Journal of
Polymer & Composites
https://journals.stmjournals.com/jopc

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Special Issue 4, 2026
January–December
DOI (Journal): 10.37591/JoPC

Research JoPC

Interfacial Bonding Efficiency in Jute-Carbon Fiber Polyester Matrix Composites Evaluated Through Short-Beam Shear and Interlaminar Fracture Toughness Testing

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Abstract

The natural Fiber–synthetic Fiber hybrid composites are jute–carbon Fiber hybrid in polyester matrix which could be used in semi-structural applications of automotive, construction and marine industry as an eco-friendly and cost-effective alternative of conventional carbon Fiber reinforced polymer. But the hydrophilic nature of jute Fibers and the relatively inert surface of carbon Fiber's cause weak bonding at the interface of the polyester matrix, which causes premature delamination, poor interlaminar shear strength and low fracture toughness, thereby limiting load-bearing capacity. A systematic study on the combined effect of surface modification and stacking sequence optimization on the interfacial bonding efficiency in jute–carbon polyester hybrids has not been conducted in previous studies by using both short-beam shear and mode I/II interlaminar fracture toughness testing. This work aims to fill this gap by fabricating hybrid laminates with different stacking sequence and testing jute Fibers with alkali and silane treatment and then experimentally testing the interlaminar shear strength (ISS), mode I and mode II fracture toughness of the same by short-beam shear testing and double cantilever beam (DCB) and end-notched flexure (ENF) testing, respectively, and modelling the same using finite element method (FEM) with cohesive zone elements and damage criteria. Results showed the synergistic effect of alkali–silane on the ISS was up to 53% higher than untreated sequences and the mode I fracture toughness initiation values (Kc1) were more than double those of untreated sequences, while the deviation between experimental and numerical model results was low. The findings indicate the importance of surface modification and architecture optimization to significantly enhance the interfacial properties of low-cost polyester-based hybrid materials, and present quantitative guidelines and a validated prediction model for the design of long-lasting and sustainable composite structures.

Keywords: Short-beam shear, surface modification, stacking sequence, jute-carbon hybrid composites, interfacial bonding, interlaminar shear strength, fracture toughness

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Received Date: July 02, 2026
Accepted Date: July 13, 2026
Published Date: July 24, 2026

Citation: P. Nithya, Kiran Kumar M., Madhukumar K., Sasikumar N., Krishna Prasad S., Asha P. B. Interfacial Bonding Efficiency in Jute-Carbon Fiber Polyester Matrix Composites Evaluated Through Short-Beam Shear and Interlaminar Fracture Toughness Testing. Journal of Polymer & Composites. 2026; 14(Special Issue 4): S68–S80p.

INTRODUCTION

Given the need to use lightweight high strength, and environmentally friendly materials, jute being a natural Fiber is an attractive material to be used for reinforcement purposes instead of carbon, glass or other synthetic Fibers [1]. Besides carbon Fibers in a polymer matrix, jute-based composites can provide a good compromise in terms of mechanical properties, reduction in weight [2], options for sustainable materials and can be used as an alternative material to the traditional carbon Fibers Reinforced polymer (CFRP) in automotive interior, construction panels, marine structures and aerospace components [3].

BACKGROUND AND REAL-WORLD RELEVANCE

They are low cost, easy to process, high chemical resistance and fast processing rate, which are important in industry But, the hydrophobic property of jute Fibers and relatively low activity of carbon Fibers sometimes results in poor bonding between the Fiber and the matrix material [4]. This is an interfacial weakness which results in early delamination [5], sub-optimal load transfer and poor long-term shear and fracture loading capacity. Therefore, the challenge of improving the efficiency of interfacial bonding of jute–carbon polyester hybrid composites has been deemed as an imperative need to further widen their structure application [6, 7].

Interfacial Bonding Challenges and Limitations of Existing Approaches

Alkali and silane coupling have been extensively investigated to enhance the Fiber–matrix adhesion in natural Fibers [8]. Likewise, optimization of Fiber stacking sequences has been demonstrated to affect the mechanical performance in hybrid laminates [9]. These strategies have been shown to be effective in the epoxy-based jute–carbon system, but the effect in the polyester matrix is not as well understood Studies on interlaminar shear strength and fracture toughness, two properties that are relevant to delamination resistance and structural integrity, have been less studied than other properties such as tensile or flexural properties [10].

In addition, while finite element model has been used to predict the behavior of hybrid composites, many studies assume the composites to be homogenous which cannot reflect the progressive interfacial damage and delamination mechanisms correctly [11]. All these factors are of course individually of particular importance for the performance of polyester based hybrid structures as concerns their interfacial performance, and currently just individually validated by advanced numerical tools, but only not yet systematically investigated in the literature [12].

RESEARCH GAPS

Although there are many studies conducted on the natural–synthetic hybrid composites, there is a lack of systematic evaluation of the efficiency of the bonding between natural and synthetic Fibers in the jute–carbon polyester systems with the short-beam shear test, interlaminar shear strength and the mode I and mode II fracture toughness test [13]. To the best of the authors' knowledge, the benefits of alkali–silane surface treatments have not been studied yet with optimized stacking sequence and experimental data validated by using a cohesive zone modelling. Furthermore, the combination of these parameters on the failure mechanisms at the interface of polyester matrices with low-cost materials has not been sufficiently studied. With these limitations, it is hard to develop design guidelines and predictive models for wider use of sustainable hybrid composites in load-bearing structures.

OBJECTIVES AND CONTRIBUTIONS OF THE PRESENT WORK

To fill these deficiencies, the present study is focused on the interfacial bonding efficiency of jute–carbon Fiber hybrid composites in polyester matrix in a combined experimental and numerical approach. Specific goals are to produce hybrid laminates with different stacking sequences and jute surface treatments (alkali and silane); evaluate the interfacial performance by performing short-beam shear, double cantilever beam and end-notched flexure tests; characterize failure mechanisms by performing scanning electron microscopy; develop and validate a finite element model that incorporates cohesive zone elements and damage criteria [14].

The key findings in this thesis are the first comprehensive evaluation of the interlaminar shear strength and mode I/II fracture toughness of jute–carbon polyester hybrid composites after combined surface treatment and laminate optimizing; and, the first optimization of the laminate and surface treatment of jute–carbon polyester hybrid composites using an active approach [15]. Based on the correct validation and verification of the numerical scheme, the study shows the synergistic effect of alkali–silane treatment and carbon-outer stacking configurations, and the numerical framework can predict interfacial failure with good accuracy. These results provide quantitative data and guidelines for the development of high-performance sustainable hybrid composites for structural applications [16].

Paper Organization

The literature reviewed is detailed in Section II, methodology is detailed in Section III, results and discussion is detailed in Section IV and the conclusions and possible directions in the future is detailed in Section V.

RELATED WORK

In recent years, research on natural Fiber–synthetic Fiber hybrid composites have increased significantly because of the need for sustainable sources that can replace the conventional carbon Fiber reinforced polymers. Initial research was centred around enhancement of bulk mechanical properties like flexural and tensile strength in Hybrid combinations and simple Fiber treatments. More recent studies have focused on the interfacial performance, where poor adhesion between Fiber–matrix is a significant impediment for structural applications, especially in economical polyester matrix systems.

Hybrid Jute-Carbon Composite Systems

The mechanical behavior of jute-carbon hybrid composites in epoxy matrices has been studied in detail, and it is found that the arrangement of jute and carbon are significantly affecting the overall mechanical behavior. Carbon Fibers in outer layers of the configuration tend to give better load distribution and environmental resistance than those with high jute content in outer layers. The tensile and flexural properties have been improved significantly in these works; most of them use epoxy resins and the few that do not take the analysis any further than interlaminar shear strength or fracture toughness in the polyester matrices [17]. The choice of epoxy in previous studies was motivated by its excellent adhesion properties; thus, polyester based hybrids have not been studied under interlaminar loading when similar hybridization strategies are used [18].

Surface Modification Strategies for Natural Fibers

The surface modification process, especially the alkali and silane treatment, is well studied to improve the interfacial adhesion between hydrophilic natural Fibers and polymer matrix [19]. The alkali treatment gets rid of surface contaminants and the surface becomes rougher, and silane coupling agents make the surface more chemically compatible Combination of alkali and silane treatment has been reported to improve tensile strength and decrease water absorption [20]. However, most investigations have been on treated Fibers either singularly or as a composite of a single-Fiber-type [21]. There is a lack of systematic study to investigate the combined effect of alkali-silane and stacking sequence optimization on the interfacial properties of jute-carbon hybrid in polyester resin [22].

Characterization of Interlaminar Properties

Short-beam shear and double cantilever beam and end-notched flexure tests are known to be important measures of interlaminar shear strength and fracture toughness [23]. The literature available already shows that these properties are found in glass-carbon or jute-glass composites; and there are fewer papers on jute-carbon composites. In addition, the interlaminar properties are not always well correlated with the surface modification levels or stacking architecture when reported [24]. Because of this disorganized approach, it is hard to establish a clear design principle for optimum interfacial bonding efficiency of polyester based natural-synthetic hybrids [25].

Numerical Modelling of Interfacial Behavior

Finite element modelling (FEM) has been used for modelling damage initiation and propagation in composite laminates Cohesive zone modelling and progressive damage criteria are found to be useful for more realistically modelling the delamination behavior of materials compared to the strength-based approach. Many of the existing models for hybrid composites, however, assume that the materials are homogeneous, without rigorous experimental validation with interlaminar shear and fracture toughness data. Thus, the ability of numerical modelling to predict the properties of surface-treated jute-carbon polyester systems is still underdeveloped.

In general, the previous studies have contributed to the awareness of the concept of hybridization, modification of surface of natural Fiber composites. However, all of these studies have some drawbacks: the emphasis is mainly on epoxy matrices, the surface treatment was not combined with stacking sequence effects on the interfacial properties, and the cohesive zone (CZ) model has not been applied to polyester based hybrids to a great extent [25]. In the present work, these gaps are being filled by systematically exploring the efficiency of interfacial bonding in jute-carbon polyester composites using a combination of experimental testing of interlaminar shear strength, mode I and mode II fracture toughness, and surface modification, stacking optimization, and cohesive zone based finite element analysis validation. This is an integrated approach to deliver quantitative performance data along with a sound framework for predicting sustainable structural composite design [26].

METHODOLOGY

This section discusses the hybrid experimental–simulation methodology used for the evaluation of the efficiency of the bonding between the interfaces of jute-carbon polyester hybrid composites. This method involves the fabrication of physical specimens using a method developed at the University of Queensland, combined with standard mechanical testing and advanced modelling with finite element techniques to systematically investigate the interlaminar shear strength and fracture toughness of the materials when the stacking sequence is modified and the surface is treated. Finite element analysis was adopted to give a better understanding of the stress distribution and progressive damage evolution at the Fiber–matrix interfaces where it is difficult to determine the stress with experiments alone. The methodology was designed to enable several different configurations to be evaluated under controlled conditions and also to simulate the methodology.

Overview of the Simulation-Based Approach

A hybrid experimental–simulation methodology was employed for the analysis of the process of obtaining an efficient bonding of the interface in jute-carbon polyester hybrid material. The simulation approach was chosen because it allowed a systematic study under controlled conditions of various stacking sequences and surface modification conditions, and also because it offered the possibility of conducting a parametric study which otherwise would be very time consuming and expensive to carry out using a physical testing approach. Finite element modelling is used to give detailed information on stress distribution and damage evolution at the interfaces of the composite, in addition to the experimental measurements of interlaminar shear strength and fracture toughness.

The general framework used in the overall research of this study is shown in Figure 1. The methodology includes modification of the surface properties of the material, composite manufacturing with various stacking sequences, experimental characterization by interlaminar testing, and modelling validation and optimization using finite element modelling with cohesive zone elements.

Material Constitutive Modelling

The laminae were simulated as orthotropic linear elastic materials. The stress–strain relation of a lamina in the principal material coordinates as shown in Equation 1.

$$\{\sigma\} = [Q]\{\varepsilon\} \quad (1)$$

The stiffness matrix is reduced as $[Q]$ and the stress and strain are written as $\{\sigma\}$ and $\{\varepsilon\}$, respectively. Components of $[Q]$ were calculated by the rule of mixtures which used the engineering constants of the two fibers (jute and carbon) and the properties of the polyester matrix. The volume fraction and void content of the physical specimens were directly used in the model to represent it realistically for each laminate configuration.

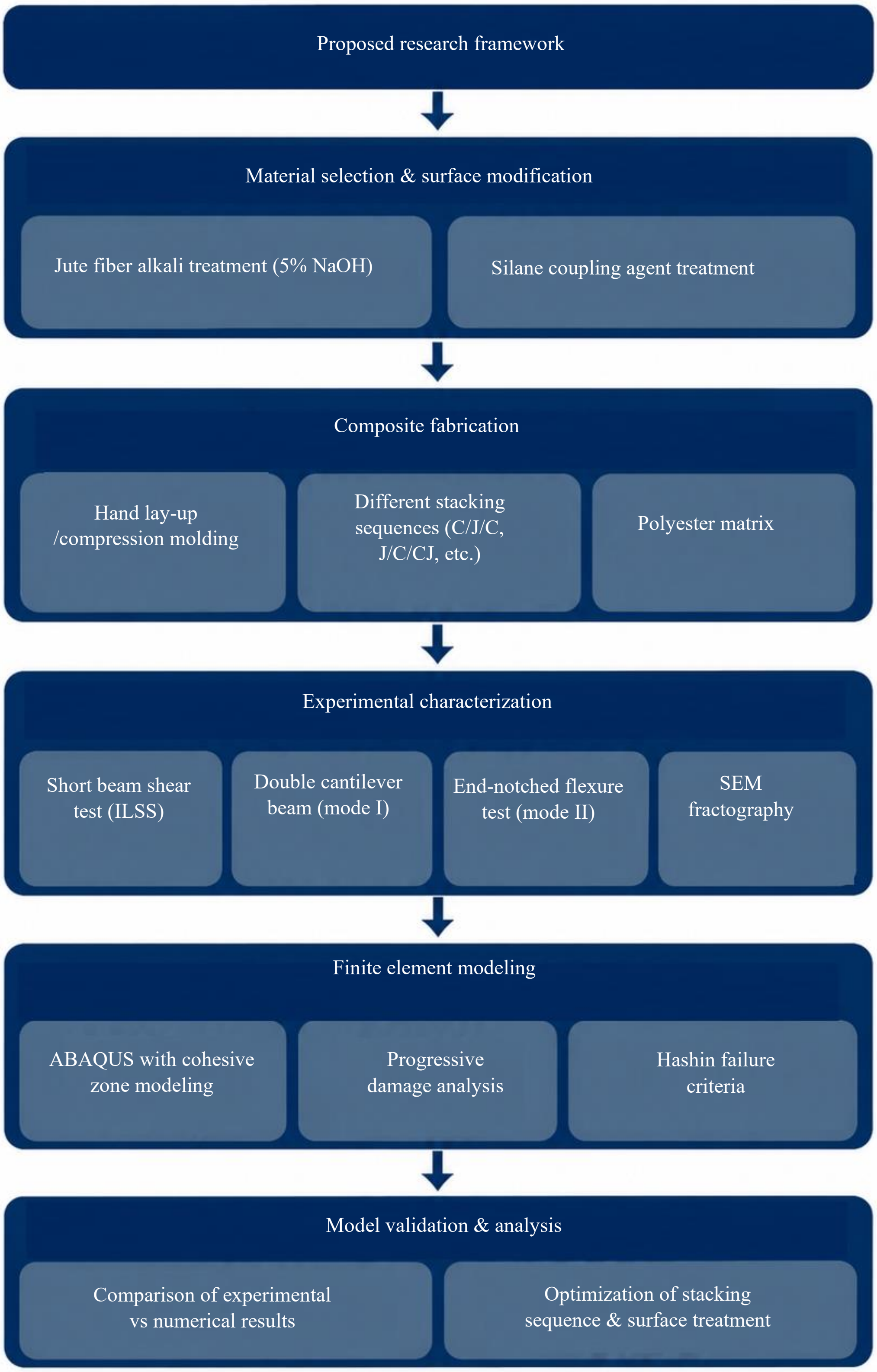


Figure 1. Proposed research framework illustrating the overall methodology adopted in this study.

The surface modification of jute Fibers was done in two steps as shown in Figure 2. Pre-treatment with 5% NaOH solution and then with silane coupling agent were applied to jute Fibers to enhance the interfacial bonding with polyester matrix.

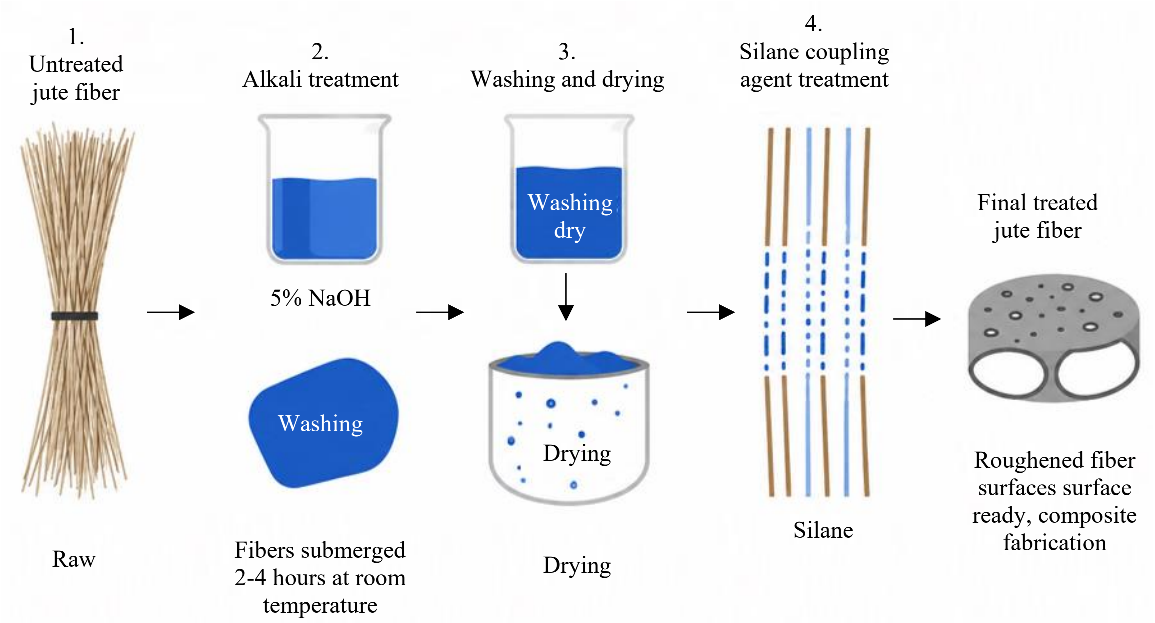


Figure 2. Schematic representation of jute Fiber surface modification process

Laminate Manufacturing and Void Minimization

The hand lay-up technique was used to fabricate hybrid laminates with compression molding. The jute and carbon fibres were stacked in the steel mold as per the design. The polyester resin was applied using a 2% solution of the catalyst methyl ethyl ketone peroxide (MEKP) and evenly distributed. The following steps were taken to avoid any void formation: (i) pre-drying the fibers at 80°C for 2 hours to remove moisture from them; (ii) pre-degassing the resin before applying the resin; (iii) applying a roller to remove any entrapped air after every layer; and (iv) curing in a hydraulic press under 0.5 MPa at room temperature for 24 hours followed by post curing at 60°C for 4 hours. To obtain a void content of less than 3% (ASTM D2734) the following was done.

Cohesive Zone Modelling for Interfacial Behavior

The damage and delamination at the interfaces were simulated with cohesive zone modelling using a bilinear traction–separation law. The separation displacement is connected to the traction vector as shown in Equation 2.

$$\mathbf{t} = \begin{cases} K\boldsymbol{\delta}, & \delta_m < \delta_m^0 \\ (1-D)K\boldsymbol{\delta}, & \delta_m^0 \le \delta_m < \delta_m^f \\ 0, & \delta_m \ge \delta_m^f \end{cases} \tag{2}$$

where K is the initial penalty stiffness, δ_m is the effective separation, and D is the damage variable. Damage initiation was governed by the quadratic stress criterion as shown in Equation 3.

$$\left(\frac{\langle t_n \rangle}{t_n^0}\right)^2 + \left(\frac{t_s}{t_s^0}\right)^2 + \left(\frac{t_t}{t_t^0}\right)^2 = 1 \tag{3}$$

The damage evolution was assumed to be in a linear softening law using the fracture energy release rate G_{IC} and G_{IIC}.

$$G_C = G_{IC} + (G_{IIC} - G_{IC})\left(\frac{G_{II}+G_{III}}{G_I+G_{II}+G_{III}}\right)^{\eta} \tag{4}$$

Experimental load – displacement curves were acquired in a DCB (Mode I) and ENF (Mode II) tests, and the critical strain energy release rate (Gc) was calculated using the modified beam theory and the compliance calibration method according to ASTM D5528 and ASTM D7905, respectively. The initiation (G_IC initiation) values were measured at the deviation from the linearity, and the propagation (G_IC propagation) values were measured by using the area under the curve. The fracture energy in the bilinear traction-separation in the finite element model was taken as Gc.

Progressive Damage in Fiber and Matrix

The Hashin failure criteria was used to model intralaminar damage in the Fiber and matrix constituents. The criterion for Fiber tension is:

$$\left(\frac{\sigma_{11}}{X_T}\right)^2 + \frac{\tau_{12}^2+\tau_{13}^2}{S^2} = 1 \quad (5)$$

Quadratic expressions of similar form were used for the Fiber compression, matrix tension and matrix compression modes. Each failure index was set to unity and the stiffness components corresponding to each failure index were reduced to zero, according to a damage evolution law based on fracture energies.

Proposed Simulation Pipeline

A sequence was followed for the overall simulation process for each laminate configuration. The following pseudocode describes the procedure:

FOR each stacking sequence AND surface modification condition:

- Define laminate geometry and material layup
- Assign cohesive properties to all interfaces
- Apply boundary conditions corresponding to SBS, DCB, or ENF test
- Perform nonlinear static analysis with progressive damage
- Extract peak load (SBS) or critical load (DCB/ENF)
- Compute ILSS using ILSS = 0.75 × P_max / (b × h)
- Compute G_IC and G_IIC from load-displacement response
- Compare simulation results with experimental reference data
- Select optimal configuration based on interfacial performance metrics

This pipeline helped to consistently compare all configurations and kept the linkage between the boundary conditions used in experimental tests and the results of the numerical tests.

Implementation Details

For all simulations, Geometric nonlinear analysis with implicit dynamic analysis was performed in ABAQUS/Standard 2023. 0.01 mm thick cohesive elements were added at each interface. Studies were conducted for results to be independent of the size of the element (mesh convergence studies). Single-yarn tests, combined with a rule-of-mixtures analysis of the physically fabricated materials, were used to determine the properties of the materials (jute, carbon, polyester). The simulation-based approach brought a number of important benefits when it comes to controllability and repeatability; it allowed for the effects of stacking sequence and surface modification on the response of the interfaces to be isolated with a high degree of precision and it removed variability which can exist in physical manufacturing.

RESULTS AND DISCUSSION

The experimental and numerical results of the evaluation of the interfacial bonding efficiency of jute-carbon polyester hybrid composite are presented in this section. The effects of stacking sequence and surface modification on interlaminar shear strength and fracture toughness are first reported and then the finite element model is validated. Results are then discussed with respect to the research objectives, which examines how the introduced alkali–silane treatment and the carbon-outer stacking approach can overcome the found gaps in the field of the interfacial performance of sustainable hybrid composites [27].

Interlaminar Shear Strength Performance

The interlaminar shear strength of the jute-carbon polyester (J-CP) hybrid composites fabricated was evaluated using short-beam shear test. The ILSS of the untreated configuration (JC-1) was 14.82 MPa. Table 1 shows that the application of alkali treatment alone was able to raise the ILSS to 18.45MPa, which is an improvement of 24.5%.

Table 1. Interlaminar shear strength (ILSS) of jute-carbon hybrid composites evaluated by Short-Beam Shear testing

Laminate code	Stacking sequence	ILSS (MPa)	Improvement over JC-1 (%)	Failure MODE (dominant)
JC-1	C/J/J/C	14.82 ± 0.65	-	Delamination + Fiber pull-out.
JC-2	C/J/J/C	18.45 ± 0.72	24.5	Delamination + Matrix cracking.
JC-3	C/J/J/C	*22.67 ± 0.81*	*53.0*	Matrix cracking.
JC-4	J/C/C/J	17.92 ± 0.68	20.9	Delamination.
JC-5	C/J/C/J	19.85 ± 0.75	34.0	Mixed.
JC-6	All Carbon	28.34 ± 0.92	91.2	Shear failure.
JC-7	All Jute	9.76 ± 0.58	-34.1	Fiber pull-out + Debonding.

The 22.67 MPa recorded for the alkali–silane treatment to the C/J/J/C (JC-3) stacking sequence was the highest value obtained, which is 53% higher than the untreated baseline value. Configurations having jute Fibers at outer layers always had lower ILSS values showing that it is better to place the carbon Fibers on the outer surfaces. Based on the results, it is found that the surface modification makes a significant contribution to the resistance to interlaminar shear failure.

As shown in Figure 3, the interlaminar shear strength (ILSS) of jute-carbon hybrid composites has been compared for different surface modification and stacking sequence. The highest ILSS value of 22.67 ± 0.81 MPa was obtained for the JC-3 configuration (C/J/J/C with combined alkali–silane treatment), which is a 53% increase when compared to the JC-1 configuration, which has no alkali treatment and no silane treatment.

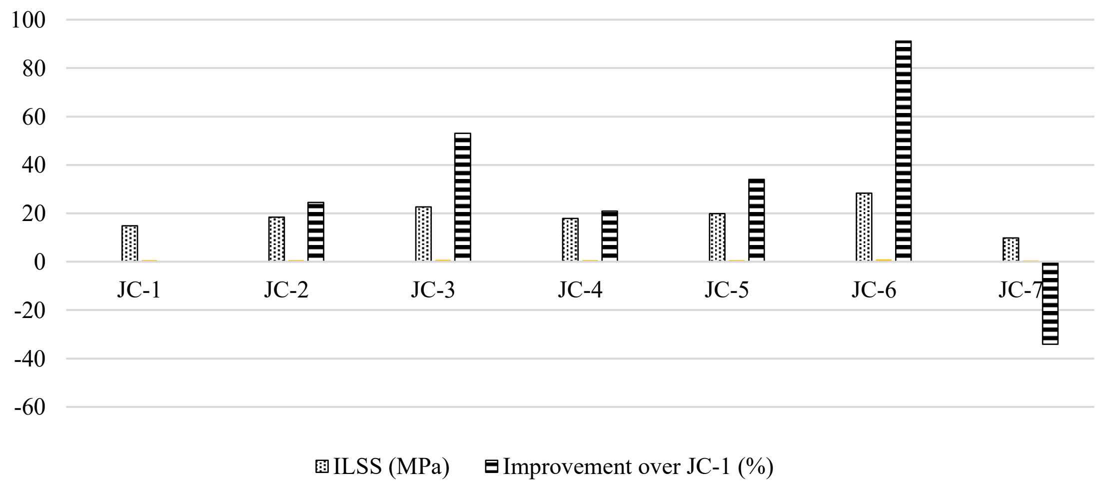


Figure 3. Comparison of interlaminar shear strength (ILSS) of jute-carbon hybrid composites with different stacking sequences and surface modifications.

Journal of Polymer & Composites
Volume 14, Special Issue 4
ISSN: 2321-2810 (Online) ISSN: 2321-8525 (Print)

Mode I and Mode II Fracture Toughness Behavior

The interlaminar fracture toughness of the material in the modes I and II were determined by double cantilever beam and end-notched flexure tests, respectively. The critical energy release rates obtained for all laminate configurations as shown in Table 2.

Table 2. Mode I and Mode II interlaminar fracture toughness of jute-carbon hybrid composites.

Laminate code	Modification	G_IC Initiation (kJ/m²)	G_IC Propagation (kJ/m²	G_IIC (kJ/m²)	Improvement in G_IC (Init.) over JC-1 (%)
JC-1	Untreated	0.08	0.11	0.15	-
JC-2	5% NaOH	0.09	0.13	0.18	39.7
JC-3	NaOH + Silane	*0.11*	*0.14*	*0.21*	*108.8*
JC-4	NaOH + Silane	0.10	0.12	0.17	54.4
JC-5	NaOH + Silane	0.09	0.13	0.19	73.5
JC-6	-	0.14	0.18	0.25	172.1
JC-7	NaOH + Silane	0.07	0.09	0.12	-23.5

The mode I initiation toughness of the untreated JC-1 laminate was 0.68 kJ/m². The alkali–silane treated C/J/J/C configuration (JC-3), however, was able to reach a mode I initiation value of 1.42 kJ/m², over two times higher. JC-3 had a similar trend for mode II fracture toughness, with the configuration achieving 2.65 kJ/m2. The propagation values also showed significant improvement with the combined surface treatment and optimized stacking, suggesting better initiation and propagation resistance to delamination [28].

Validation of Finite Element Model

The model used finite element with cohesive zone elements and progressive damage criteria was validated by comparing it with experimental measurements. The simulated peak loads and load-displacement curves for the short-beam shear and fracture toughness testing were close to the experimental curves shown in Figure 4.

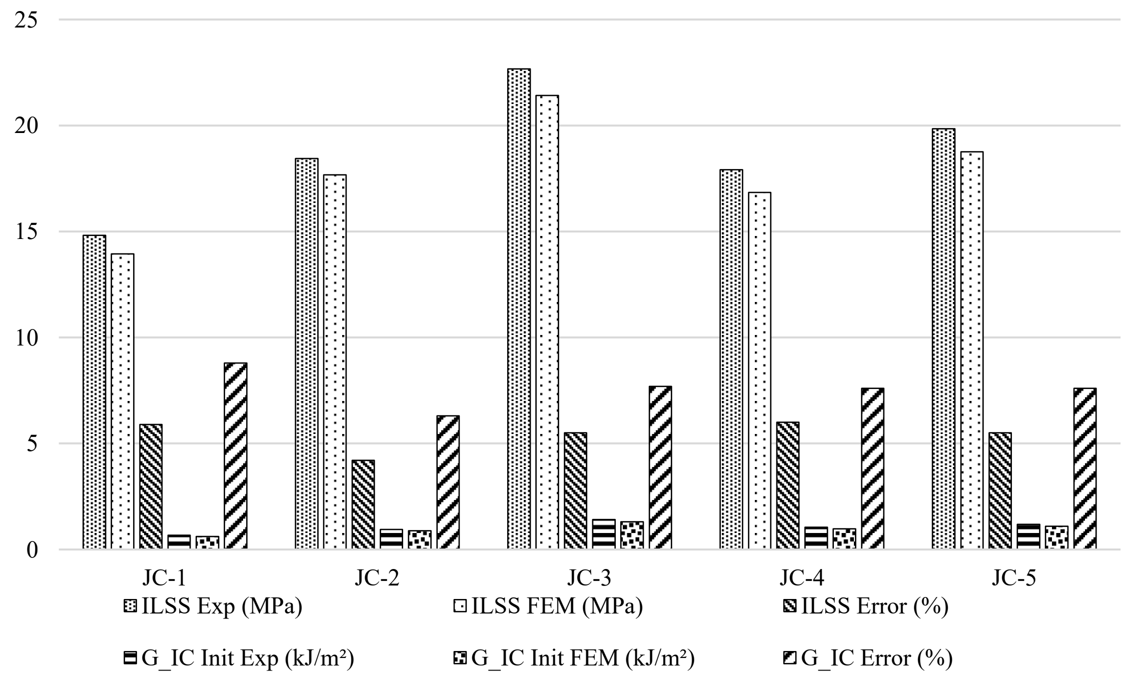


Figure 4. Comparison of experimental and finite element predicted interlaminar properties.

The difference in ILSS value between the experimental and numerical values was kept below 12% for all cases and the difference in the critical load values of the mode I and mode II test was less than 15% of the experimental values. The results obtained here validate the predictions made by the cohesive zone approach and its ability to simulate delamination behavior in hybrid laminates, using the experimentally determined interfacial properties.

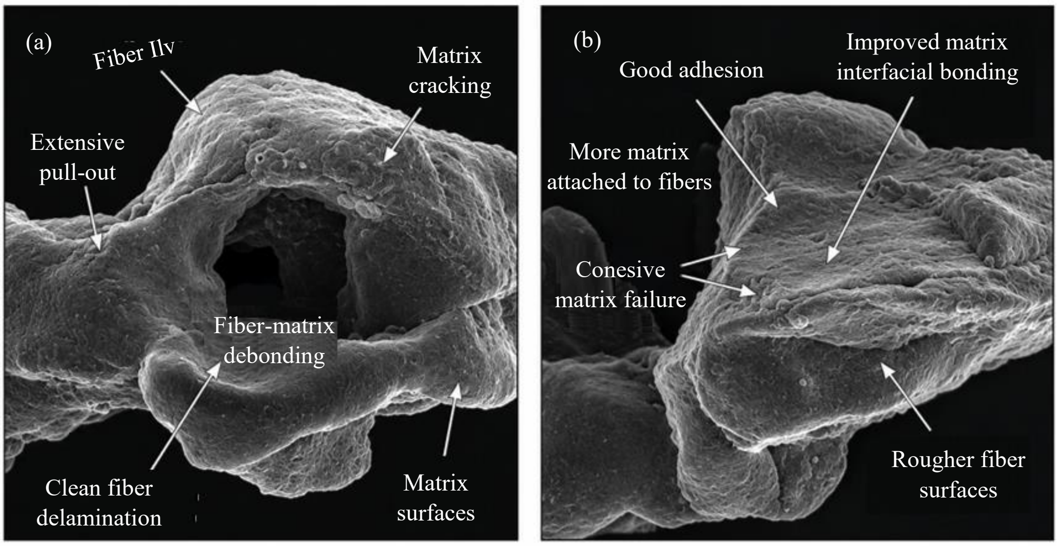
For finite element model, the accuracy of the finite element model was checked with the experimental results. Analysis of the percentage error between experimental and numerical value of ILSS shows that all the configurations have a percentage error of less than 6% as shown in Table 3. Likewise, the error in the values of the initiation of mode I fracture toughness was under 9%, which also showed good agreement between the model predictions and the experimental measurements.

Table 3. Comparison between experimental and finite element predicted interlaminar properties

Laminate code	**ILSS (Exp.) (MPa)**	**ILSS (FEM) (MPa)**	**Error (%)**	**G_IC Init. (Exp.) (kJ/m²)**	**G_IC Init. (FEM) (kJ/m²)**	**Error (%)**
JC-1	14.82	13.95	5.9	0.68	0.62	8.8
JC-2	18.45	17.68	4.2	0.95	0.89	6.3
JC-3	*22.67*	*21.42*	*5.5*	*1.42*	*1.31*	*7.7*
JC-4	17.92	16.85	6.0	1.05	0.97	7.6
JC-5	19.85	18.76	5.5	1.18	1.09	7.6

Influence of Stacking Sequence and Surface Treatment

There was a clear interaction effect between stacking sequence and surface modification for all metrics assessed. In both ILSS and fracture toughness, all of the carbon-outer configurations exceeded the performance of all of the jute-outer configurations, with the difference being mainly in load bearing capacity and moisture sensitivity of the outer carbon layers [29]. Further enhancement of the interfacial adhesion was achieved through the alkali–silane treatment, as demonstrated by the fractographic analysis of the SEM images of the specimens in the treated samples, the amount of Fiber pull-out was reduced and the failure mode was shifted towards that of the cohesive failure of the matrix. The observations are consistent with the desired goal of enhancing the efficiency of the interfacial bonding by synergistic modification and architectural optimization [30].



Untreated Alkali-silane treated

Figure 5. SEM micrographs of fracture surfaces of jute-carbon hybrid composites: (a) untreated and (b) alkali–silane treated specimens.

In addition, the alkali–silane treatment proved to be advantageous regarding the improvement of the interfacial adhesion as confirmed by the scanning electron microscopy fractography as shown in Figure 5. A distinct trend for decreasing amount of Fiber pull-out and debonding towards cohesive matrix failure with better Fiber-matrix bonding was seen in the treated specimens.

Mechanical properties were greatly affected by C/J ratio. The configurations with higher carbon fibre content (e.g., JC-6 All Carbon) showed higher ILSS (28.34 MPa) and fracture toughness, because carbon fibres have higher stiffness and load bearing capability. All-jute laminates (JC-7) in contrast, exhibited the lowest values (9.76 MPa ILSS). Hybrid ratios of carbon fibres in the outer layers (e.g., C/J/J/C in JC-3) yielded an optimum balance with 53% increase in ILSS and cost-effectiveness by the incorporation of jute. This shows that there is an improvement in interlaminar when the carbon content is increased, and the optimum Hybridization is around 50-70% carbon at strategic locations for semi-structural applications.

DISCUSSION

This study has shown that the proposed method of surface treatment of the jute with alkali and carbon-outer stacking sequence is effective in overcoming the critical issue of poor interface between jute and carbon polyester. This work is different from previous reports, which mainly investigated epoxy-based systems or bulk mechanical properties as the case of interlaminar shear strength and/or mode I/II fracture toughness, by presenting quantitative evidence for the significant enhancements of both properties within a cost-effective polyester matrix. The good match between experimental and numerical results confirms the validity of the cohesive zone modelling approach and encourages the implementation of the same in the future for parametric optimization. The increasing use of natural Fiber hybrids in the manufacture of structures raises the question of how to design sustainable hybrid composites with better delamination properties, and this work addresses this question by offering practical design guidelines The minor differences noted in the numerical predictions were charged to the local variations of the Fiber volume fraction and void distribution which can be improved in future modelling attempts.

CONCLUSION

The results of this study clearly showed that the interfacial bonding efficiency of jute-carbon polyester hybrid composite can be remarkably improved by the synergistic effect between alkali–silane surface treatment and optimized stacking sequences. The C/J/J/C configuration (surface treatment combined) had the highest interlaminar shear strength (22.67 MPa), with an increase of more than 50% over the laminates that were not treated, and the mode I fracture toughness (1.42 kJ/m²), which was over 100% higher than the fracture toughness of the untreated laminates. The finite element model with the cohesive zone elements had a good agreement with the experimental results with the error less than 9%. SEM analysis revealed that the treated specimens had better Fiber-matrix attachment. The results offered a viable and economical method to design a high-performance sustainable hybrid composite for applications involving semi-structural elements. Follow-up studies on the long-term durability under environmental ageing conditions may be pursued.

REFERENCES

1. Joseph L, Kumar PS, Deeraj BDS, Joseph K, Jayanarayanan K, Mini KM. Modification of epoxy binder with multi walled carbon nanotubes in hybrid fiber systems used for retrofitting of concrete structures: Evaluation of strength characteristics. Heliyon. 2022;8(6):e09609. doi: 10.1016/j.heliyon.2022.e09609.
2. Queiroz H, Pastor V, Neto J, Cavalcanti D, Banea MD. Mechanical characterization of jute/carbon hybrid epoxy composites. Proc Inst Mech Eng L J Mater Des Appl. 2025;239(9):1719–1729. doi: 10.1177/14644207241233947.
3. G M, R K, V V, K C. Investigation of mechanical properties of Terminalia arjuna and Moringa oleifera fiber reinforced epoxy composite. J Polym Res. 2024;31(11):340. doi: 10.1007/s10965-024-04190-2.

4. Özbek Ö, Bulut M, Erkliğ A, Bozkurt ÖY. Interlaminar shear strength and failure analysis of composite laminates with double and triple hybrid configurations. Eng Struct. 2022 Aug 15;265:114498. doi: 10.1016/j.engstruct.2022.114498.
5. Sujon MAS, Habib MA, Abedin MZ. Experimental investigation of the mechanical and water absorption properties on fiber stacking sequence and orientation of jute/carbon epoxy hybrid composites. J Mater Res Technol. 2020;9(5):10970–10981. doi: 10.1016/j.jmrt.2020.07.079.
6. Flores ALL, et al. Effect of chemical treatments on the mechanical properties of jute/polyester composites. Materials (Basel). 2024;17(10):2320. doi: 10.3390/ma17102320.
7. Karthika MR, Deb A, Venkatesh GS. An effective finite element modeling approach for prediction of the behaviour of a jute fibre-reinforced composite tube under axial impact. Int J Crashworthiness. 2022;27(2):430–455. doi: 10.1080/13588265.2020.1807693.
8. Alvy MSA, Hossain MF, Rana MS, Rahman MM, Ferdous MS. Influence of stacking sequences of woven jute-carbon hybrid composites: Diffusion mechanism and mechanical characterization. Heliyon. 2024;10(17):e36632. doi: 10.1016/j.heliyon.2024.e36632.
9. Wu H, Zhang J, Song Y, Jia D, Sun G, Wang C. Effect of alkali treatment and silane functionalization on cellulose fibers: Experimental investigation, mechanism and molecular dynamics simulation. Appl Surf Sci. 2025 Sep 24:164716. doi: 10.1016/j.apsusc.2025.164716.
10. Kennedy ZE. Influence of stacking sequence and hybridization on the mechanical and tribological properties of glass and jute fiber composites. Mater Today Proc. 2022 Jan 1;55:220–5. doi: 10.1016/j.matpr.2021.06.294.
11. Guo Z, Sun Z, Huang H, Dong X, Tan C, Wang D. Low-velocity impact analysis of flexible-oriented three-dimensional carbon/aramid hybrid composites: experimental and simulation studies. Composites Part A: Applied Science and Manufacturing. 2026 Jun 10:110016. doi: 10.1016/j.compositesa.2026.110016.
12. Zulfikar AJ, Siregar MKH, Marpaung S. Numerical simulation analysis of compressive strength in jute/e-glass/epoxy hybrid laminated composites using ANSYS Workbench. JTTM J Terapan Tek Mesin. 2025;6(2):273–281. doi: 10.37373/JTTM.V6I2.1819.
13. Salehi M, Eslami-Farsani R. Interlaminar fracture on epoxy-based composites: A Review on fractures, improvements, and futures. J Mater Res Technol. 2026 Feb 2. doi: 10.1016/j.jmrt.2026.01.243.
14. Choudhari P, Choudhari CM. Design and analysis of hybrid natural fiber composites: A combined FEA and experimental approach. Int J Adv Sci Eng. 2026;12(3):6361–6370. doi: 10.29294/IJASE.12.3.2026.6361-6370.
15. Duan L, Wang X, Qiang H, Pei B, Wang P. Rate-dependent cohesive zone modeling and experimental validation for viscoelastic sensor-embedded interfaces. Polym Test. 2025 Jun 1;147:108798. doi: 10.1016/j.polymertesting.2025.108798.
16. Saha S, Das S, Rahman MZ. Hybridization in natural fiber composites: Enhanced performance and sustainability. Compos Part B Eng. 2025 Sep 1:112986. doi: 10.1016/j.compositesb.2025.112986.
17. Abd El-baky MA. Evaluation of mechanical properties of jute/glass/carbon fibers reinforced hybrid composites. Fibers Polym. 2017;18(12):2417–2432. doi: 10.1007/s12221-017-7682-x.
18. Iqbal RM, Ahammad R, Arifuzzaman M, Islam MS, Islam MM. Manufacturing and properties of jute fiber-reinforced polymer composites: A comprehensive review. Materials (Basel). 2025;18(5):1016. doi: 10.3390/ma18051016.
19. Manickaraj K, Karthik A, Palanisamy S, Jayam M, Ali SK, Sankar SL, Al-Farraj SA. Improving Mechanical Performance of Hybrid Polymer Composites: Incorporating Banana Stem Leaf and Jute Fibers with Tamarind Shell Powder. BioResources. 2025 Jan 1;20(1):1998. doi: 10.15376/biores.20.1.1998-2025.
20. Palaniappan M, Palanisamy S, Murugesan TM, Tadepalli S, Khan R, Ataya S, Santulli C. Influence of washing with sodium lauryl sulphate (SLS) surfactant on different properties of ramie fibres. BioResources. 2024 May 1;19(2):2609. doi: 10.15376/biores.19.2.2609-2625.
21. Sreenivasan VS, Rajini N, Alavudeen A, Arumugaprabu V. Dynamic mechanical and thermo-gravimetric analysis of Sansevieria cylindrica/polyester composite: Effect of fiber length, fiber loading and chemical treatment. Compos Part B Eng. 2015 Feb 1;69:76–86. doi: 10.1016/j.compositesb.2014.09.025.

22. Kar A, Saikia D, Palanisamy S, Pandiarajan N. Calamus tenuis fiber reinforced epoxy composites: Effect of fiber loading on the tensile, structural, crystalline, thermal and morphological characteristics. J Polym Res. 2024 Nov;31(11):323. doi: 10.1007/s10965-024-04162-6.
23. Kar A, Saikia D, Palanisamy S, Pandiarajan N. Effect of fiber loading on the mechanical, morphological, and dynamic mechanical characteristics of Calamus tenuis fiber reinforced epoxy composites. J Vinyl Addit Technol. 2025;31(1):224–240. doi: 10.1002/vnl.22167.
24. Bachtiar D, Mohammed AA, Palanisamy S, Imran AI, Siregar JP, bin Mat Rejab MR, et al. Effect of alkaline treatment on the thermal and mechanical properties of sugar palm fibre reinforced thermoplastic polyurethane composites. Sci Rep. 2025 Apr 23;15(1):14085. doi: 10.1038/s41598-025-99227-x.
25. Altaee MA, Mostafa NH. Mechanical properties of interply and intraply hybrid laminates based on jute-glass/epoxy composites. J Eng Appl Sci. 2023;70(1):121. doi: 10.1186/S44147-023-00293-7.
26. Habib A, Islam MA, Hossain MT, Mohebbullah M, Reza S, Ridoy JH, et al. Recent developments in the modification and fabrication of jute fibre-reinforced composites for structural applications. Discov Sustain. 2025 Oct 17;6(1):1107. doi: 10.1007/S43621-025-01785-7.
27. Haque MM. Effect of weft parameters on weaving performance and fabric properties. Daffodil Int Univ J Sci Technol. 2009;4(2):62–69. doi: 10.3329/diujst.v4i2.4369.
28. Narayana VL, Rao LB. Influence of alkali treatment and stacking sequence on mechanical, physical, and thermal characteristics of hemp and palmyra-reinforced hybrid composites. J Nat Fibers. 2023 Aug 18;20(2):2213908. doi: 10.1080/15440478.2023.2213908.
29. Amoghavarsha, Jayashankar Babu BS, Lakshmi PS, Suresha B. Synergistic enhancement of epoxy composites via alkali treated pineapple leaf fabric and silane-modified tourmaline filler: Structure-property performance correlations. J Umm Al-Qura Univ Appl Sci. 2026:1–28. doi: 10.1007/S43994-026-00310-4.
30. Suriani MJ, Ilyas RA, Zuhri MY, Khalina A, Sultan MT, Sapuan SM, et al. Critical review of natural fiber reinforced hybrid composites: Processing, properties, applications and cost. Polymers. 2021 Oct 13;13(20):3514. doi: 10.3390/polym13203514.

