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Enhancement of Mechanical Properties in Epoxy Composites via Bamboo and Glass Fiber Hybridization

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Abstract

This study investigates the mechanical enhancement of natural fiber composites through hybridization with synthetic fibers. A hybrid composite was fabricated using chemically treated natural bamboo fibers (treated with 5% NaOH) and woven E-glass fibers within an epoxy matrix using the hand lay-up technique. The mechanical performance was evaluated specifically through Tensile (ASTM D3039) and Flexural (ASTM D790) testing. Experimental results demonstrate that the Bamboo-Glass hybrid composite significantly outperforms the bamboo-only composite. The hybrid composite achieved an Ultimate Tensile Strength of 83.83 MPa and a Young's Modulus of 74.12 GPa, compared to 46.87 MPa and 63.12 GPa for the bamboo fiber composite, respectively. Furthermore, the Flexural Strength of the hybrid composite was recorded at 183.22 MPa, substantially higher than the 73.67 MPa observed in the non-hybrid samples. These findings confirm that hybridizing bamboo fibers with glass fibers effectively overcomes the inherent mechanical limitations of natural fibers, yielding a material with superior strength and stiffness suitable for semi-structural applications.

Keywords
Bamboo Fiber, E-Glass Fiber, FRP, Mechanical Characterization, Alkali Treatment, Hand Lay-up Technique.

1. Introduction

In the last few decades, the need for lightweight, high-performance materials has led to a lot of new ideas in the field of material science, especially in the creation of Fiber Reinforced Polymer (FRP) composites. Composite materials are made up of two or more materials that have very different physical or chemical properties. They are stronger and stiffer than regular metallic alloys. These traits have made them necessary in many fields, including aerospace, automotive, and civil construction.

Synthetic fibers like glass, carbon, and aramid have been the most common reinforcements in polymer composites because they are very strong and stable at high temperatures. People use a lot of glass fiber, especially E-glass, because it is cheaper than carbon fiber and has high tensile strength. But the widespread use of synthetic composites has raised environmental concerns about their inability to break down, the high energy used to make them, and the health risks of breathing in fibers. This environmental pressure has changed the focus of research on Natural Fiber Polymer Composites (NFPCs). Jute, sisal, hemp, and bamboo are all examples of natural fibers that can be used again, break down naturally, have a low density, and don't scratch processing equipment. Bamboo is especially important in Bangladesh. It is a plentiful, fast-growing resource with a microfibrillar structure that gives it great specific mechanical properties.

But natural fibers have some problems that make them not very useful for structural applications. They usually have lower tensile strength than synthetic fibers, their properties can change a lot, and they don't work well with hydrophobic polymer matrices because they are hydrophilic. This causes problems like fibers absorbing moisture and weak bonding between the fiber and the matrix. The idea of hybridization is used to get around these problems. Hybrid composites use two or more types of fibers in one matrix. You can change the properties of the material to find a balance between performance, cost, and environmental sustainability by mixing high-strength synthetic fibers (like glass) with low-cost, eco-friendly natural fibers (like bamboo). The synthetic fibers add strength and resistance to moisture, while the natural fibers lower the cost and density of the composite.

This study concentrates on the production and analysis of a hybrid epoxy composite fortified with bamboo and E-glass fibers. We chose epoxy resin as the matrix material because it doesn't shrink much, is very strong, and sticks well to other materials. This study seeks to validate the potential of this hybrid system as a semi-structural material by examining its tensile and flexural behaviors, leveraging local natural resources while ensuring the mechanical reliability necessary for engineering applications.

1.1 Objectives

The primary aim of this thesis is to evaluate the mechanical enhancement of epoxy composites achieved by hybridizing natural bamboo fibers with synthetic glass fibers. This study assesses the viability of utilizing such hybrid composites in structural applications that require optimized strength-to-weight ratios and enhanced stiffness.

- To fabricate a hybrid composite reinforced with chemically treated bamboo fibers and woven E-glass fibers using the hand lay-up technique.
- To experimentally investigate the mechanical behavior of the fabricated composites, specifically focusing on tensile and flexural properties, in accordance with ASTM standards.

2. Literature Review

A composite material system is composed of two or more physically distinct phases whose combination produces aggregate properties that are different from those of its constituents. Composites can be very important because of its strong and stiffness, yet very light in weight, so ratios of strength to weight and stiffness to weight are several times stronger than steel or aluminum and possible to achieve combinations of properties not attainable with metals, ceramics, or polymers alone (Ashik & Sharma, 2015a). In recent years, natural fibers reinforced composites are treated as most promising material in different applications due to its attractive properties.

Natural fibers are now dominating the automotive, construction and sporting industries by its superior mechanical properties. These natural fibers include flax, hemp, jute, sisal, kenaf, coir and many others (Ashik & Sharma, 2015b). The various advantages of natural fibers are low density, low cost, low energy inputs and comparable mechanical properties and better elasticity of polymer composites reinforced with natural fibers, especially when modified with crushed fibers, embroidered and 3-D weaved fibers.

Swain et al. studied the physical and mechanical properties of Al2O3 filled jute fiber reinforced epoxy composites (Swain, 2013). They carried out experiments to identify the effect of filler on properties of composites. Jute and Al2O3 are taken as reinforcement and epoxy as matrix, they have observed that filler makes significant changes on different properties of composites. In addition, they have observed that Hardness, strength, flexural and tensile modulus increased with increase in the fiber and filler and interlaminar shear strength increased only by increasing fiber and decreased in addition of filler on composites.

Alavudeen et al. studied the mechanical properties of woven banana fiber, kenaf fiber and banana/ kenaf hybrid fiber composites. The mechanical strength of woven banana/kenaf fiber hybrid composites increases due to the hybridization of kenaf with banana fibers. Tensile, flexural and impact strengths of the woven hybrid composite of banana/kenaf fibers are superior to those of the individual fibers. Sodium lauryl sulfate (SLS) treatments appear to provide an additional improvement in mechanical strength through enhanced interfacial bonding. Morphological studies of fractured mechanical testing samples were performed by scanning electron microscopy (SEM) to understand the de-bonding of fiber/matrix adhesion (Alavudeen et al., 2015).

M. Ramesh et al. investigated the mechanical properties of sisal, jute and glass fiber reinforced polyester composites. They observed that the addition of glass fiber into jute fiber composite resulted in maximum tensile strength. In the same way they have observed that jute and sisal mixture composites sample is capable having maximum flexural strength and maximum impact strength was obtained for the sisal fiber composite (Ramesh et al., 2013).

The variation of tensile strength, flexural strength and compressive strength of epoxy-based sisal-glass hybrid composites has been studied by H. Ranganna et al. They have observed that 2 cm fiber length hybrid composites showed maximum optimal tensile, flexural and compressive strength than 1 and 3 cm. The effect of alkali treatment on the tensile flexural and compressive properties has also been studied. It is found that treated hybrid composites showed higher strength than untreated composites (Ragunath et al., 2018). Gopinath et al. experimentally studies the mechanical behavior of jute fiber in polyester and epoxy matrices and the results showed that jute-polyester processing time is far less as compared to jute-epoxy laminate (Gopinath et al., 2014).

Gowthami et al. developed sisal natural fiber composites with and without silica by incorporating 100% biodegradable sisal fibers as reinforcement in the polyester matrix. The results showed that the tensile strength and tensile modulus of composites with silica are 1.5 and 1.08 times greater than that of composite without silica respectively. The impact strength of composites with sand is 1.36 and 1.8 times greater than that of composites without silica and plain polyester, respectively (Gowthami et al., 2010).

Amar Patnai et al. studied the three-body abrasive wear and mechanical properties of particulate filled glass epoxy composites. Their work aimed to study on abrasive wear behavior of randomly oriented glass fiber (RGF) reinforced with epoxy resin filled with Al2O3, SiC and pine bark dust. Dry sand/rubber wheel abrasion tests (RWAT) were carried out at 100 rpm test speed. The tests were carried out at 50 and 75 N loads by varying the abrading distance from 200 to 600 m. Experimental results of abrasive wear tests revealed that wear of composite was sensitive to variations of abrading distance and less sensitive to sliding velocity (Patnaik et al., 2010).

Hemalata Jena et al. studied the effect of bamboo fiber composite filled with cenosphere. They have reported that the impact property of bio-fiber reinforced composite is greatly influenced by addition of cenosphere as filler and lamina. For a given laminated composite, the impact strength is increased with addition of filler up to a certain limit and after which it is decreased on further addition. The results reveal the sensitivity of the impact properties to the concentration of the fillers. Increase in lamina from 3 to 7, the impact strength is increased and on further increasing the lamina to 9, the strength is decreased. Among all 7 layers composite with 1.5 wt% of chemosphere has the maximum impact strength of 18.132 KJ/m2. There is also seen that decrease in density of the composites which are also greatly dependent on the content of fillers and fiber (Jena et al., 2012a).

Girisha, C. et al. studied the mechanical properties of composites of chemically treated fibers from husk of recant and fibers from the fruit of tamarind. They observed that treated fibers showed better results when compared to untreated fibers. They also noticed that the strength of the hybrid composites increases with increase in volume fraction of fiber in the hybrid composites. In the investigation, recant fruit husk fibers and tamarind fruit fibers were reinforced with Epoxy matrix and composites have been developed by manual hand layup technique. From the experiment it was found that all the hybrid natural fiber composites shown maximum mechanical properties for 40% - 50% of the fiber reinforcements (*International Journal of Engineering Research and Applications*, 2011).

Singh et al. studies the effect of weight percentage of jute fiber reinforced in polypropylene based composites and found out that mechanical properties enhanced as the jute weight percentage increased up to 40% (Singh et al., 2008). D. dash et al. concluded that the mechanical properties of composites such as tensile strength and compressive strength of natural fiber composite was reported and compared with the data for glass/epoxy composites. It has been seen from tests that bamboo composite laminates have higher tensile strength and stiffness than jute composite laminates, but not at par the glass fibre reinforced composite. Compressive tests show that compressive strength and modulus of jute composite is higher than bamboo composite, but less than glass composite the fibre orientation angle of 0/90, 15/−75, 30/−60, and 45/−45, on tensile behaviour were analyzed and showed that the fiber orientation of 0 provides higher strength and modulus than 45 directions of fiber orientation. The mechanical property also depends upon individual material property. The glass fiber was manufactured artificially in an industrial plant with special tool while the bamboo and jute fiber was available from nature & manufactured by simple tool and/or manually that may result inconsistency during manufacturing of product. Due to this reason the strength of natural fibers does not come up to the level of traditional e-glass fiber. But the natural fiber reinforced composite can be used in places where light load application is important and the economics of natural fiber composite materials is more beneficial as compared to e-glass fiber composites (Dash et al., 2013).

Chaitanyan al. concluded that the composite with 50% sisal-glass fiber and 50% resin combination has maximum tensile strength of 97.71 MPa. The breaking load of sisal-glass fiber reinforced composite is found as high (10.285 KN). It is found that breaking load of sisal-glass fiber reinforced composite is 1.10 times higher than sisal-coir-glass fiber reinforced composite and 1.33 times higher than coir-glass fiber reinforced composite. The percentage elongation of coir-glass fiber reinforced composites is found to be higher than the other composites and hence it may have more ductile property in nature. The hybrid composite with 40% sisal- coir-glass fibers and 60% resin combination has high flexural strength (138.87 MPa) and high impact strength (1.429 KJ/m2) (Chaitanyan, 2015).

Jena et al. studied the mechanical properties of jute/glass reinforced polyester with water absorption condition. Composites are subjected to various water conditions and tests were performed by immersing composite specimens into three different water conditions, distilled water, sea water and acidic water, and water was in room temperature for a period of three weeks and effect of the various water environments on the flexural and compression characteristics were investigated in this study. It found out that the jute composite is not suitable for underwater applications (Jena et al., 2012b).

3. Materials and Methodology

3.1 Description of Materials

Natural Epoxy resin and hardener were used as a binder or matrix material to create bamboo-glass fiber composites along with natural bamboo fiber and woven E-glass fiber for reinforcement. Grease can also be used as a release agent for various tasks. bamboo fiber, woven E-glass fiber as a reinforcing agent, and epoxy resin and hardener were used to create bamboo-glass fiber composites. Grease also has a release agent use. The following materials were used:

- Bamboo Fiber: Natural processed bamboo fiber was used as a reinforcing material. The bamboo was sourced locally from Khulna, Bangladesh.
- Glass Fiber: Glass fiber is also known by the trade name fiberglass, was used as a reinforcing material in a parallel study. The glass fiber was also sourced from local markets. Here is the composition of the glass fiber.

Table 1. Chemical composition of E-glass fiber

Constituent	**Quantity in %**
SiO_2	55.2
Al_2O_3	14.8
B_2O_3	7.3
MgO	3.3
CaO	18.7
K_2O	0.2
Na_2O	0.2
Fe_2O_3	0.2
Fe_2	0.1

- Matrix Materials: Dhaka, Bangladesh's local hardware market supplied the epoxy ly556 and hy951. They were the primary matrix materials for the two composites.
- Grease: Grease was used as a releasing agent.
- Other Materials: Other materials like glue, scissors, blades, polythene, rollers, masking tape, etc were also sourced from local markets.

3.2 Materials Processing

3.2.1 Chemical Treatment

The bamboo fibers were chemically treated with a 5% Sodium Hydroxide (NaOH) solution to improve the composite's mechanical performance. This process is known as mercerization. This treatment changes the way the fibers look on the outside by making them swell and become more porous when they are immersed. This porosity helps textiles take in more dye, but in composite fabrication, it helps the epoxy resin bond better by letting it get deeper into the fiber structure. The treatment also gets rid of waxy and other surface impurities, which clean the fiber surface. This change makes the individual fibers stronger and longer, which makes the reinforcement phase of the hybrid composite last longer (Figure 1).

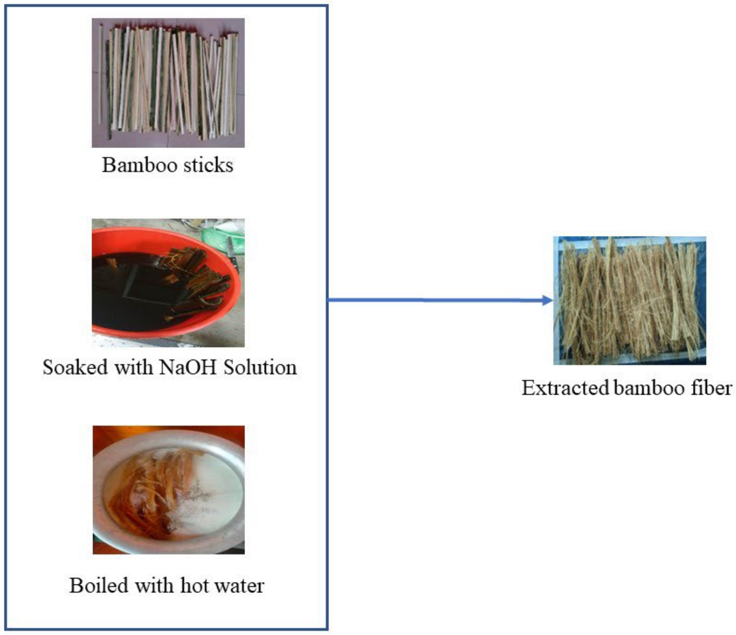

Figure 1. Bamboo fiber extraction process.

3.2.2 Mold Preparation

During Standard composite fabrication often uses complicated aluminum or mild steel frames. However, these systems often need extra clamping mechanisms, which can cause uneven load distribution and limit the bearing capacity. A gravity-based compression method was used to fix these problems and make sure that pressure was spread evenly without the need for external loading systems. The mold was held in place by a flat, mild steel plate that weighed about 100 kg. After the lay-up process, a flat structure with the same weight was put on top of the laminate. This setup effectively sandwiched the fiber and resin matrix between the two rigid plates. The steel's natural weight created a steady, even compressive force during the curing cycle (Figure 2).

Figure 2. Bamboo fiber extraction process.

3.3 Fabrication

The composite laminates were fabricated using the Hand Lay-up technique. This method was selected for its simplicity and suitability for low-volume composite production. The fabrication process was divided into four distinct stages.

3.3.1 Fiber Mat Preparation (Sizing)

Before the lay-up process, the necessary dimensions of the composite laminates were determined to ensure that they would fit the mold. The bamboo and glass fiber reinforcement mats were cut into squares that were 30 cm by 30 cm

(300 mm by 300 mm). Before trimming, masking tape was put along the cutting lines to keep the dimensions accurate and stop the fibers from fraying or coming undone at the edges (Figure 3).

Bamboo Fiber   Bamboo Fiber

Figure 3. Required size of bamboo fiber and glass fiber mat.

3.3.2 Fiber Mat Preparation (Sizing)

Epoxy LY 556 resin and HY 951 hardener were used to make the matrix phase. Before the final fabrication, several tests were done to make sure the mixture was as good as it could be. We looked at different resin-to-hardener weight ratios, such as 2:1, 3:1, and 10:1. The 3:1 ratio was found to give better optical clarity and uniformity than the other options. Because of this, this ratio was used to make all composite samples so that the matrix properties would be the same and it would be easier to see how the fibers were impregnated.

3.3.3 Lay-Up Technique

The first step in the hand lay-up process was to put a clear polyethylene sheet over the mild steel mold base to act as a release interface. Using a hand roller, the base layer of the epoxy resin-hardener mix was evenly spread over this sheet. After that, the pre-cut fiber reinforcement mats were placed on top of the resin layer, and more resin was added. The process can be seen on Figure 4.

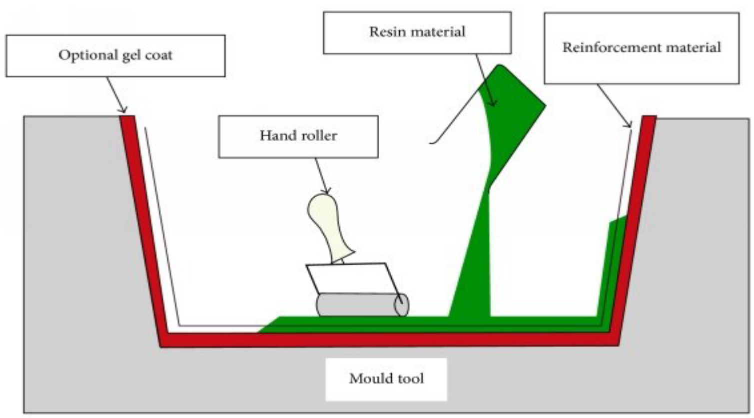

Figure 4. Schematic diagram of the hand lay-up process

A roller was carefully used to soak the fibers, making sure they were completely saturated and that any air pockets that got trapped were removed to avoid dry spots. This stacking process was repeated until the desired laminate thickness was reached. Then, a final sheet of polyethylene was placed over the assembly to seal the composite and reduce porosity during the curing phase. The final products are seen in Figure 5.

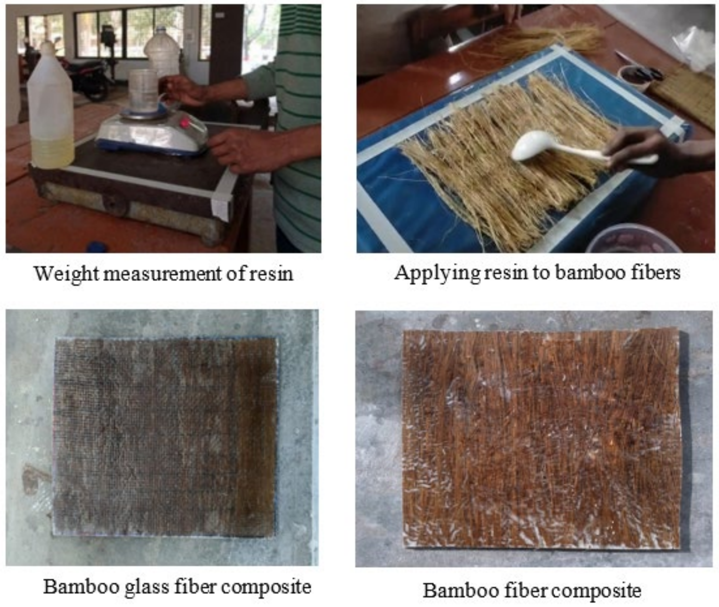

Figure 5. Composite making process.

3.4 Experimental Procedure

All mechanical testing was conducted using a computer-controlled Universal Testing Machine (UTM) (Shimadzu) located at the Department of Mechanical Engineering, KUET. The tests were performed at room temperature to evaluate the tensile and flexural properties of the hybrid composites. The setup for the two test are described in detail below.

3.4.1 Tensile Test

The tensile properties of the composites were evaluated in accordance with the ASTM D3039 standard. We used rectangular samples to find the tensile properties according to the ASTM D3039 standard (Figure 6).

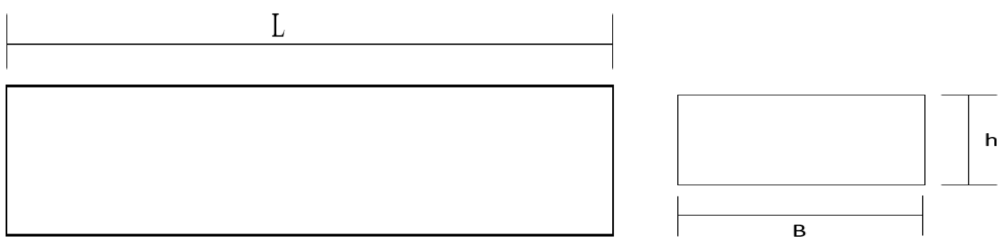

Figure 6. Schematic size of tensile specimen

These specimens underwent uniaxial tensile loading until fracture to determine the ultimate tensile strength and Young's modulus. The size of the specimens is shown in Table 1. below.

During the procedure, each specimen was securely clamped within the jaws of the testing machine and subjected to a continuous axial load until fracture occurred. The breaking load was recorded via the machine's digital interface, and the ultimate tensile strength was calculated using the standard tensile strength formula (Table 2).

Table 2. Tensile test specimen dimensions

Type of Composite	Length L (mm)	Width b (mm)	Thickness h (mm)
Bamboo glass fiber composite	250 ± 0.05	25.10 ± 0.1	6.17 ± 0.02
Bamboo fiber composite	250 ± 0.05	27.15 ± 0.1	7.7 ± 0.2

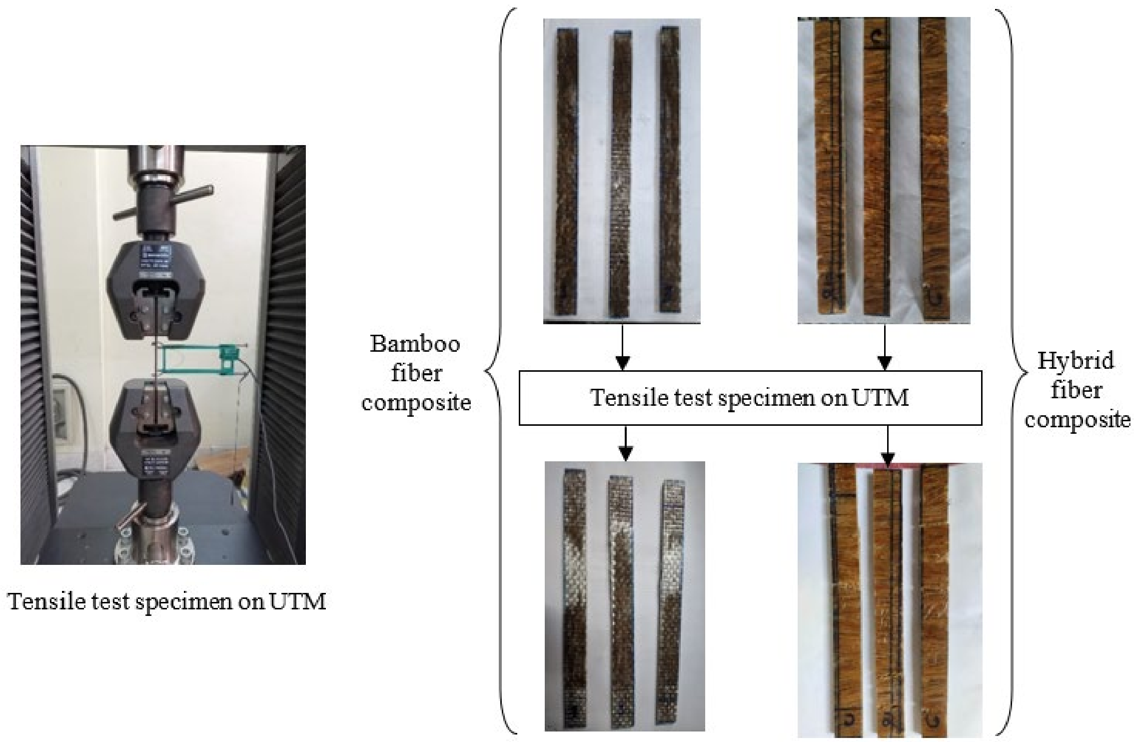

Figure 7. Test of both types of specimens on UTM.

3.4.2 Flexural Test

The ASTM D790 standard was used to test the flexural properties of the hybrid composites by using the three-point bending configuration. This is the standard way for industry to test the bending strength and stiffness of semi-structural composite materials. The load direction is shown in the following Figure 7 and Figure 8.

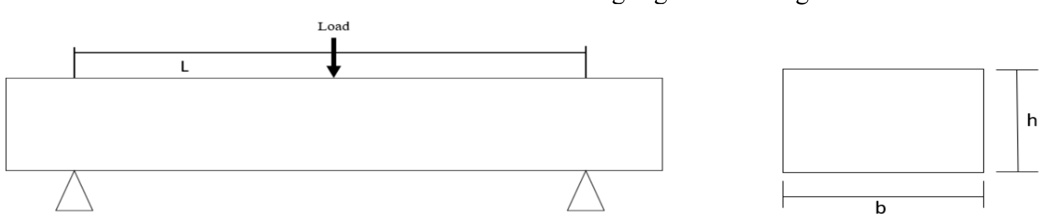

Figure 8. Schematic diagram of Flexural strength test specimen

Three identical rectangular specimens were tested for each type of composite to make sure the results were statistically reliable. The size distribution is shown in the following Table 3.

Table 3. Tensile test specimen dimensions

Type of Composite	Length L (mm)	Width b (mm)	Thickness h (mm)
Bamboo glass fiber composite	96 ± 0.05	13.20 ± 0.15	6.05 ± 0.05
Bamboo fiber composite	128 ± 0.05	27.15 ± 0.1	8.2 ± 0.05

The experimental analysis utilized a Universal Testing Machine (UTM) situated in the Mechanics Laboratory of the Department of Mechanical Engineering at KUET. In this test, the specimen was placed horizontally on two supports, and a compressive load was applied in the middle of the span length until it broke. The machine's crosshead displacement constantly measured how much the specimen bent. The ultimate flexural strength was calculated using the standard flexural stress formula. The after products of the test are shown in Figure 9.

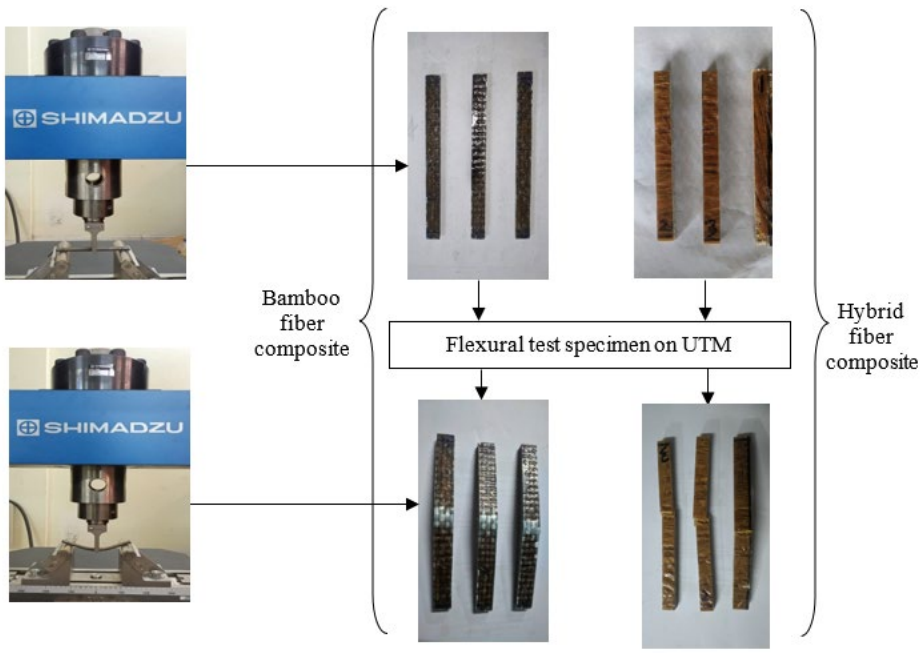

Figure 9. Three-point bending test procedure.

4. Results and Discussion

This chapter evaluates the mechanical performance of the fabricated composites through tensile and flexural testing. A comparative analysis between the Bamboo-Glass hybrid and bamboo-only composites is presented using stress-strain curves and statistical data, demonstrating the improvements in strength and stiffness achieved through hybridization.

4.1 Tensile Test

4.1.1 Tensile Test of Bamboo-Glass fiber composite

The tensile strength, defined as the maximum stress a material can withstand before fracture, was evaluated for three identical hybrid specimens. The recorded ultimate tensile strength (UTS) values were 81.06 MPa, 83.48 MPa, and 86.96 MPa, with Sample 3 exhibiting the highest load-bearing capacity as can be seen in Figure 10.

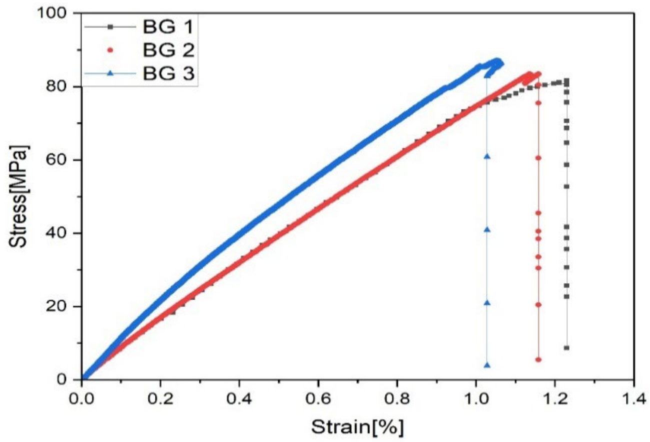

Figure 10. Tensile test stress vs strain curve for Bamboo-Glass fiber composite.

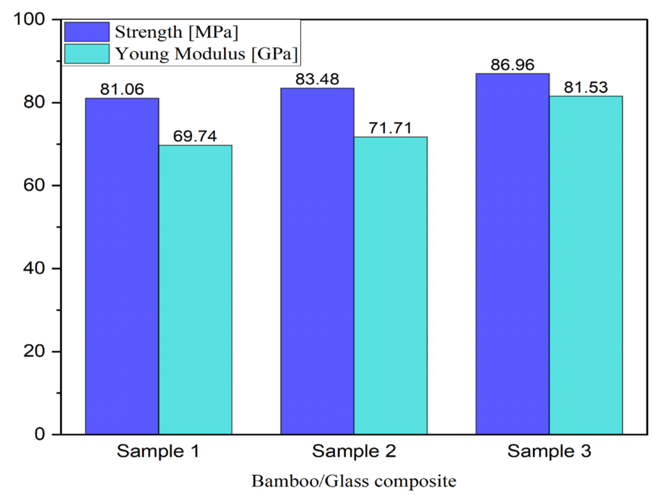

Figure 11. Tensile test value comparison of Bamboo-Glass composite.

From Figure 11 similarly, the stiffness of the material was quantified via Young's modulus. The modulus values ranged from 69.74 GPa to 81.53 GPa, with Sample 3 again demonstrating the highest rigidity. The robust performance of these samples can be attributed to the inclusion of high-strength E-glass fibers, which effectively bridge the mechanical limitations of the natural bamboo matrix. Consequently, while Sample 3 showed the superior individual result, the average of these values provides the most accurate representation of the composite's bulk mechanical properties.

4.1.2 Tensile Test of Bamboo-Glass fiber composite

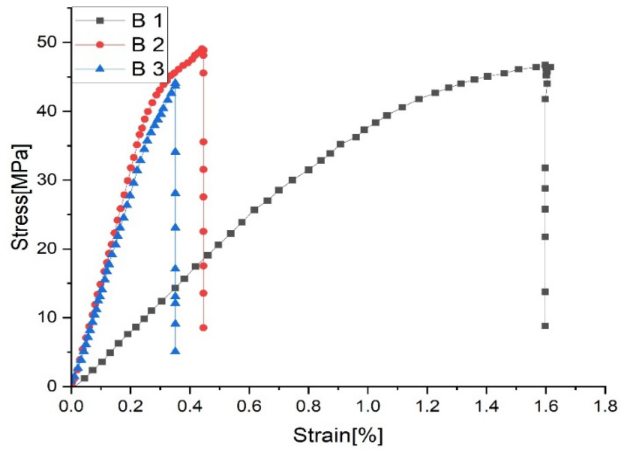

Figure 12. Tensile test stress vs strain curve for Bamboo fiber composite.

The specimens had UTS values between 44.08 MPa and 48.14 MPa. Sample 2 had the highest tensile resistance (48.14 MPa), followed closely by Sample 1 (46.41 MPa). Sample 3 had the lowest strength (44.08 MPa) (Figure 12).

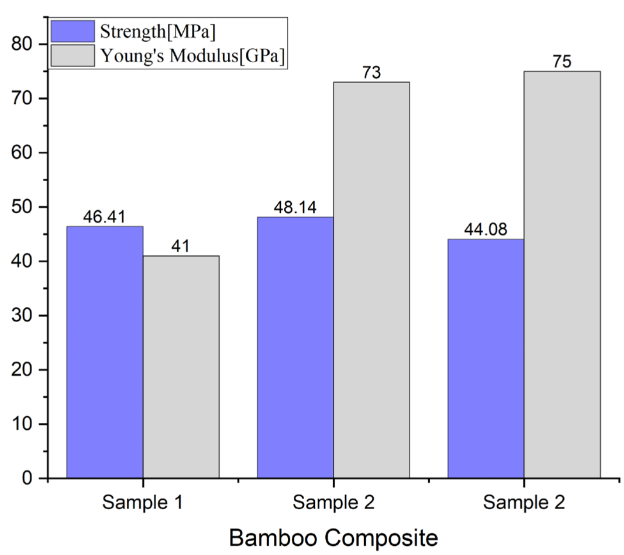

Figure 13. Tensile test value comparison for all 3 Bamboo fiber composite specimens.

As for stiffness analysis, the Young's modulus showed a lot of variation when it came to rigidity. Sample 3 was the stiffest at 75 GPa, and Sample 2 was the second stiffest at 73 GPa. Sample 1, on the other hand, had a much lower modulus of 41 GPa. This difference shows how natural fiber composites are different from synthetic ones (Figure 13).

4.1.3 Comparison graph between Bamboo-Glass composite and Bamboo fiber composite for the Tensile test

Subsequently, comparing the pure Bamboo fiber composite to the Bamboo-Glass hybrid composite, we can see the clear benefits of hybridization on Figure 14.

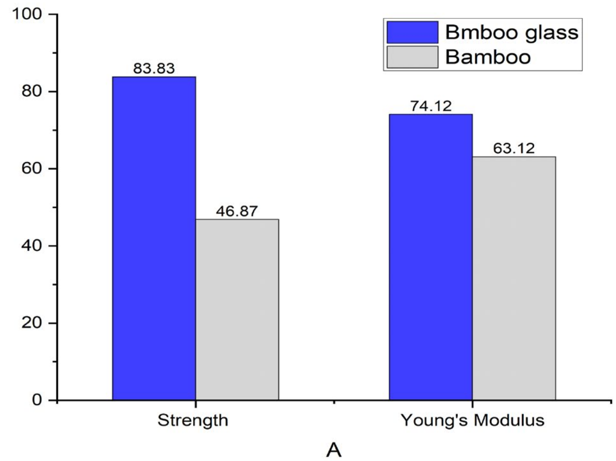

Figure 14. Tensile test value comparison of all composites.

The experimental data show that adding E-glass fibers significantly increases the load-bearing capacity. The average ultimate tensile strength of the Bamboo-Glass hybrid was 83.83 MPa, which is 78.8% higher than the average of 46.87 MPa for the pure Bamboo composite. The synthetic glass fibers have better mechanical properties that stop cracks from spreading and bear most of the tensile load. The bamboo fibers, on the other hand, add bulk and lower the density of the composite (Table 4).

Table 4. Comparison of the Tensile test values of different composites

Composite type	Ultimate Tensile Strength, σ (MPa)	Young Modulus (GPa)
Bamboo-Glass	83.83	74.12
Bamboo	46.87	63.12

Improvement in Stiffness (Young's Modulus): Hybridization also made the material much stiffer. The Young's modulus went up from 63.12 GPa in the bamboo-only samples to 74.12 GPa in the hybrid samples. This means that the samples became about 17.4% more rigid. This means that the hybrid composite is better at resisting elastic deformation when stress is applied, which is very important for the stability of structures.

The results show that bamboo fibers are an eco-friendly way to add strength, but they don't work well on their own. When you mix them with glass fiber, you get a material system that is good for the environment and strong and stiff enough for semi-structural uses in the construction and automotive industries.

The current results using the hand lay-up method are good, but they could be even better if the fiber-matrix interface were optimized. Advanced manufacturing methods like vacuum infusion or filament winding could make fiber dispersion better and lower void content compared to the manual lay-up method used in this study. This could lead to even higher strength and stiffness values.

4.1 Flexural Test

4.1.1 Flexural Test of Bamboo-Glass fiber composite

The results of the three-point bending test show that the Bamboo-Glass hybrid composites can hold more weight than other materials. The samples had ultimate flexural strength values between 172.00 MPa and 191.04 MPa. Sample 2 had the highest flexural resistance at 191.04 MPa, followed closely by Sample 1 at 186.11 MPa. Sample 3 had the lowest strength. These high numbers prove that the hybrid reinforcement strategy works because the outer layers of woven glass fiber can handle the compressive and tensile stresses that happen when bending. The results are shown on Figure 15.

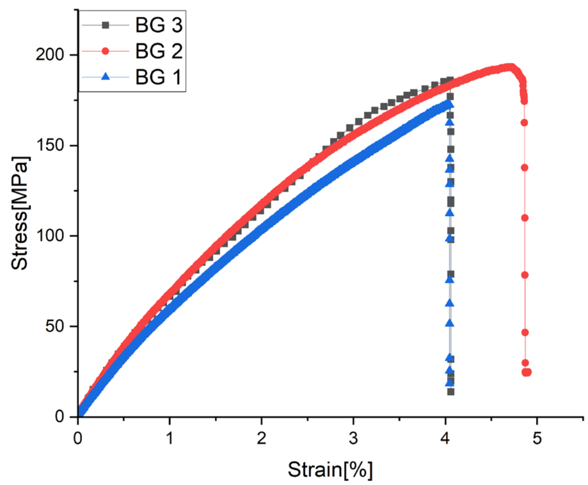

Figure 15. Flexural test stress vs strain curve for Bamboo Glass composite.

The flexural modulus was more variable than the strength when it came to stiffness. Sample 3 was the stiffest, with a modulus of 40.64 GPa. Sample 2 was the next stiffest, with a modulus of 37.16 GPa. Sample 1 had a much lower modulus of 26.44 GPa, which is interesting because it was very strong.

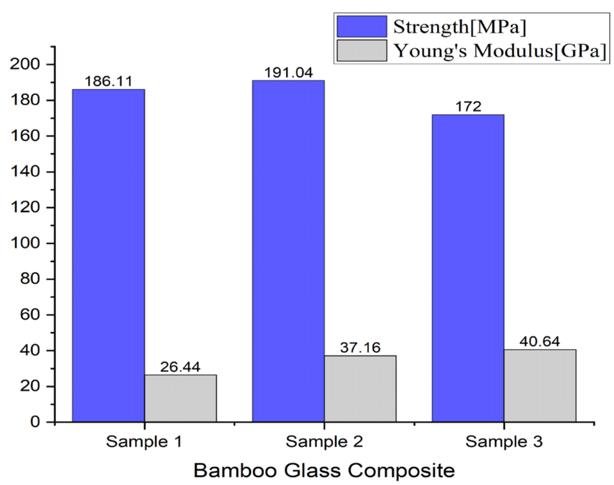

Figure 16. Flexural test value comparison of all 3 Bamboo glass composite specimens.

This anomaly indicates that although the specimen could endure substantial ultimate loads, its resistance to initial elastic deformation was impaired, possibly due to localized variations in the fiber-matrix interface (Figure 16).

4.1.2 Flexural Test of Bamboo Fiber Composite

The flexural performance of the pure bamboo fiber composites as shown in Figure 17. showed a lot of differences between the samples that were tested. Sample 2 had the best mechanical response, with the highest ultimate flexural strength (98.42 MPa) and the highest stiffness (29.29 GPa). This shows that the fibers and the matrix stick together well and that the load is transferred well in this specimen.

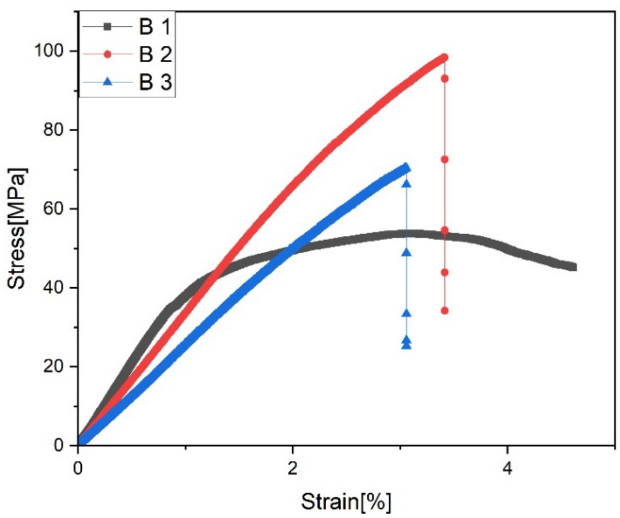

Figure 17. Flexural test stress vs strain curve for Bamboo composite.

Sample 1, on the other hand, had the lowest flexural strength at 53.80 MPa. Sample 3, on the other hand, had a mixed performance with an intermediate strength of 70.40 MPa but the lowest stiffness (23.20 GPa). The fact that Sample 2 is almost 83% stronger than Sample 1 shows how unpredictable natural fiber reinforcements can be (Figure 18).

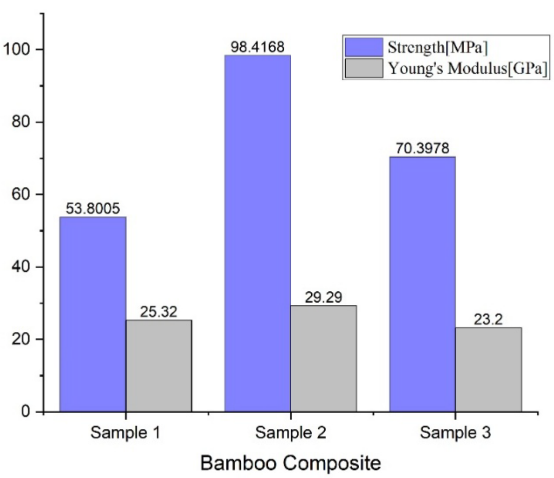

Figure 18. Flexural test value comparison of all 3 Bamboo composite specimens.

4.2.3 Comparison graph between Bamboo-Glass composite and Bamboo fiber composite for the Flexural test

A comparative evaluation of the flexural properties, as shown in Figure 19. indicates that the hybridization of bamboo with glass fibers results in a significant enhancement of structural performance.

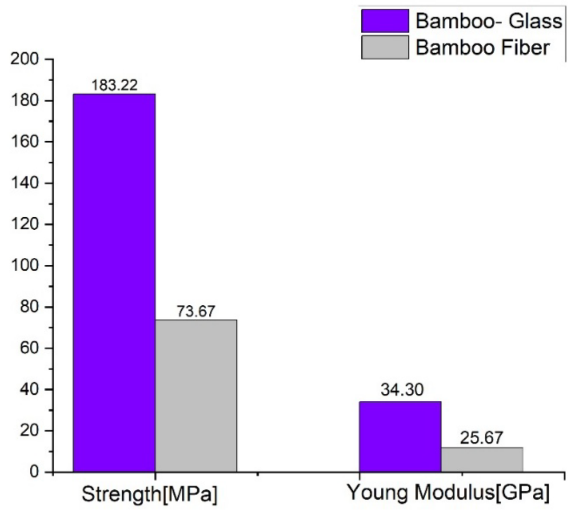

Figure 19. Flexural test value comparison of both composite samples.

The most noticeable change was in the flexural strength. The Bamboo-Glass hybrid composite had an average strength of 183.22 MPa, which is much higher than the 73.67 MPa of the Bamboo fiber composite. This is an amazing 148.7% increase in how much weight it can hold. The placement of the high-strength glass fibers is what made this big improvement possible. When the specimen is bent, the outer surfaces feel the most tensile and compressive stress. The synthetic glass fibers are better at withstanding mechanical stress than bamboo, so they can handle these peak stresses without breaking down right away (Figure 19))

Table 5. Comparison of the flexural test values of different composites

Composite type	Ultimate Flexural Strength (N/mm^2)	Young Modulus (GPa)
Bamboo/ Glass	183.22	34.30
Bamboo	73.67	25.67

As seen in Table 5. The material's stiffness also got better in a measurable way. The flexural modulus went up from 25.67 GPa in the bamboo-only composite to 34.30 GPa in the hybrid composite. This means that the hybrid composite is 33.6% more rigid. This means that the hybrid composite is much less likely to bend or break when it is under bending loads, which is very important for structural parts like beams or panels.

The statistical scatter seen in each group was caused by differences in manufacturing parameters (like curing pressure and manual lay-up consistency) and the fact that the raw materials were not all the same. However, the main reason for the performance difference between the two groups is composition. The hybrid design works because combining low-density bamboo with the high-modulus glass fiber makes it work better. The glass fibers are the main way to strengthen the composite, while the bamboo fibers add bulk and keep costs down without hurting the composite's strength.

5. Conclusion

This research effectively produced and analyzed a hybrid epoxy composite reinforced with chemically modified bamboo fibers and woven E-glass fibers. We tested the mechanical performance of the hybrid composite and compared it to a pure bamboo fiber composite. The following conclusions can be drawn from the tensile and flexural testing results:

- **Successful Hybridization:** The hand lay-up method, which used a 3:1 resin-to-hardener ratio and bamboo fibers treated with 5% NaOH, worked well to make hybrid laminates that had no deficiencies. Adding glass fibers made the natural fiber composite's mechanical profile much better.

- **Tensile Performance:** The Bamboo-Glass hybrid composite had better tensile properties than the bamboo composite made from just one material. The ultimate tensile strength went up by about 78.8%, from 46.87 MPa (Bamboo) to 83.83 MPa (Hybrid). The stiffness (Young's Modulus) also got better, going from 63.12 GPa to 74.12 GPa. This means that the glass fibers can handle the main tensile loads, making up for the fact that the natural fibers are not as strong.

- **Flexural Performance:** The change in flexural properties was even more noticeable. The hybrid composite had a flexural strength of 183.22 MPa, which is a huge 148% more than the bamboo composite (73.67 MPa). The flexural stiffness also went up by 33.6%, from 25.67 GPa to 34.30 GPa. This means that the hybrid composite is very good for uses that need high bending resistance.

- **Overall Viability:** The study shows that mixing natural bamboo fibers with synthetic glass fibers is a good way to make semi-structural materials. The hybrid composite keeps the eco-friendly benefits of bamboo while also being as strong and stiff as regular engineering materials. This makes it good for use in the construction, automotive, and housing industries.

6. Future Work

Based on the findings and limitations of this study, several avenues for further research are proposed to optimize the performance and applicability of Bamboo-Glass hybrid composites.

- **Optimization of Fiber Architecture:** Future studies should investigate the effect of varying fiber orientations and stacking sequences on the mechanical anisotropy of the composite. Additionally, optimizing the weight fraction ratio between bamboo and glass fibers could identify the ideal balance between cost reduction and mechanical reinforcement.

- **Expanded Mechanical Characterization:** To fully validate the material for structural use, the testing regime should be expanded to include Impact Testing (Izod/Charpy) to assess energy absorption, Compression Testing, and Hardness Testing. These properties were outside the scope of the current study but are critical for engineering applications.

- **Cost-Benefit and Life Cycle Analysis:** A comprehensive cost-benefit analysis should be conducted to quantify the economic advantages of this hybrid composite over traditional materials. Furthermore, a Life Cycle Assessment (LCA) is recommended to verify the environmental impact and sustainability credentials of the material.

- **Finite Element Analysis (FEA):** Computational modeling using software such as ANSYS or Abaqus could be employed to simulate the mechanical behavior of the composite. Validating experimental results with numerical models would provide deeper insights into the failure mechanisms at the fiber-matrix interface.

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Nurul Hasnat is a graduate of the Department of Mechanical Engineering at Khulna University of Engineering & Technology (KUET), Bangladesh. During his undergraduate studies, he gained research experience in composite laminate fabrication, finite-element and representative volume element (RVE) analysis of composite structures, and exploratory work on geopolymer-based cementitious materials. He was a former member of a Formula Student recognized team, overseeing aerodynamic package development and fiber reinforced vehicle body construction, and also worked as an Administrative Assistant for an engineering journal, supporting editorial and review workflows. His current research interests include composite materials, solid mechanics, and the development and characterization of advanced structural and cementitious materials.

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