fiber placement, the mold was closed and fastened using bolts at each corner to maintain tight compression between the top and bottom plates. Additional mechanical clamps were applied to enhance sealing pressure. A sealant tape was applied along all mold edges to prevent air leakage during vacuum application. The inlet and outlet ports were connected using flexible silicone tubing—one end leading from the resin reservoir to the mold inlet, and the other from the mold outlet to the vacuum trap inside the chamber, as schematically shown in Figure 4.

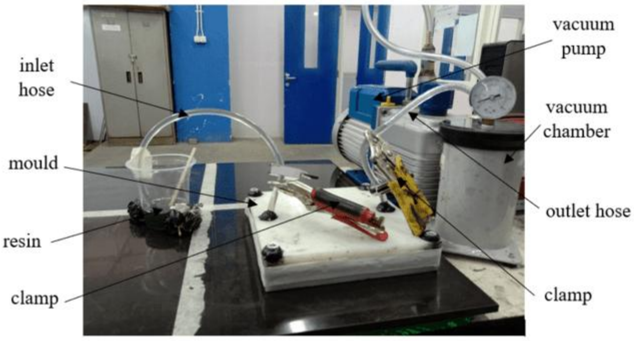

Figure 4 Vacuum Resin Infusion Process
Source: Adapted from Negru et al. (2025)

Before initiating the resin infusion, the vacuum integrity of the system was verified by clamping the inlet hose from the resin container using pliers, activating the vacuum pump, and opening the main valve. A stable vacuum reading confirmed that the system was free of leakage and ready for infusion. Once the vacuum condition was validated, the resin systems were prepared according to the required ratios. For the unsaturated polyester resin, a 100 : 1.5 weight ratio of resin to methyl ethyl ketone peroxide (MEKP) catalyst was used. For the epoxy system, the resin and EPH 555 hardener were mixed in a 1.5 : 1 weight ratio, as recommended by the manufacturer. The resin and hardener were stirred gently for approximately 2--3 minutes to ensure uniform mixing while minimizing air entrapment (Patel et al., 2023).

The resin was then drawn into the mold by vacuum pressure. During infusion, the vacuum pump remained operational continuously to ensure consistent flow and thorough resin impregnation of the jute layers. The process was terminated when resin reached the vacuum trap or when the resin level in the reservoir was nearly depleted. The valve at the pump was then closed, and the pump was turned off before the reservoir emptied to prevent air ingress that could cause porosity or delamination in the cured composite (Nurazzi et al., 2021). The combination of the VARI process with precise resin control ensured a low void fraction and homogeneous fiber distribution, which are critical to achieving optimal flexural performance (Owen et al., 2025).

After curing, the solidified composite sheets were demolded and cut into test specimens using a band saw machine, following the dimensional requirements of ASTM D7264/D7264M--21 for flexural testing (ASTM International, 2021). Each experimental condition was replicated three times (n = 3) to ensure statistical reliability and reproducibility of results (Acosta Ortiz et al., 2023; Nurazzi et al., 2021).

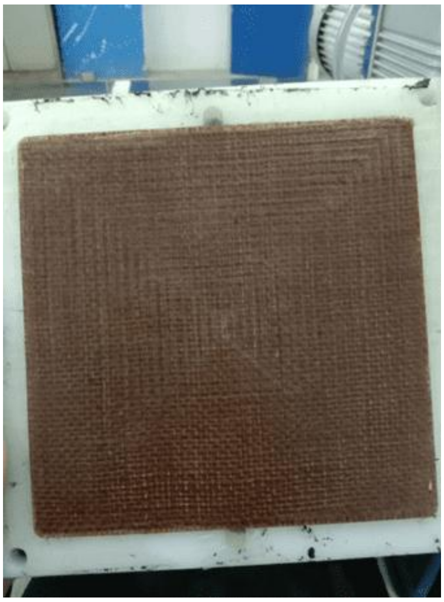

Figure 5 Composite before cutting

Source: Original photograph taken during the experiment (2025)

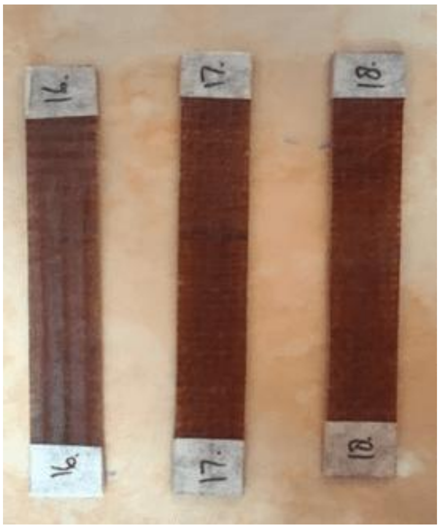

Figure 6 Composite after cutting

Source: Original photograph taken during the experiment (2025)

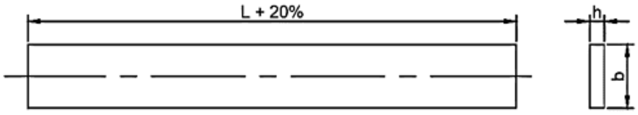

Figure 7 Flexural test specimen

Source: Based on ASTM D7264 standard

The three-point bending tests were conducted using a Universal Testing Machine (UTM) equipped with a load cell to record applied load and deflection. The testing configuration and loading setup are shown in Fig 8. Each experimental condition was replicated three times (n = 3) to ensure statistical reliability and reproducibility of results [13], [22].

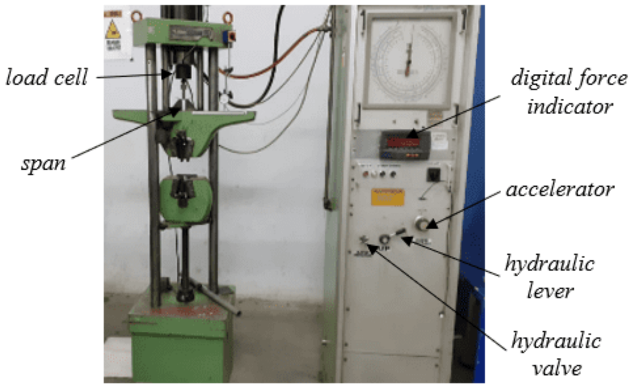

Figure 8 Universal Testing Machine

Source: Original photograph taken during the experiment (2025)

Flexural strength

After the composite panels were fully cured, they were trimmed to remove edge irregularities and ensure uniform dimensions. From each variation, three rectangular specimens were prepared for flexural testing. The cut surfaces were polished using fine-grade emery paper to eliminate surface irregularities that could affect load distribution during testing. The specimen dimensions followed ASTM D7264/D7264M–21, the standard test method for determining the flexural properties of polymer-matrix composites.

Flexural testing was carried out using a Universal Testing Machine (UTM), brand Tarno Grocki, with a maximum capacity of 10 tons, functioning as the primary instrument for three-point bending. The setup employed a Shimadzu SBL-5KN load cell (capacity 5 kN) to record applied loads accurately. A NEC Avio strain amplifier (model AS-1803, Dynamic AC Strain Amplifier) was used to amplify the analog signal from the load sensor prior to data conversion. The amplified signal was converted into digital data through an Interface PCI-3126 analog-to-digital converter (ADC), sampling at 1000 samples/s. This converter transferred the digital output to a computer, where results were displayed and recorded in real time using WaveJumper software.

During composite fabrication, a VALUE VE2100N vacuum pump (1 HP, 12 cfm, dual stage) was employed to maintain vacuum pressure, ensuring the absence of air bubbles or voids within the composite structure.

The flexural stress (σ), flexural strain (ε), and flexural modulus (E) were determined using the following equations :

$$\sigma = \frac{3FL}{2bd^2} \qquad (1)$$

$$\varepsilon = \frac{6dv}{L^2} \qquad (2)$$

$$E = \frac{FL^3}{4bd^3} \qquad (3)$$

In which:

σ = flexural stress (MPa)
ε = flexural strain (mm/mm)
E = flexural modulus (MPa)
F = applied load at midspan (N)
L = support span (mm)
b = specimen width (mm)
d = thickness (mm)
v = midspan deflection (mm)

RESULTS AND DISCUSSION

Table 1. Flexural strength

Variance	Flexural Strength (MPa)
P1	78.89
P2	86.76
P3	96.88
P4	85.86
E1	68.27
E2	80.92
E3	92.91
E4	95.47

Source: Processed experimental data from three-point bending tests (2025)

As shown in Figure 9, the jute–polyester composite exhibited higher flexural strength than the jute–epoxy composite for fiber stacking numbers of one, two, and three layers. However, when the number of fiber layers increased to four, the flexural strength of the jute–polyester composite decreased and became lower than that of the jute–epoxy composite. The highest flexural strength was obtained in the jute–polyester composite with three fiber layers, reaching a value of 96.88 MPa. This indicates that this configuration possessed the greatest toughness and bending resistance among all tested specimens. In contrast, the lowest flexural strength was observed in the jute–epoxy composite with a single fiber layer, with a value of 68.27 MPa.

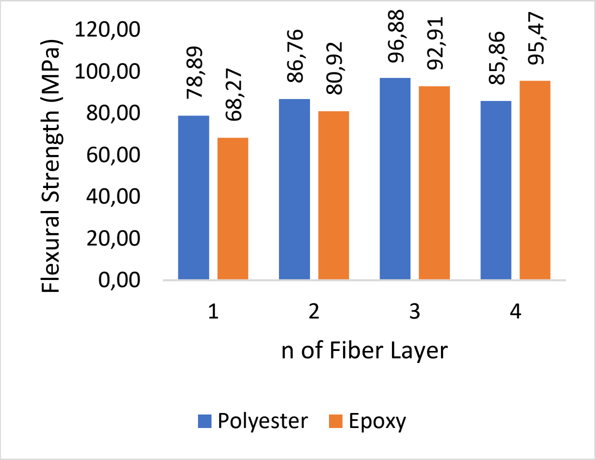

Figure 9 Flexural strength comparison chart
Source: Processed experimental data (2025)

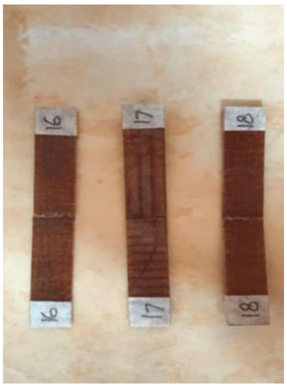

Figure 10 Flexural test result specimen

Source: Original photograph taken during the experiment (2025)

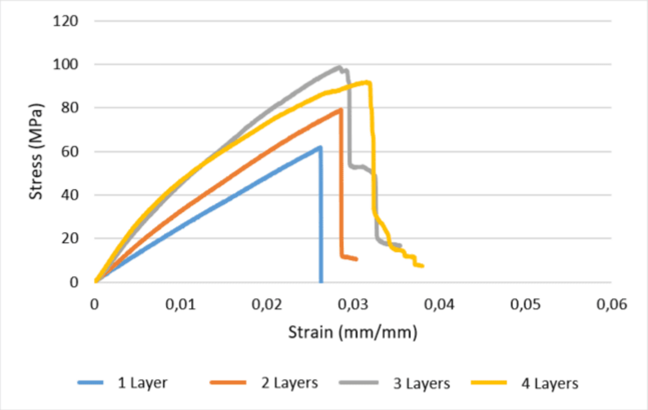

Figure 11 Stress-Strain Diagram (Polyester)

Source: Processed experimental data (2025)

As shown in Figure 11, the highest flexural strength was obtained in the jute–polyester composite with three fiber layers. This behavior indicates that, at this stacking configuration, the polyester matrix was able to achieve optimum fiber impregnation and interfacial bonding, resulting in efficient stress transfer between the matrix and the jute fibers. The presence of sufficient resin surrounding each fiber bundle minimized interlaminar voids and resulting in improved ability of the composite to carry bending loads efficiently.

The highest flexural strain, however, was observed in the composite with four fiber layers. This result suggests that the matrix could no longer fully penetrate and bond the densely packed fiber layers, leading to resin-deficient zones and weak fiber–matrix interfaces. As a consequence, the composite exhibited greater overall deflection before failure, which reflects localized plastic deformation rather than an increase in strength.

The stress–strain curve further showed that after reaching the maximum flexural stress, the material did not fracture abruptly but displayed a gradual decrease in stress, indicating a progressive cracking or semi-ductile failure mode. This gradual decline suggests the occurrence of matrix microcracking and fiber–matrix debonding, followed by energy absorption before final fracture. Such behavior is typical for polyester-based natural fiber composites, which tend to exhibit limited ductility due to delayed crack propagation within the polymer matrix.

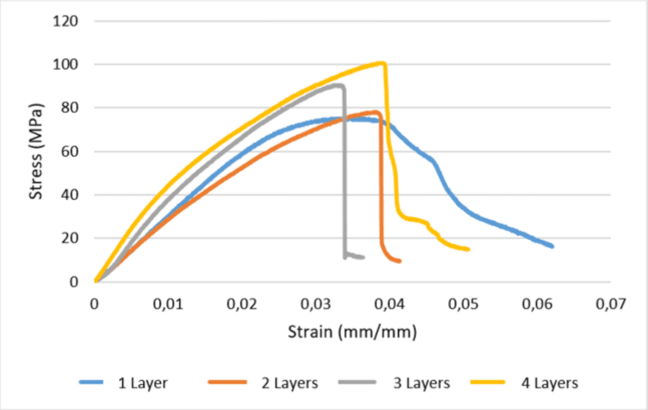

Figure 12 Stress-Strain Diagram (Epoxy)
Source: Processed experimental data (2025)

As shown in Figure 12, the jute–epoxy composite with four fiber layers exhibited the highest flexural strength compared to the other three configurations. This improvement can be attributed to the higher fiber volume fraction, which enhanced the overall stiffness and stress transfer efficiency within the laminate. The epoxy matrix in this configuration was still able to effectively impregnate and bond the jute fibers, thereby distributing the applied bending load uniformly across the composite structure. As a result, the material demonstrated superior load-carrying capability and resistance to flexural deformation.

The highest flexural strain was also observed in the four-layer composite, indicating that despite its higher stiffness, the laminate retained a certain degree of strain tolerance before failure. This suggests that the epoxy matrix provided strong fiber–matrix interfacial adhesion, which delayed crack initiation and allowed progressive energy absorption during bending. The stress–strain curve further shows a sharp peak followed by a rapid drop, characteristic of brittle or semi-brittle fracture behavior typical of epoxy-based composites.

Overall, the findings show that the epoxy matrix system tends to produce composites with greater flexural strength and rigidity as the number of jute layers increases, provided that resin impregnation is still adequate. This is mainly due to the strong adhesion that develops at the interface between the resin and the fibers, combined with a dense crosslink structure that promotes efficient transfer of bending stresses and delays the formation of cracks (Patel et al., 2023).

In comparison, the polyester matrix reaches its optimum performance at an intermediate stacking level, typically at three layers. When additional fiber sheets are introduced, the matrix begins to form areas that lack sufficient resin, which encourages interlaminar defects and early crack propagation. These conditions lower the flexural performance even though the reinforcement content increases.

Processing technique also has a major influence. The use of vacuum assisted resin infusion generally decreases void content and enhances flexural strength for both resin types. However, epoxy benefits more from this technique since its performance is more sensitive to interface quality (Negru et al., 2025). Environmental factors such as moisture absorption degrade flexural behavior in both systems by softening the polymer and weakening the bonding at the interface. Studies report that the decline is more severe for polyester, whereas epoxy retains a larger portion of its bending strength after exposure (Patel et al., 2023).

In summary, the current results are consistent with recent studies showing that epoxy composites demonstrate higher ultimate flexural strength at larger ply counts, while polyester composites can still exhibit comparable properties near their optimum configuration if fabric architecture and curing conditions are well controlled (Negru et al., 2025).

CONCLUSION

The experimental results reveal that resin type and fiber layer number significantly affect the flexural strength of jute fiber-reinforced polymer composites, with strength generally rising with additional layers up to an optimal point before declining due to factors like resin impregnation quality, interfacial bonding, and interlaminar voids. Polyester matrix composites peaked at 96.88 MPa with three layers (values: 78.89, 86.76, 96.88, 85.86 MPa for 1–4 layers), showing semi-ductile behavior with gradual crack propagation, while epoxy composites steadily increased to a maximum of 95.47 MPa at four layers (68.27, 80.92, 92.91, 95.47 MPa), exhibiting brittle fracture with sharp post-peak stress drops owing to superior stiffness and stress transfer. For future research, investigators should explore hybrid resin systems or surface treatments for jute fibers to mitigate void formation in multi-layer configurations and enhance ductility across both matrices, potentially using advanced imaging techniques like micro-CT to quantify interfacial defects.

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