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Original Article

Investigation of Flexural Properties of Jute Fibre Reinforced Hybrid Composite Material for Axial Flow Fan Blades

Venkata Sushma Chinta[1], Nagini Yarramsetty[2], Kiran Kumar Amireddy[3], Ashutosh Sahu[4], P. Kiran Kumar[5], K.N.V. Sreedevi[6]

[1, 2, 3, 4, 5, 6]*Department of Mechanical Engineering, Chaitanya Bharathi Institute of Technology (A), Telangana, India.*

[1]*Corresponding Author : venkatasushmachinta_mech@cbit.ac.in*

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Abstract *- Axial Flow Fans (AFF) often supply the airflow needed for mass and heat transfer in industrial applications. Glass-fibre Reinforced Polymer Composites (GFRC) are the most common material used to make these fan blades. Composites are increasingly being made using glass fibers. However, non-biodegradable composite reinforcement poses serious risks to human health and the environment, especially at the end of its useful life. Recycling glass fiber is costly and not justified. However, because of their sustainability and practicality, researchers and academics highly value natural fibers like jute and fibers derived from vegetable plants. They are, hence, appropriate for polymer composites. To improve the biodegradability of GFRC beyond their service life, it is vital to determine the extent to which natural fibers may be included without significantly changing their mechanical properties. This study provides a thorough analysis of composite fan blades used in AFF. AFF combine glass fiber and partially woven jute (WJ) reinforcing material inside an epoxy matrix. Six hybrid composites were used in this study. Material* A_1 *was made of glass fibre-reinforced epoxy. Materials* A_2 *to* A_6 *were prepared by replacing one layer of* A_1 *with woven jute and changing its location in* A_1*. All materials are tested for flexural modulus and flexure strength as per ASTM D-790. The conventional fan blade material (*A_1*) exhibited a flexural modulus of 19.7 GPa and a corresponding flexural strength of 347.1 MPa in flexural tests. Exploring variations in the position of woven jute in composite (*A_2 *to* A_6*) revealed noteworthy findings.* A_5*, featuring woven jute in the 8*th *position, demonstrated a remarkable flexural modulus of 19.5 GPa, representing 99.3% of* A_1*, highlighting the significant influence of the jute layer's position. Flexural strength analysis emphasized the superiority of* A_5*, exhibiting a strength of 345.2 MPa (99.4% of* A_1*), marking a 25% increase compared to* A_2*. Classical Lamination Theory (CLT) and ANSYS finite element software assessed flexural modulus and stress, respectively, showing commendable agreement with experimental values. This study recommends replacing GFRC composite with woven jute in the 8*th *layer (*A_5*), maintaining comparable flexural properties while enhancing biodegradability. The findings contribute to advancing sustainable composite materials with potential applications in AFF industries.*

Keywords *- Axial flow fan blade, Glass fibre- Woven Jute Reinforced Epoxy, Flexural Strength, Flexure modulus, Layup sequence.*

1. Introduction

Axial flow fans are pivotal in facilitating heat transfer and mass transfer in various industrial sectors. Typically, these fans incorporate blades made of Glass-Fibre-Reinforced Polymers (GFRP), a widely adopted material [1]. The utilization of glass fibers in composites is steadily increasing, with the global market projected to reach an estimated value of 42 billion pounds by 2035. Despite their widespread use, the non-biodegradable nature of composite reinforcements raises serious risks to human health and the environment, especially when their service life is ending. Traditionally, the disposal of glass-fibre reinforced plastics has been approached without due consideration for environmental impact, with recycling proving to be an expensive and impractical solution [2-4]. On the contrary, there is a rising inclination towards incorporating bio-based polymer matrices, bio-based fillers, and natural fibres into composite materials, marking a current trend in the industry. Natural Fiber-Reinforced Composites (NFRC) are gaining substantial interest across several applications [6]. These composites, characterized by their reduced weight, cost-effectiveness, renewable sourcing, acceptable specific properties, processing versatility, abundance, minimal health risks, and biodegradability, are becoming increasingly preferable to their synthetic counterparts [6-7]. Prominent players in the industry, including Audi Group, BMW, Daimler Chrysler, Ford, Mercedes-Benz, Opel, Volkswagen, and Proton Business, among others, are actively incorporating natural fiber-reinforced polymer composites into their products. Beyond the automotive sector, these NFRCs find applications in building, construction, aircraft manufacturing, packaging, sports, and various other industries.

The study conducted by Malkapuram et al. [8] examines the hybrid composites intended for automotive applications, incorporating hemp and short carbon fibres. The composites demonstrated enhancements in density, water absorption, tensile strength, and flexural strength, suggesting their capability to replace synthetic fibres while promoting sustainability and reducing carbon emissions. Natural fibers like jute are gaining prominence in academic and research circles due to their sustainable characteristics. Recognizing the environmental challenges posed by traditional materials, researchers are exploring jute-based polymer composites as an eco-friendly alternative. This transition toward sustainable techniques corresponds with global environmental aims and answers concerns about the disposal of non-biodegradable waste. The absorption of moisture from the surrounding environment presents a challenge in the utilization of natural fibres, leading to weak bonding between the polymer and the fiber [11-12]. This challenge is attributed to the distinct chemical structures of both the matrix and fibre [13].

The bond between the fibre and matrix significantly influences the performance of polymeric composites [14]. To mitigate this problem, it is crucial to treat the natural fibres with chemicals. Consequently, modifications to fibres are essential for minimizing moisture absorption and enhancing the bonding between matrix and natural fibres [15-16]. Numerous researches explored the mechanical characteristics of hybrid composites reinforced with natural and synthetic fibres. Abd El-baky et al. [17] investigated the impact of the layup sequence on the mechanical characteristics of NFRC.

In flexural impact tests, the hybrid composite featuring a flax fibre core and glass fibre skin exhibited demonstrated superior performance compared to the counterpart with a flax fiber skin and glass fiber core. In Subagia et al.'s [18] study, it was discovered that [$C_3B_4C_3$], featuring a basalt fiber core, exhibited a flexural strength 13% higher than that of [$B_2C_6B_2$], where carbon fibers constituted the core. In a study by Sanjay et al. [19], the results revealed that placing kenaf and E-glass fibres in the outer layers and jute fibers in the core led to optimal improvements in flexural performance. Ahmed et al. [20] study revealed that, among the examined composites, both [$G_2J_2G_2$] and [$G_3J_4G_3$] exhibited identical flexural strength.

The former comprised four glass layers and six jute layers, while the latter had six glass layers and four jute layers. Despite the additional glass layers in the latter, it demonstrated an equivalent flexural strength to the former. This observation indicates that the inclusion does not affect the flexural characteristics due to low strength and low stiffness layers at the core. Selver et al. [21] studied two jute/glass hybrid laminates: one with the glass layers as the skin and jute layers forming the core and vice versa. The study revealed a 50% increase in flexural strength when jute fiber layers were positioned in the core of the laminate than at the skin. This implies that incorporating high-flexural stiffness fibers on the composite's outer layers could potentially result in greater flexural strength. Das et al. [22] analysed the flexural strength of [GJGJG], [GJG], and [JGJGJ] hybrid composites, finding that [GJG] had 91% higher flexural strength compared to [JGJGJ]. This highlights the significant influence of the arrangement of low-strength layers and high-strength on a hybrid composite's flexural performance. Research suggests that for optimal flexural strength, glass fibers should be positioned in the layers of skin, with jute fibers placed at the core.

Andoh et al. [23] examined the process of fabricating and testing wind turbine blades that utilize bamboo fibre reinforced with recycled HDPE plastic. It presents a sustainable and cost-effective alternative for wind energy generation in Ghana. The bamboo-plastic composite blade achieved a reduction in energy costs to 0.016 GHC/kWh, in contrast to the 0.018 GHC/kWh associated with conventional blades. Conventional blades exhibited marginally superior strength and an extended lifespan; however, the bamboo composite presented a substantial cost advantage, being 13 times less expensive.

It is evident that natural fibres are used in making turbine blades; this study makes a substantial contribution to the field of composite materials by addressing an important gap and introducing a novel approach to enhance the sustainability of axial flow fan blades. To enhance the sustainability of the blade material, an AFF blade reinforced with a single layer of woven jute was selected. By systematically varying the position of the woven jute layer, the impact on the flexural characteristics of the blade material was found. This endeavor not only preserves flexural strength but also enhances biodegradability post-service life, marking a significant stride towards sustainable composite materials.

2. Materials

The standard fan blade sizes are 8', 12', 18', 24', and 26'. Thus, the research considers the median size, which is 18 feet. The resin and hardener used are the same regardless of the fan's size, i.e., EP306 and EH-758. The number of fibre layers in a blade varies according to the fan blade size. According to the product line-up of the high-flow fans company, the 18' fan blade incorporates 14 layers of different glass fibre varieties. These encompass Woven Roving Mat (WRM) weighing 360 GSM, Glass Roving Mat (GRM) with a weight of 280 GSM, Chopped Strand Mat (CSM) of 450 GSM and a Unidirectional Fibre Mat (UDM) of 1200 GSM.

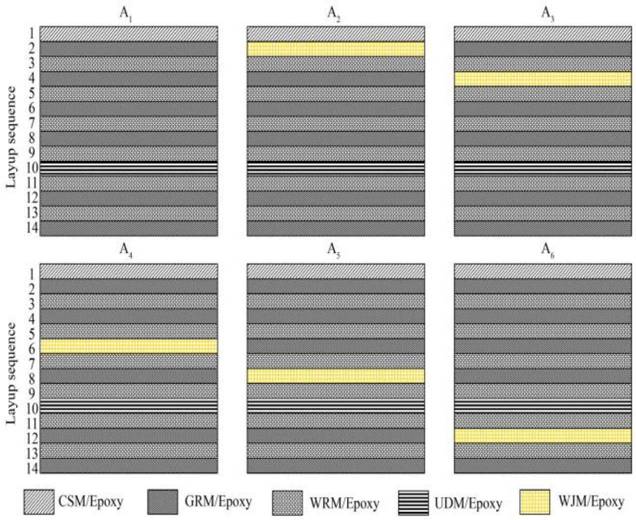

Fig. 1 Configuration order of GFRC blade incorporating woven jute reinforcements [CSM/ (GRM/WRM)$_4$/UDM/(WRM/GRM)$_2$]

The layup sequence for an 18' fan blade, denoted as A_1 and illustrated in Figure 1, comprises one layer of CSM, six layers of WRM, six layers of GRM, and one layer of UDM. Notably, GRM has the same weight as woven jute mats. Consequently, it was proposed to substitute GRM with woven jute at 2, 4, 6, 8, and 12 locations in the GFRP structure. However, the 14th layer, serving as the external layer prone to moisture absorption, should not be replaced with Woven Jute Mat (WJM). To conduct flexural tests, a total of 6 scenarios were examined. The GFRC fan blade material is designated as A_1, and by substituting one layer of GRM at various positions within the GFRC structure, cases A_2 to A_6 were examined, as depicted in Figure 1.

3. Woven Jute Surface Treatment

India holds the position of the 2nd largest exporter of jute products globally, following Bangladesh. The primary contributor to India's jute production is West Bengal, accounting for 69.8% of the total jute acreage. Often referred to as "golden silk" in India, jute stands out for its exceptional mechanical properties among natural fibers. Jute fibers typically consist of 61 to 72 percent cellulose, 13 to 19 percent hemicellulose, 13 to 14 percent lignin, and 0.45 percent wax. To enhance the adherence of jute to the matrix and mitigate its tendency to absorb moisture, surface treatments are employed on WJM with a 5% NaOH solution [13]. In this process, WJ fabric undergoes soaking in a 5% NaOH solution for 4 hours at 28°C. Subsequently, the WJ is thoroughly rinsed with distilled H_2O until reaching a final pH of 7. The treated fabric is then subjected to oven drying for six hours at 100°C after resting at room temperature for 48 hours.

4. Fabrication

The manufacturing process involved the utilization of a hand layup technique for crafting composite laminates. Following the configuration depicted in Figure 1, fiber layers were systematically applied for each composite. Layer by layer, fibers were positioned on the mold, and on each layer, resin impregnation took place. This impregnation process, facilitated by rollers or brushes, was crucial for effectively infusing the resin into the fabric. Subsequently, the laminates underwent curing under atmospheric conditions.

4.1. Estimation of Weight of the Fibre and Resin for GFRC (A_1)

The fibre volume fraction was taken as 55%, while the matrix volume fraction was taken as 45%. The rule of mixtures was used to compute the weights of each component.

$$(1/\rho) = (wf_g/\rho_g)+(wf_m/\rho_m) \tag{1}$$

$$vf_g = (\rho_c/\rho_g)^* wf_g \tag{2}$$

The composite density is calculated using Equation 1, while the volume fraction of fibre is determined using Equation 2. By solving these equations, the weight fraction of glass fibre in A_1 is found to be wf_g= 0.73, and the weight fraction of matrix is wf_m=0.27. The weight of the glass fibres (w_g) used in fabrication is found to be 525g. The total weight of composite A_1 is calculated to be w_c = 720 g, while the resin weight is estimated at 195 g. To account for potential oozing losses, an additional 50% resin was used.

4.2. Estimation of the Weight of the Fibre and Resin for Woven Jute-Reinforced Composites (A_2 -A_6)

The fiber volume fraction was chosen to be 0.55, meaning that,

$$vf_g + vf_j = 0.55 \tag{3}$$

The volume fraction of jute fiber is related to its weight fraction as:

$$vf_j = (\rho_c/\rho_j)^* wf_j \tag{4}$$

By solving equations (2), (3), and (4), the ratio of the weight fractions of glass fiber to jute fiber is determined to be 20.

The density of the hybrid composite is

$$(1/\rho_c) = (wf_g/\rho_g)+ (wf_j/\rho_j) + (wf_m/\rho_m) \tag{5}$$

The volume fraction of the matrix and fiber is related to its weight fraction as:

$$vf_m = (\rho_c/\rho_m)^* wf_m \tag{6}$$

By solving equations (5) and (6), the weight fraction of glass fibre is found to be wf_g = 0.69, the weight fraction of jute fibre is wf_j = 0.0345, and the weight fraction of matrix is wf_m = 0.2755. The total weight of the composite is calculated to be

w_c = 725 g, while the weight of the resin is estimated at 200 g. To account for oozing losses, an additional 50% resin was used.

4.3. Estimation of Density by Experiment

The density of the composite materials was determined in accordance with the ASTM D792-13 standard [25] using a pycnometer, a specialized device for measuring specific gravity. Figure 2 illustrates the A_1 coupons, which were cut from the respective composite plates for specific gravity measurement.

$$\text{Specific gravity (S)} = (w_4-w_1)/\ (w_2-(w_4-w_1)) \qquad (7)$$

The experimental density of A_1 was found using Equation 9 as 1.88 g/cc, while the experimental density of materials A_2 to A_6 was found to be 1.76 g/cc. The Theoretical density of GFRC (A_1), calculated using Equation (1), is 1.91 g/cc, and for the WJRC A_2 to A_6, the theoretical density was found to be 1.87 g/cc using Equation (7). The void fractions of the materials were then estimated by using Equation (8), with A_1 having a void fraction of 1.9 % and A_2 to A_6 having a void fraction of 6%.

$$v_v = (\rho_{et} - \rho_{ct})/\ \rho_{ct} \qquad (8)$$

Fig. 2 Specific gravity estimation of specimens (A_1) using the pycnometer

5. Flexure Test

The ASTM D 790 standard was followed in the execution of the flexural test [26-28]. The specimens were prepared by cutting laminates to dimensions of 108 x 13 x 5.56 mm^3. The span length was taken as 90 mm. The flexural test was conducted using the Nano UTM at CBIT in Hyderabad, with a 25 kN load cell with a crosshead speed of 2 mm/min. The specimens were positioned in three-point bending test fixtures, adhering to an L/B ratio of 16:1, as depicted in Figure. 3. The flexural modulus was measured by computing the slope of the beginning segment of the load-deflection curve.

$$\text{Flexural modulus } E_b = (mL^2)/(4wt^3) \qquad (9)$$

Where m represents the slope of the load-deflection curve. The flexural stress is expressed as:

$$\sigma_f = \ (3P_mL)/(2wt^2) \qquad (10)$$

In this context, P_m represents the failure load, and L represents the span in mm, while t and w refer to the thickness and width of the specimen in mm, respectively. Each stacking sequence underwent examination with five specimens, and the results were averaged.

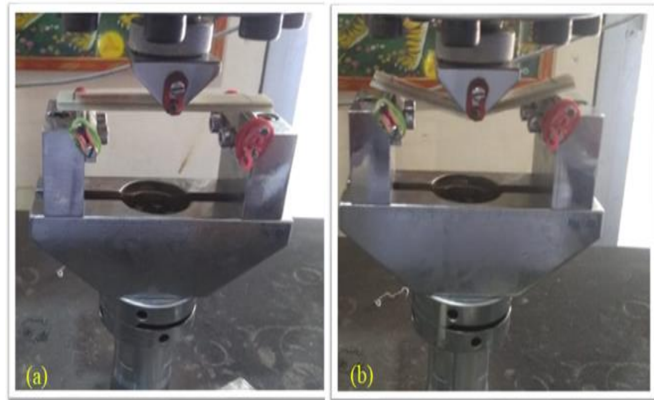

Fig. 3 A_5 specimen on 3-point flexural set-up a) before loading and b) after loading

5.1. Flexural Modulus from Experiment

Figure 4 illustrates load-deflection curves for various hybrid laminates, specifically A_1 and A_5, when subjected to flexure test. The curves demonstrate non-linear characteristics, with the departure from linearity signifying the initiation of failure attributed to crack development on the tension side. The parameter m is obtained from the load-deflection graphs, and the flexural modulus is calculated using Equation (9). In Figure 5, a comparison is presented regarding the flexural modulus of laminates with different stacking sequences. Within the spectrum of composites, A_1 representing the conventional blade material, boasts the highest flexural modulus at 19.62 GPa. Notably, among single-layer WJRC A_5, where the woven jute is placed in the 8th layer of the blade material -exhibits the highest flexural modulus at 19.49 GPa, representing 99.3% of that of A_1. An intriguing observation is the trend of the flexural modulus, which increases from A_2 to A_5 and subsequently decreases from A_5 to A_6.

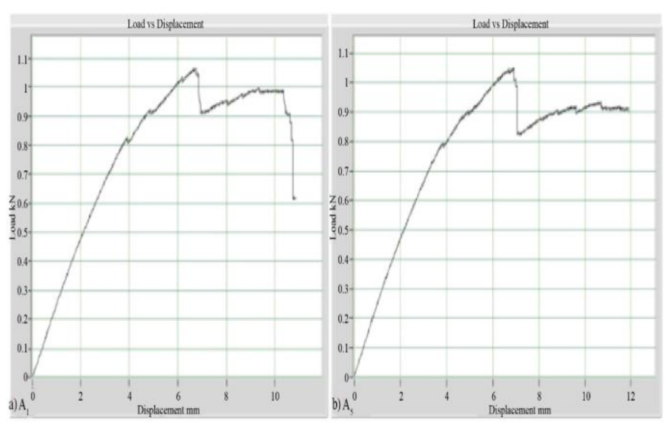

Fig. 4 Load Vs deflection of a) A_1 specimen and b) A_5 specimen

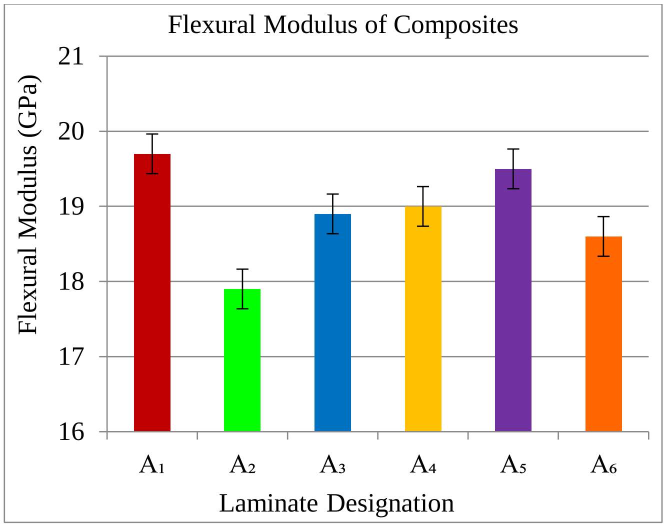

Fig. 5 Flexural modulus of laminates

5.2. Estimation of Flexure Modulus by CLT

As per Equation (11), it is established that the effective flexural modulus is inversely proportional to the flexural stiffness factor D'_{11}. The effective flexural modulus of A_1 is found as 20615 MPa and for A_5 as 20609 MPa.

Figure 6 illustrates the D'_{11} values of laminates. The D'_{11} is the least for A_1, so it has the highest effective flexural modulus among all the composites. For A_2 to A_5, the D'_{11} decreases, so the flexural modulus increases, and $_{it}$ increases from A_5 to A_6, so the flexural modulus decreases.

The effective flexural modulus is,

$$E_{fx} = 12/(D'_{11}\, t^3) \tag{11}$$

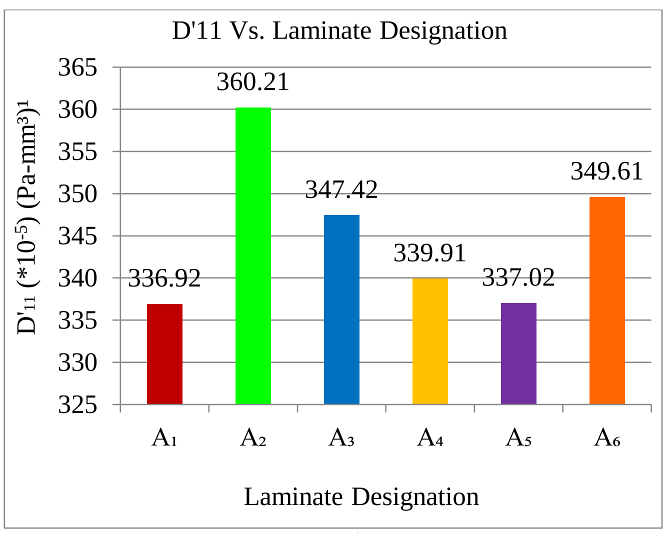

Fig. 6 Variation of D'_{11} for laminates

Figure 7 illustrates the flexural modulus derived through CLT in comparison to the flexural test results. The CLT outcomes, while generally satisfactory, tend to be slightly elevated when contrasted with the experimental values across all laminates. This discrepancy is expected and can be attributed to various factors. CLT model presupposes an excellent bond between fibers and the matrix, which, in reality, may not be as robust.

The inherent weakness in bonding between natural fibers and epoxy can lead to certain fabric disorientation during layups. Additionally, manufacturing factors such as the presence of voids in composite samples significantly influence mechanical test outcomes, thereby impacting modeling results. Despite these factors, the flexural modulus values obtained from both the CLT and experiment exhibit good agreement, with a minimum variation of 4.85% for A_1 and a maximum variation of 7.49% for A_4.

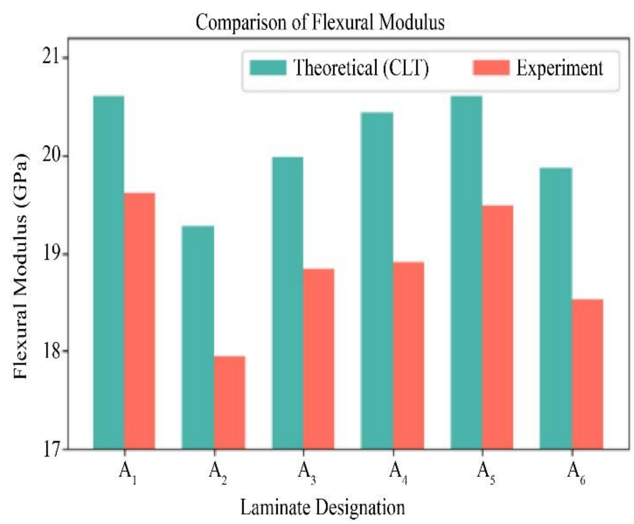

Fig. 7 Comparison of Flexural modulus

5.3. Flexural Strength from Experiment

In Figure 8, the flexural strength of laminates derived from flexural tests is presented. Among all the tested composites, A_1 exhibits the greatest flexural strength at 347.1 MPa. In the group of WJRC, A_5 showcases the maximum flexural strength at 345.1 MPa, which is equivalent to 99.4% of A_1. This outcome is attributed to the distribution of flexural stresses, which start at zero at the neutral axis and increase toward the outer layers. The neutral axis in the composite being analyzed is positioned between the 8th and 9th layers. As a result, upon loading A_5, the flexural stresses experienced by the woven jute in the 8th layer remain comparatively low. Therefore, A_5 exhibits the highest flexural strength among the WJRC.

In contrast, A_2 shows the lowest flexural strength at 259.1 MPa. In contrast, A_2 registers the lowest flexural strength at 259.1 MPa. Remarkably, A_5 displays a 25% higher flexural strength than A_2, emphasizing the critical role of the woven jute's placement in the blade material in achieving flexural strength comparable to A_1.

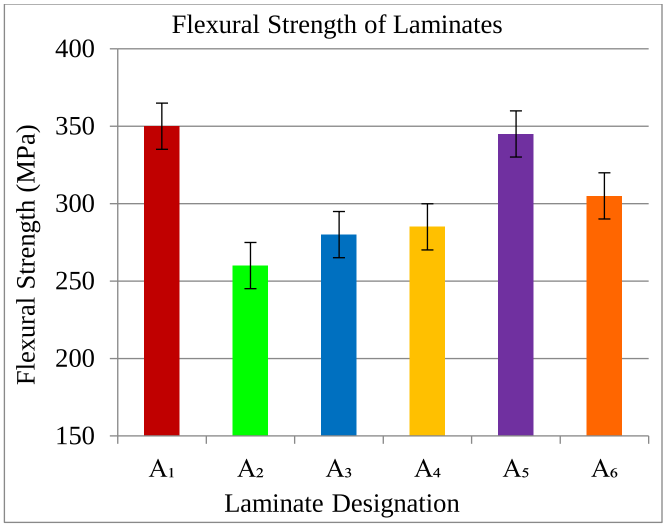

Fig. 8 Flexural strength of laminates

5.4. Flexural stresses from ANSYS

The flexural stress was calculated utilizing ANSYS, with the maximum load derived from the flexural test applied in the analysis.

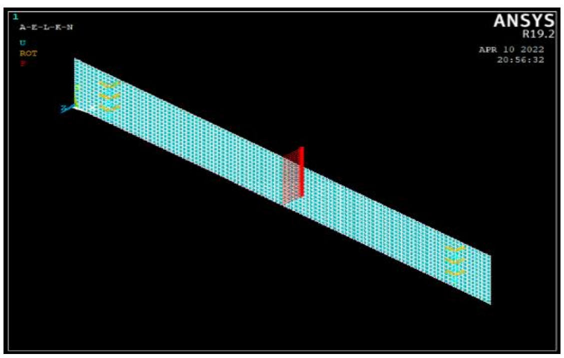

Fig. 9 Boundary conditions applied to flexural specimens

Flexural specimen analysis employed Shell 281 elements, chosen specifically for the task. A total of 1404 elements are formed, and 4455 nodes are formed. To represent supports at span Ux, Uy, Uz, Rotx, and Rotz are constrained, as shown in Figure 9. The maximum load obtained from the flexural test is applied at the center of the specimen. The maximum flexural stress developed in the laminate is evaluated by activating SMISC 37 in the element table. Figure 10 shows the flexure stresses developed in laminates. Table1 demonstrates that the experimental values and those obtained from ANSYS are in close agreement, with a deviation limited to 1.53%. Among all single-layer woven jute-reinforced specimens, A_5 has the highest flexure strength, and the deviation between experimental values and ANSYS value is 0.74%. Finite element analysis is very useful in estimating flexural stress developed in composites. The ANSYS was effectively utilized to ascertain the equivalent stress that the material undergoes when subjected to the maximum load from the flexural test applied to the specimen.

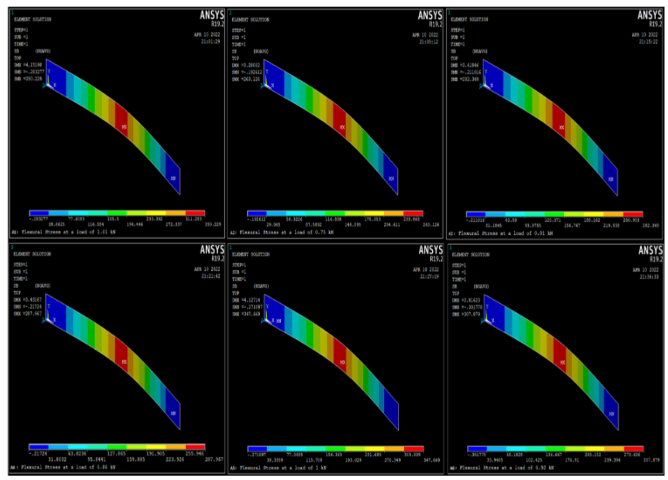

Fig. 10 Flexure stresses from ANSYS

Table 1. Flexure strength and Flexure modulus

	Average load (kN)	Experiment Flexural modulus (GPa)	Flexural Modulus (MPa) from CLT	% Deviation	Experiment with Flexural strength (MPa) from	Flexural stress (MPa) from ANSYS	% Deviation
A_1	1.01	19.62 ± 0.15	20.615	4.85	347.1 ± 11.9	350.23	0.89
A_2	0.75	17.94 ± 0.23	19.282	6.98	259.1 ± 1.01	263.13	1.53
A_3	0.81	18.84 ± 0.26	19.991	5.79	278.7 ± 5.86	282.35	1.29
A_4	0.86	18.91 ± 0.32	20.433	7.49	285.5 ± 8.14	287.97	0.85
A_5	1	19.49 ± .28	20.609	5.47	345.1 ± 10.6	347.67	0.74
A_6	0.92	18.52 ± 0.18	19.866	6.8	305.9 ± 7.06	307.88	0.64

6. Conclusion

An axial flow fan blade, measuring 18 ft, fabricated from a material partially reinforced with woven jute, underwent successful assessment for flexural properties.

- The flexural test revealed a flexural modulus of 19.62 GPa for the traditional fan blade material (A_1), with a corresponding flexural strength of 347.1 MPa.
- The flexural properties of single-layer WJRF (A_1 to A_6) were examined. Notably, A_5, where woven jute is positioned in the 8th layer, exhibited the greatest flexural modulus of 19.49 GPa. A_5's flexural modulus represents 99.3% of A_1's value. In contrast, A_2 displayed the lowest flexural modulus at 17.94 GPa. This observation underscores the impact of the placement of woven jute in

the GFRC on flexural modulus, with A_5 demonstrating an 8.5% higher flexural modulus than A_2.

- A_1 boasts the highest flexural modulus at 347.1 MPa. Conversely, A_5 exhibits a flexural strength of 345.1 MPa, representing 99.4% of A_1's strength. In contrast, A_2 records the lowest flexural strength at 259.1 MPa. Notably, by situating the jute layer in the 8th position within the blade material, the stress-bearing capacity of A_5 increases by 25% compared to A_2. This emphasizes the substantial influence of the jute layer's location on the flexural properties.

- The flexural modulus of A_1 to A_6 was determined using CLT. A notable concordance is observed between the experimental and CLT flexural modulus values, with a maximum variation of 7.49% for A_4 and a minimum variation of 4.85% for A_1.

- Moreover, the flexural stress experienced by A_1 to A_6 was assessed using ANSYS. Remarkably, the flexural stress values obtained from both the experimental results and ANSYS exhibited outstanding agreement, with a maximum deviation of merely 1.53 percent.

- Substituting GFRC with woven jute in the 8^{th} layer (A_5) was recommended due to its comparable flexural properties to GFRC. This replacement enhances biodegradability after the service life while preserving the required flexural capabilities.

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