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Experimental Investigation of Tensile Strength of Bamboo Fiber/Synthetic Glass Fiber

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Abstract

In this work, hybrid fiber reinforced composites (HFRCs) with enhanced mechanical and physical characteristics are created by reinforcing composite laminates using a blend of natural bamboo fiber and synthetic glass fiber. The primary goal of the inquiry is to assess these composites' tensile and impact properties. In comparison to non-hybrid composites, the hybrid composite, which consists of two layers of bamboo fiber and one layer of bidirectional glass fiber, had the highest tensile strength among the configurations examined. This is explained by the reinforcing action of bidirectional glass fibers, which more efficiently disperse the stress in several directions. The findings also show that bidirectional glass fiber has a substantially better tensile strength than composites made of one layer of unidirectional glass fiber and two layers of bamboo fiber. The benefit of hybridization is further supported by the discovery that composites composed completely of bamboo fibers in three layers have a much lower tensile strength. It has been shown that hybrid composites have almost double the tensile strength of laminates made entirely of bamboo fiber. Furthermore, bamboo fiber composites exhibit better tensile performance when compared to hybrid laminates that incorporate coconut sheath. Surprisingly, impact testing demonstrates a different pattern: out of all the combinations, the composite with three layers of bamboo fiber exhibits the highest impact energy absorption. This implies that although tensile strength is improved by hybridization, impact resistance is more successfully contributed by the inherent toughness of bamboo fibers, underscoring the need of customizing composite design according to particular mechanical performance requirements.

Keywords: Bamboo fiber, coconut sheath fiber, glass fiber, hybrid composites, natural composites, tensile strength

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INTRODUCTION

A sizable amount of composite-based technical items and components are disposed of in landfills after their useful lives, where they might linger for a long time since they are not biodegradable. This disposal method is a major problem considering contemporary waste management and sustainability initiatives as it contributes to long-term environmental deterioration. Composite trash is becoming more and more common worldwide since composite materials are used in a variety of industries, such as consumer products, automotive, aerospace, and construction. Conventional composites are not biodegradable and present major difficulties in recycling and end-of-life processing since they are mostly reinforced with synthetic fibers like glass, carbon, or aramid. The environmental impact of these materials has prompted the hunt for sustainable substitutes that balance environmental responsibility with performance.

Natural fiber integration into composite materials has become a viable way to address these escalating environmental issues. Because they are biodegradable, renewable, and frequently accessible locally, natural fibers may greatly lessen the environmental impact of composite goods. Their combination makes it possible to create recyclable or biodegradable parts that provide good substitutes for conventional synthetic composites. Natural fiber-reinforced polymer (NFRP) composites are becoming more popular, which is in line with worldwide trends in circular economy principles, sustainable product design, and green engineering. Nowadays, designers, and material scientists are paying more attention to reducing environmental effects at every stage of the product lifecycle without sacrificing performance standards. As a result, within the larger framework of environmentally responsible engineering methods, sustainability, profitability, and efficient waste management are becoming interconnected goals [1].

The use of renewable and biodegradable materials in a range of engineering applications has increased due to recent developments in materials science and engineering. Growing consumer demand for green products, in addition to environmental and regulatory concerns, is driving research and industry interest in eco-friendly composites. For a composite material to be deemed both feasible and sustainable in this context, it must meet two essential requirements: it must be biodegradable and possess sufficient mechanical qualities, such as tensile, flexural, and impact strengths [2,3,4]. Composites reinforced with natural fibers are becoming more and more acknowledged for their capacity to satisfy these requirements. Lower material prices, simplicity of processing, lower industrial energy usage, and fewer carbon emissions are only a few of their many clear benefits. Additionally, they are appropriate for applications where environmental performance is a crucial factor due to their biodegradability at the end of their useful lives [5,6].

Numerous natural fibers, such as jute, flax, hemp, kenaf, coir (coconut sheath), and sisal, have been investigated for use in polymer matrix composites. To produce lightweight composites with improved mechanical characteristics, these fibers are usually incorporated in thermoset or thermoplastic polymer matrices [7,8,9,10]. Although many semi-structural applications have found success with the use of single natural fibers, hybrid composites are becoming more and more popular. To capitalize on the distinct advantages of each form of reinforcement, they blend two or more fiber types, either entirely natural or a combination of natural and synthetic fibers like glass, carbon, or Kevlar. By customizing characteristics like stiffness, impact resistance, and durability, hybrid composites provide a useful way to improve the performance of biodegradable systems. Improving mechanical performance and changing moisture absorption properties are two major drivers of hybridization, which are essential for expanding the range of applications for composites [11,12,13].

A number of design parameters, such as the manufacturing technique used, fiber orientation, fiber volume fraction, and stacking sequence, have a significant impact on the performance of hybrid composites. A suitable balance of mechanical strength, toughness, and environmental resistance can be attained by properly designing hybrid composites. For instance, because of their durability, accessibility, and biodegradability, coconut sheath fibers have garnered a lot of interest for use in composite designs. These fibers have demonstrated potential as a substitute for synthetic reinforcements in non-essential structural elements, especially in the automobile sector where weight reduction and sustainability are crucial design objectives. To provide environmental advantages without sacrificing functionality, composites reinforced with coconut sheath fibers are being explored for use in dashboards, headliners, door panels, and automobile interiors [14].

The efficiency of hybrid composites, which combine synthetic fibers like glass or carbon with natural fibers like jute or coconut sheath, has been shown in several research. One of the most popular production processes for creating these hybrid materials is still the manual lay-up method. Because of its simplicity and low cost, it is especially well-suited to low-volume manufacturing and researchoriented fabrication. One noteworthy experimental finding is that mechanical performance is much enhanced when glass fiber layers are placed on the exterior surfaces and natural fibers, like coconut sheath, are placed in the center. Composites with better tensile and flexural qualities result from this configuration, which improves stress distribution and fiber-matrix bonding [15]. like this, although it has mostly been used in synthetic fiber composites, the vacuum bagging method has been used to improve fiber compaction and lower void content. These materials have been suggested for non-load-bearing applications where longevity and low weight are more important than structural strength, such as wall cladding, interior doors, furniture, and roofing panels [16].

Simulating the mechanical behavior of hybrid composites under varied loads and environmental conditions is being done in tandem with experimental studies using computational tools, such as ANSYS. When compared to experimental data, numerical models provide valuable insights into failure processes, deformation behavior, and stress-strain distributions. According to one noteworthy research, chemical treatments can greatly enhance the interfacial interaction between natural fibers and the polymer matrix, especially when alkali or silane agents are used. It was discovered that the best treatment weight fraction for increasing thermal stability and mechanical strength was 10%. These results highlight how crucial fiber surface alterations are to maximizing composite performance for real-world uses [17].

The tribological behavior of natural-synthetic hybrid composites, especially in wear-intensive environments, is another important research topic. The effects of adding tungsten carbide fillers to hybrid composites made of glass, sisal, and jute fibers have been studied. These fillers improved overall mechanical performance in addition to increasing wear resistance. Such composites are being positioned for heavy-duty applications, such as gears, bearings, and impact-resistant panels in industrial and automotive machinery, by decreasing frictional losses and increasing service life [18,19,20].

The study of hybrid composites that combine glass fiber with bamboo and coconut sheath fibers is noticeably lacking, despite the increasing amount of research in this area. Whereas coconut sheath fiber offers toughness, biodegradability, and affordability, bamboo fiber is well known for its exceptional tensile qualities, lightweight nature, and quick renewability. Glass fiber combined with these two natural fibers might provide a well-balanced composite material that can be used in a variety of technical applications. However, there is still a lack of research on this particular combination in the literature. Current studies examining the tensile strength of hybrid fiber-reinforced polymer composites employing different mixes of glass, bamboo, and coconut sheath fibers have been spurred by this research gap. To determine the most promising designs for structural and semi-structural applications, researchers compare the mechanical behavior of various composites under controlled settings. It is anticipated that these results will offer helpful direction for creating sustainable composites of the future that balance cost, performance, and environmental effect.

MATERIALS AND METHODS

Materials and Methods

Both synthetic glass fiber and bamboo fiber are used as reinforcing materials. The epoxy LY 556 and the hardener K-6 are used in an 80:20 ratio as a matrix. The tight, consistent holding pressure that the vacuum bag method gives to the whole surface, regardless of the material being laminated, is one of its numerous advantages that led to its adoption. Three distinct types of composites are depicted in Figure 1. The first type, designated AAA, has three layers of bamboo fiber. The second type, designated ABA, has two layers of bamboo fiber and one layer of unidirectional glass fiber. The third type, designated ACA, has two layers of bamboo fiber and one layer of bidirectional glass fiber.

In accordance with ASTM D3039 standards for tensile testing of polymer matrix composite materials, the specimens were carefully fabricated and precision-cut using a specialized cutting tool to ensure dimensional consistency and minimize edge defects. The final test specimens measured 250 mm in length, 25 mm in width, and 2.5 mm in thickness, adhering strictly to the dimensional tolerances prescribed by the standard. These prepared specimens are illustrated in Figure 2(a, b, c), representing the different composite laminate configurations evaluated in this study. Subsequently, tensile tests were conducted using a Universal Testing Machine (UTM) under controlled laboratory conditions. The test setup, including load application, grip alignment, and environmental conditions, was maintained as per ASTM D3039 requirements to ensure data reliability and repeatability. Figure 3 captures the test setup, showing the loading arrangement, sample positioning, and test environment, which collectively contributed to accurate assessment of the tensile behavior of the composite laminates. The results obtained from this standardized approach provide a reliable comparison of mechanical performance across different fiber and laminate configurations.

RESULT AND DISCUSSIONS

Five composite laminate samples from each layup configuration were tested using a universal testing machine (UTM), with results summarized in Table 1 and Figure 4. The figure illustrates the load vs. deflection behavior of each laminate type. As shown in Figure 4(a), the non-hybrid AAA laminate—composed entirely of bamboo fiber layers—exhibited the lowest tensile strength, averaging around 29 MPa. All five samples followed a similar load-deflection trend, indicating uniformity in fabrication but limited load-carrying capacity due to the absence of high-strength reinforcements. The ABA laminate, with two layers of bamboo fiber and one layer of unidirectional glass fiber, displayed moderately improved tensile strength—about 38 MPa—as seen in Figure 4(b). This improvement is likely due to the enhanced axial stiffness provided by the glass fiber. However, the interfacial bonding between the dissimilar fibers may not be optimal, potentially limiting the laminate's ability to fully utilize the mechanical properties of glass fiber. The similarity in load-deflection behavior across all five samples also suggests consistent bonding quality and fabrication but moderate reinforcement efficiency.

Figure 1. Hybrid composite laminate (a) AAA (b) ABA (c) ACA.

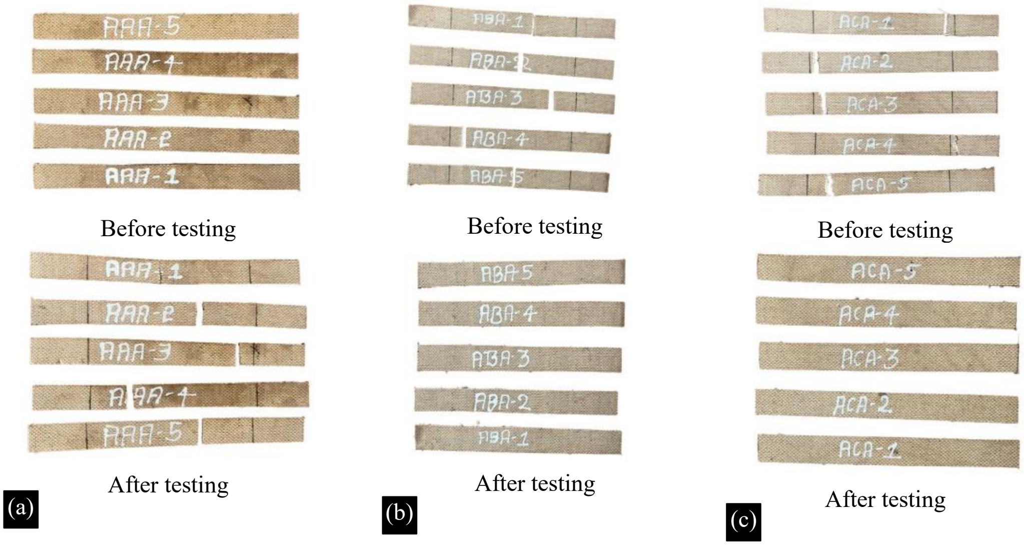


Figure 2. Hybrid specimens before and after testing.

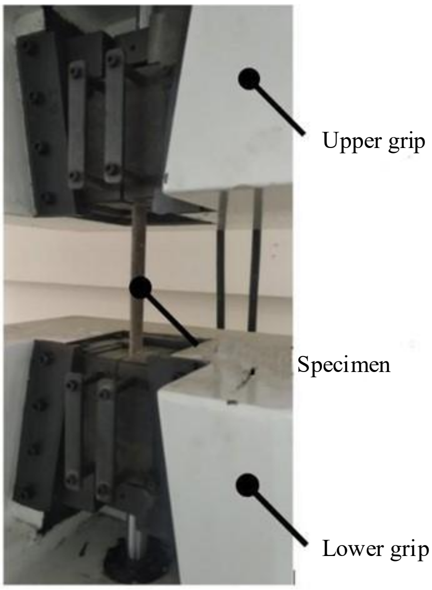
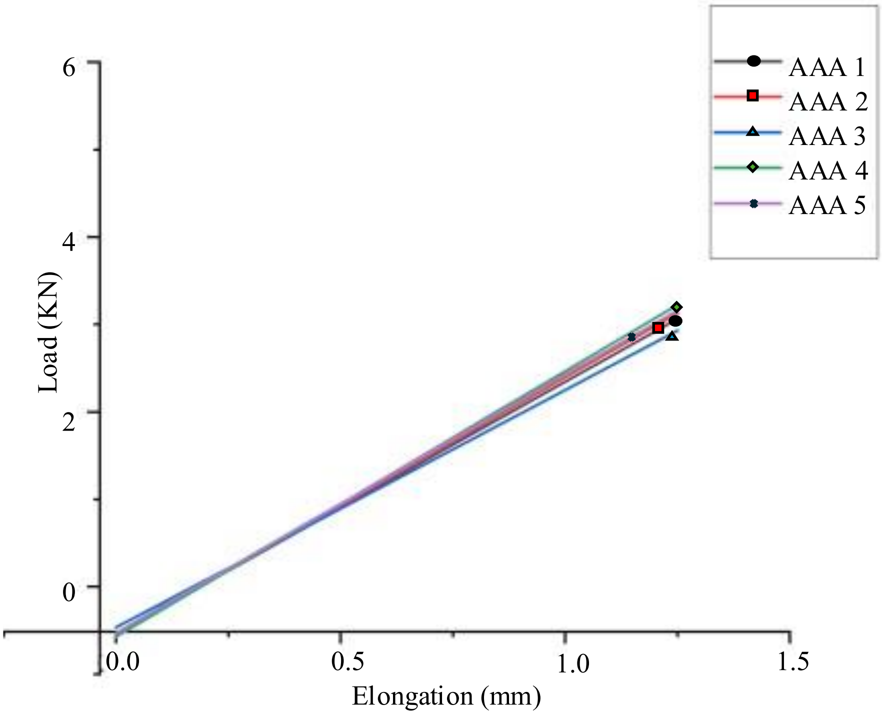


Figure 3. Tensile testing of specimen in UTM.

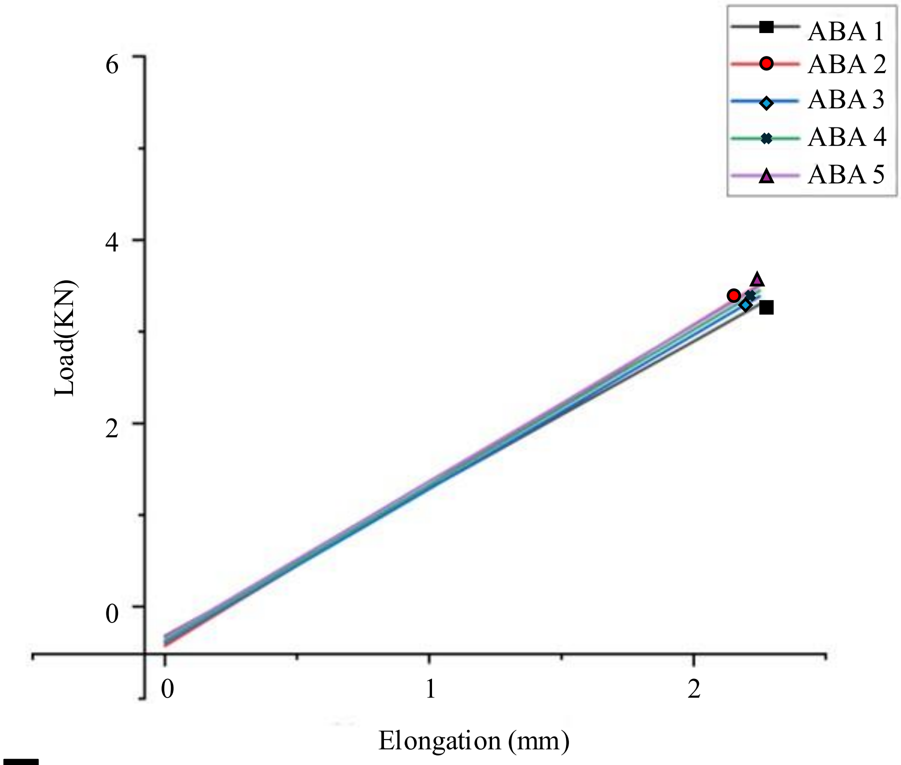
Table 1. Tested data of different composition sample.

Sample	Load at yield (kN)	Elongation at yield (mm)	Yield stress (N/mm^2)	Peak load (kN)	Elongation at peak(mm)	Tensile strength (N/mm^2)	Load at break (kN)	Elongation at break (mm)
AAA1	1.25	3.5	25	1.25	4.62	25	1.2	5.63
AAA2	1.14	3.56	26	1.2	4.5	27	1.5	4.67
AAA3	1.2	3.4	25	1.55	4.6	31	1.25	4.66
AAA4	1.17	3.6	26	1.6	5.18	32	1.5	5.24
AAA5	1.28	3.65	24	1.55	4.97	31	1.2	4.97
ABA1	1.24	0.86	25	2.1	3.45	42	0.1	3.7
ABA2	1.3	0.87	24	1.86	2.95	37	0.1	2.95
ABA3	1.26	0.9	25	1.51	2.6	32	0.1	2.6
ABA4	1.32	0.89	26	2.2	3.66	44	0.15	3.84
ABA5	1.3	0.72	24	1.9	3.99	38	0.35	3.99
ACA1	2.2	2.1	44	4.1	4.96	62	2.3	4.96
ACA2	1.95	1.85	39	3.35	3.69	67	2.35	3.69
ACA3	2.35	2.69	47	3.95	3.58	59	1.3	3.58
ACA4	1.98	1.95	39	3.85	3.99	57	1.75	3.99
ACA5	2.15	2.48	42	3.45	4.78	69	2	4.78

The ACA laminate, which incorporates bidirectional glass fiber between two bamboo fiber layers, showed significantly higher tensile strength, with an average value of 63 MPa, as illustrated in Figure 4(c). The bidirectional glass fiber not only reinforces the laminate in multiple directions but also enhances stress distribution during tensile loading. Stronger interfacial adhesion and more efficient stress transfer likely contribute to this superior performance. In Figure 5, the tensile strengths of all three laminates are compared, clearly showing the advantage of hybridization, particularly with bidirectional reinforcement. Failure mode analysis indicates that fiber pull-out, matrix cracking, and delamination are the predominant mechanisms in the non-hybrid laminate. In hybrid laminates, particularly ABA, localized debonding between bamboo and glass fibers is observed, suggesting weaker interfacial adhesion due to differences in surface chemistry and stiffness mismatch. In contrast, ACA exhibits progressive failure, with fiber breakage and minimal delamination, pointing to better fiber-matrix integration and mechanical compatibility. Compared to other natural fibers, such as jute, flax, or hemp, bamboo fiber offers higher tensile strength and stiffness, largely attributed to its high cellulose content and dense microstructure. It also demonstrates good energy absorption and biodegradability. However, its natural variability, moisture sensitivity, and inconsistent surface morphology pose challenges to interfacial bonding with synthetic fibers or polymer matrices.



(a)



(b)

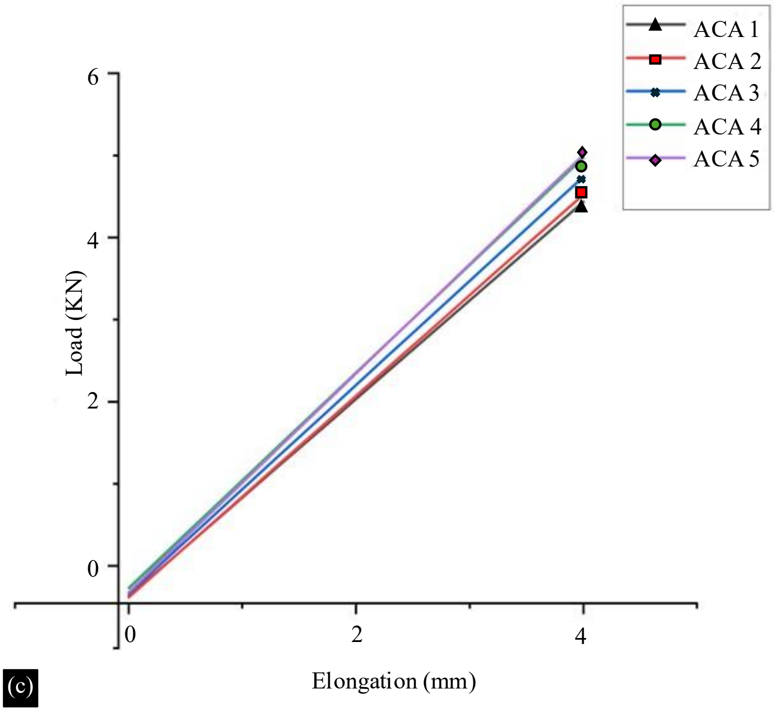


Figure 4. Load vs deflection curve for sample (a) AAA (b) ABA (c) ACA.

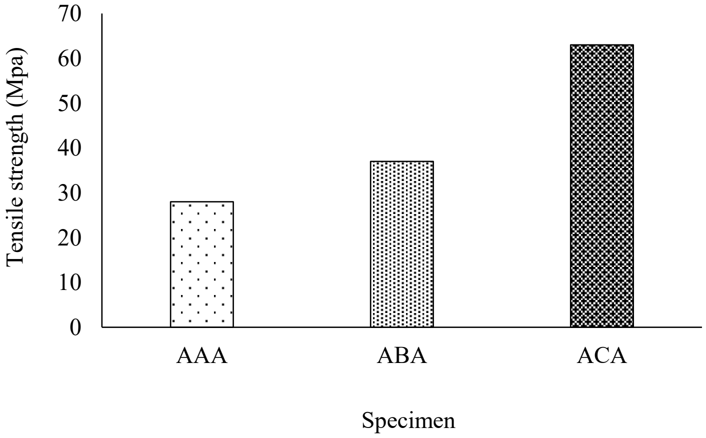


Figure 5. Comparison of tensile strength of specimens.

The Comparison Between Tensile Strength of Two Hybrid Composite Laminates

Figure 5, shows the comparisons made between laminates fabricated with three layers of bamboo fiber (AAA-B) and those with three layers of coconut sheath fiber (AAA-C). As shown in Figure 6, the AAA-B laminate exhibited higher tensile strength than AAA-C, indicating that bamboo fibers have superior load-bearing capability in a non-hybrid laminate configuration When unidirectional glass fiber was introduced as a core layer, forming hybrid laminates ABA-B (bamboo + glass) and ABA-C (coconut + glass), the tensile strength increased for both configurations. However, as shown in Figure 7, ABA-B still outperformed ABA-C, reinforcing the conclusion that bamboo fiber has a more favorable mechanical profile than coconut sheath fiber when used in hybrid composites. A similar trend is observed in the ACA sequence, where ACA-B (bamboo with bidirectional glass) showed greater tensile strength than ACA-C (coconut with bidirectional glass), as illustrated in Figure 8. The superior performance of bamboo fiber hybrid laminates can be attributed to several factors. First, bamboo fiber has a higher cellulose content and a more aligned fibrous structure compared to the loosely packed and more porous structure of coconut sheath fiber. This results in better load transfer and improved stiffness in bamboo-based laminates. Second, the interfacial bonding between bamboo fiber and the polymer matrix tends to be more consistent, likely due to bamboo's smoother surface and lower lignin content, which facilitate better adhesion. Coconut sheath fiber, by contrast, often exhibits a rougher surface, higher lignin, and greater moisture content, which can weaken the fiber-matrix interface and introduce microvoids or delamination during loading. Failure mode analysis supports these observations. Coconut fiber-based laminates (AAA-C, ABA-C, ACA-C) predominantly failed through fiber pull-out, interfacial debonding, and early matrix cracking, suggesting weaker cohesion between the fiber and matrix. In contrast, bamboo fiber laminates displayed progressive failure, with a combination of fiber fracture and matrix yielding, indicative of stronger interfacial bonding and more effective stress distribution. In ACA configurations especially, the presence of bidirectional glass fiber helped in dispersing loads uniformly; however, bamboo-based laminates (ACA-B) better leveraged this advantage due to more compatible mechanical behavior between bamboo and glass fibers. In comparison to other natural reinforcements, such as jute, flax, or kenaf, bamboo fiber continues to demonstrate a favorable balance of tensile strength, ductility, and fiber-matrix compatibility. Its lightweight nature, renewability, and cost-effectiveness make it especially promising for hybrid composite applications in automotive, construction, and lightweight structural components.

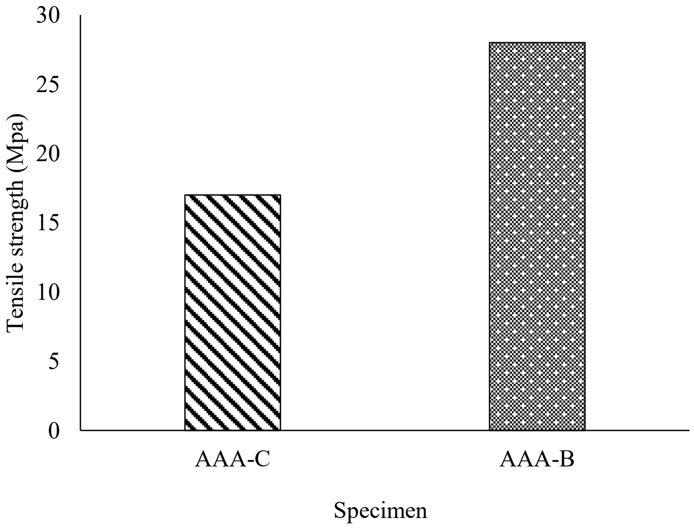


Figure 6. Comparison of tensile strength of three layers coconut and bamboo composite laminates.

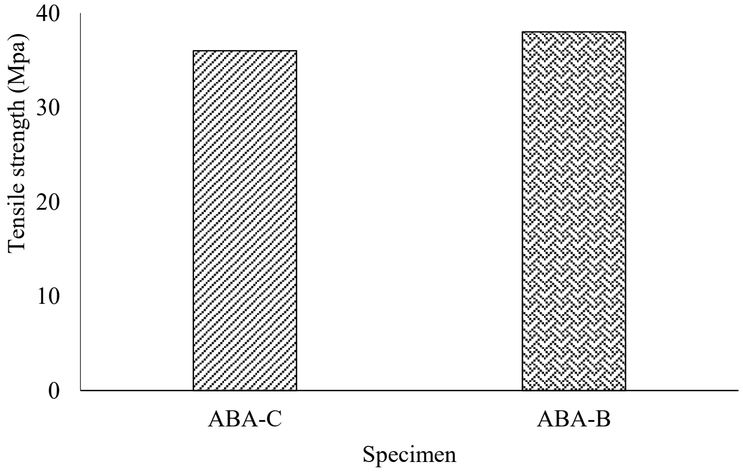


Figure 7. Comparison of tensile strength of two layers Coconut and bamboo fiber and one layer of unidirectional glass fiber composite laminates.

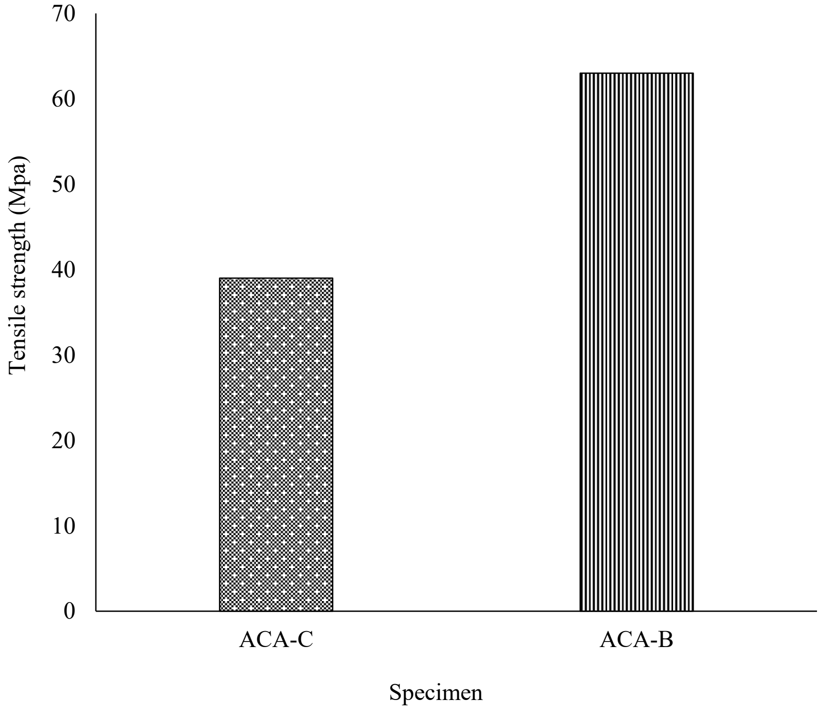


Figure 8. Comparison of tensile strength of two layers coconut and bamboo fiber and one layer of Bi-directional glass fiber composite laminates.

IMPACT TEST

Bamboo fiber hybrid composite laminates were subjected to a drop impact test to evaluate their energy absorption characteristics. Three distinct layup sequences were examined: AAA, composed entirely of three layers of bamboo fiber; ABA, comprising two layers of bamboo fiber and one layer of unidirectional glass fiber; and ACA, consisting of two layers of bamboo fiber and one layer of bidirectional glass fiber. Three specimens were tested for each configuration. As shown in Table 2, the AAA laminate—a non-hybrid—exhibited the highest impact energy absorption, approximately 0.0560 joules, indicating bamboo fiber's strong intrinsic energy dissipation capacity under dynamic loading. The ABA configuration absorbed about 0.0499 joules, slightly less than AAA. The presence of unidirectional glass fiber in the middle layer may have improved directional stiffness, but this possibly restricted energy dissipation due to limited interfacial compatibility between glass and bamboo fibers. In contrast, the ACA laminate, featuring bidirectional glass fiber, showed the lowest impact energy absorption, averaging 0.04272 joules. The rigid, multi-axial nature of bidirectional glass fiber layers may have contributed to premature failure by inducing stress concentrations and reducing the laminate's flexibility under impact. Failure mode analysis revealed that delamination and matrix cracking were more pronounced in hybrid laminates, particularly in ACA, suggesting weaker interfacial bonding between bamboo and glass fibers. The natural surface roughness of bamboo enhances mechanical interlocking with the matrix, but inconsistent fiber geometry can lead to voids and stress risers. Additionally, fiber pull-out and fiber breakage were more evident in AAA specimens, confirming stronger fiber-matrix adhesion and a more ductile failure mode, which aids in energy absorption. When compared to other natural reinforcements like jute, flax, or coir, bamboo fiber demonstrates superior toughness and tensile strength, making it a promising alternative for hybrid composite applications. Its relatively high cellulose content and structural rigidity contribute to better performance under impact loading. However, variability in fiber morphology and moisture sensitivity remains a challenge.Future studies could benefit from advanced surface treatments or compatibilizers to improve fiber-matrix interfacial bonding, thereby enhancing the performance of hybrid laminates and mitigating failure mechanisms, such as delamination and crack propagation.

Table 2. Tested data of different composition sample.

Sample	Deflection(mm)	Load (KN)	Height(m)	Impact energy absorbed (joules)
AAA1	3.336	49	0.1	0.05154
AAA2	3.320	48	0.1	0.0597
AAA3	3.333	48	0.1	0.05698
ABA1	3.548	49	0.1	0.05647
ABA2	3.483	50	0.1	0.05312
ABA3	3.461	49	0.1	0.04022
ACA1	3.23	48	0.1	0.04397
ACA2	3.56	47	0.1	0.04195
ACA3	3.52	49	0.1	0.04224

CONCLUSION

This study shows that non-hybrid laminates without glass fiber exhibit the lowest tensile strength. Incorporating glass fibers enhances tensile strength significantly due to their mechanical properties. Additionally, the inclusion of bamboo sheath fiber reduces the overall cost of the hybrid composite while maintaining acceptable tensile strength. The hybrid laminate demonstrates approximately twice the strength of the non-hybrid counterpart. However, the study has some limitations. The natural variation in bamboo sheath fiber thickness introduces inconsistencies in mechanical behavior, as reflected in some deviations observed in the experimental graphs. Minor defects, such as micro-holes and cracks in the adhesive layer between fibers may have also influenced the results. Future research can focus on optimizing the fiber treatment and alignment process to reduce variability and defects. Additionally, exploring the fatigue and thermal performance of bamboo-based hybrid laminates under different environmental conditions would provide further insight into their long-term applicability in structural and automotive applications.

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