Numerical Investigation of Flax/Bamboo Fiber Reinforced Hybrid Composites under Tensile Load

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Abstract

Natural fibers are a more environmentally sustainable and cost-effective alternative to synthetic fibers. Hybrid composites made from both natural and synthetic fibers have gained popularity due to improved mechanical properties and cost-effectiveness. In this study, we have investigated the mechanical behavior of flax/glass/epoxy and flax/bamboo/epoxy hybrid composites under tensile load utilizing Finite Element Analysis (FEA) software ABAQUS. Flax/bamboo/epoxy hybrid composites were compared to flax/glass/epoxy composites using FEA software to evaluate their layup configurations. The result reveals that flax/bamboo/epoxy composite deforms less than flax/glass/epoxy composite for the same layup patterns and force applied. The maximum modulus of elasticity of flax/bamboo/epoxy was found 8485.80 MPa which is better compared to the flax/glass/epoxy composite. So, it is possible to use flax, bamboo, and epoxy composites as a more affordable and eco-friendly option instead of flax, glass, and epoxy composites. The use of flax/bamboo/epoxy composites is a viable option in manufacturing various automotive parts like door panels, instrument panels, armrests, headrests, and seat shells.

Keywords
Hybrid Composite, Tensile Properties, Stacking Sequence, Finite Element Analysis.

1. Introduction
Researchers are exploring the use of natural fibers as an alternative to synthetic ones, which are harmful to the environment and non-biodegradable. Research on designing new materials for future industries focuses on environmental sustainability and economic issues. Several research (Asif et al.2020, Islam et al. 2019, Jubair et al. 2021) have been conducted on the potential use of natural fiber-reinforced epoxy composite to be used in construction. Chakrabarti et al. (2020) studied the effect of chemical treatment on the mechanical properties of luffa fiber-reinforced epoxy composites and found that after NaOH treatment, the tensile and flexural properties have been improved. Belal et al. (2023) numerically investigated the potential of replacing glass fiber with Bamboo fiber in Flax/Glass hybrid composite under bending load and found that the Glass fiber can be replaced by Bamboo fiber for the composite in bending. Bamboo and flax have the potential to replace synthetic fibers in composites. Flax fiber-reinforced composites have potential applications in sports, maritime, automotive, and aeronautical industries (Moudood et al. 2019). The renewability and rapid growth of bamboo have led to an upsurge in research on bamboo-based products in industries such as housing, furniture, packaging, and transportation (Khalil et al.2012). The hybrid composite made of flax and bamboo has great potential. Xu et al. (2019) analyzed the mechanical properties of four composite materials using both analytical and numerical modeling to validate experimental results obtained from tensile tests.

The hybrid composite reinforced with flax and glass fibers exhibited the highest elastic modulus and tensile strength. Cebru & Botis (2017) conducted a numerical investigation of the bending behavior of glass/flax/epoxy and then flax/epoxy hybrid composites. The results showed that glass/flax/epoxy hybrid composites had a greater modulus of elasticity values than flax/epoxy composites. Gu et al. (2018) investigated the viability of substituting bamboo fibers for flax fibers in thermoplastic (polypropylene) reinforcements in terms of mechanical and environmental performance. The bamboo fiber-reinforced composites performed better in environmental performance and the flax fiber-reinforced composites showed better mechanical performance. Khan et al. (2017) performed both experimental and numerical investigations on fracture behavior of bamboo/epoxy fiber-reinforced composites. Experimental data showed that 25 mm length of fibers had the highest fracture toughness value and 10 mm length fibers had the lowest fracture toughness value. The FEA model using ABAQUS software matched the experimental study.

Hybrid composites help to attain a superior blend of characteristics compared to single-fiber reinforced composites. Composites can have improved physical, mechanical, and thermal properties through this process. Flax-glass-epoxy hybrid composites have become popular for making various automotive parts as it has a high elastic modulus and load withstand capabilities. With the world moving towards sustainable materials, bamboo fiber can replace synthetic fibers like glass fiber. The research aims to analyze the potential of flax/bamboo/epoxy hybrid composites and compare them with flax/glass/epoxy hybrid composites, using finite element analysis. Additionally, the research will investigate the effects of different stacking sequences on hybrid composites.

2. Computational Modeling

Commercially available Finite Element Software Abaqus was used in this analysis. A 3D model of a dog bone shape was created following the EN ISO 527-4 (ISO, 1997). The overall length of the part is 150 mm and the thickness is 3.9 mm. The flax/epoxy composite material displays transverse isotropy, meaning that it demonstrates the same mechanical properties in all directions perpendicular to its longitudinal axis. The glass/epoxy and bamboo/epoxy composites are considered isotropic materials because they use the same fibers in both longitudinal and transverse orientations. The properties of flax/epoxy and glass/epoxy layers in Table 1 are from previous research conducted by Cebru & Botis (2017). The properties of the bamboo/epoxy layer in Table 1 were calculated using the rule of mixture. The bamboo fibers are considered to be obtained from 4-year-old bamboo strips. The volume fraction of bamboo fiber is considered to be 40% in each bamboo/epoxy layer. The modulus of elasticity and Poisson's ratio of the bamboo/epoxy composite layer are calculated using the following,

$$E_c = E_f V_f + E_m V_m \quad (1)$$

$$\nu_c = \nu_f V_f + \nu_m V_m \quad (2)$$

Where, E_f, E_m = Modulus of elasticity of bamboo fiber and epoxy matrix respectively; V_f, V_m= Volume fraction of bamboo fiber and epoxy matrix respectively; ν_f, ν_m = Poisson's ratio of bamboo fiber and epoxy matrix respectively. The properties of bamboo fiber were defined according to (Anwar et al., 2009, Lu et al., 2022): $\mathbf{E_f}$ = 17813 MPa; $\boldsymbol{\nu_f}$ = 0.29. The properties of the epoxy matrix were (Cebru & Botis 2017) $\mathbf{E_m}$ = 3100 MPa; $\boldsymbol{\nu_m}$ = 0.35. The material was assigned by generating a composite shell section and assigning it to the desired region.

Table 1**.** Material properties used in the model

Properties	Flax-epoxy composite	Glass-epoxy composite	Bamboo-epoxy composite
E_1 (MPa)	2136.85	6155	8985.2
E_2 (MPa)	1883.67	6155	8985.2
ν_{13}	0.337	0.15	0.326
ν_{23}	0.4	-	-
G_{12} (MPa)	1300	2676.08	3388.08
G_{13} (MPa)	1300	2676.08	3388.08
G_{23} (MPa)	1318.57	2676.08	3388.08

The composite layups were made with a conventional shell type. The flax-epoxy layer has a thickness of 0.675 mm, the glass-epoxy layer is 0.3 mm thick, and the layer constructed of bamboo/epoxy composite material is also 0.3 mm thick. Figure 3 shows the layup configurations of Flax/Glass/Epoxy and FB-1 composite. Each composite layup was made up of eight layers. Table 2 shows the composite layups of different stacking sequences.

One end of the specimen was fixed while the other was subjected to a coupling constraint to apply concentric force as shown in Figure. 1 (b). Displacement/Rotation type of boundary condition has been used. The magnitude of the load was calculated from the displacement analysis of flax/glass/epoxy (weft direction) done by Xu.et.al. (2019). All the specimens were subjected to the same magnitude of load. A 4-node quadrilateral shell element that was labeled as S4R in ABAQUS, is used for meshing the part. The part was meshed by 48480 elements.

Table 2**.** Composite layups for different stacking sequence

Layer	Flax/Glass/Epoxy	FB-1	FB-2	FB-3	FB-4	FB-5	FB-6
Layer-1	Glass	Bamboo	Flax	Bamboo	Flax	Flax	Bamboo
Layer-2	Glass	Bamboo	Flax	Flax	Bamboo	Flax	Bamboo
Layer-3	Flax	Flax	Bamboo	Bamboo	Flax	Bamboo	Flax
Layer-4	Flax	Flax	Bamboo	Flax	Bamboo	Bamboo	Flax
Layer-5	Flax	Flax	Bamboo	Bamboo	Flax	Flax	Bamboo
Layer-6	Flax	Flax	Bamboo	Flax	Bamboo	Flax	Bamboo
Layer-7	Glass	Bamboo	Flax	Bamboo	Flax	Bamboo	Flax
Layer-8	Glass	Bamboo	Flax	Flax	Bamboo	Bamboo	Flax

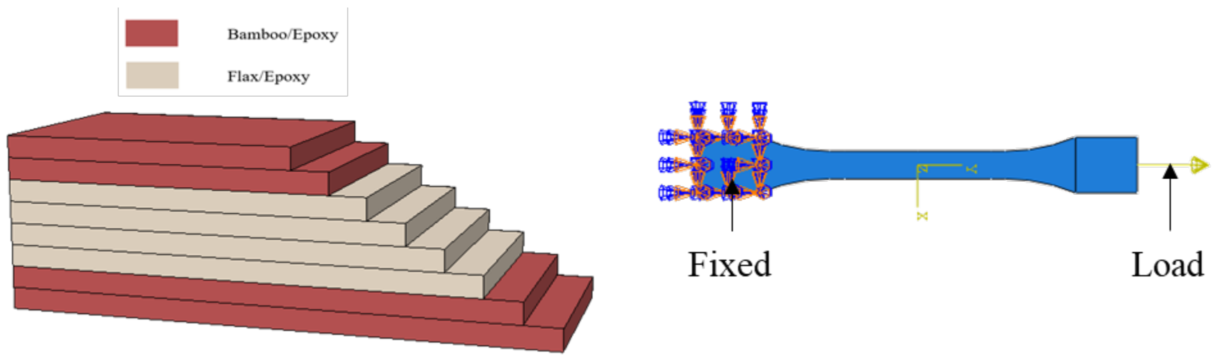

Figure 1. (a) Layup configurations for model FB-1, and (b) loading and boundary conditions

3.0 Results and Discussion

A numerical simulation was executed to carry out a tensile test on a Flax/Glass fiber-reinforced epoxy composite. The stress-strain relationship resulting from this simulation is shown in Figure 2(a), along with the stress-strain data obtained from the study conducted by Xu.et.al. (2019). The Figure indicates that the current model effectively predicts the stress-strain response observed in the experiment. Given that the emphasis of the analysis was on the linear-elastic region, this figure displays the linear-elastic segment of the experimental graph.

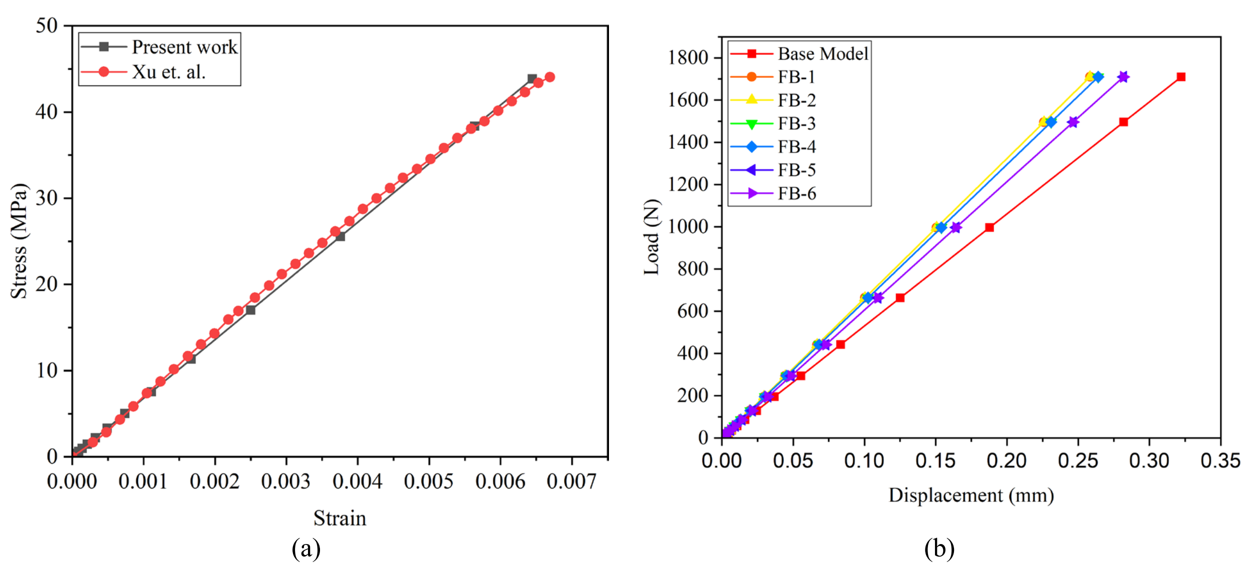

Figure 2. (a) Comparison of stress-strain between present model and experimental results by Xu.et.al. [3] and (b) load-displacement response for all models

Figure 2(b) shows the load-displacement response for all models. This Figure reveals that Model FB-1 and FB-2 exhibit steeper slopes compared to the other models, implying a higher modulus of elasticity. Despite experiencing the same load, these models are anticipated to possess a higher modulus of elasticity. Displacement distribution across the various composite structures is presented in Figure 3. It is evident from this figure that models FB-1 and FB-2 manifest smaller displacements in comparison to the remaining models. The base model has the highest displacement of 0.6319 mm, as listed in Table 3. In contrast, models FB-1 and FB-2 demonstrate a 20.08% reduction in displacement relative to the base model, representing the lowest displacement within the studied models. Additionally, FB-3 and FB-4 show an 18.30% decrease in displacement compared to the base model. Among the flax/bamboo/epoxy specimens, the greatest displacement is identified in FB-5 and FB-6, still showing a 12.88% decrease relative to the base model.

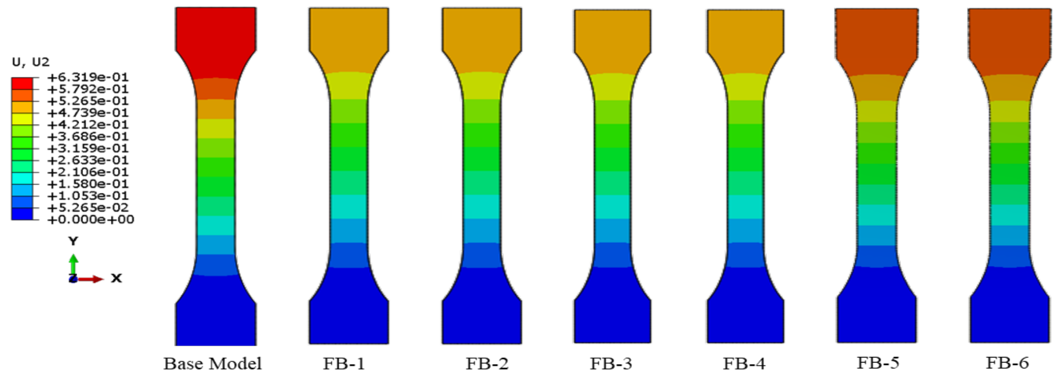

Figure 3. Displacement distribution for all models

Figure 4 shows the von-Mises stress distribution of all models. It is observed from this Figure that the von-Mises stress for models FB-5 and FB-6 are higher compared to the other models. Table 3 shows the numerical values of maximum von-Mises stress for all models along with the percentage change compared to the base model. It is found from this Table that the maximum von-Mises stress for the base model is 42.30 MPa. A 13.61% increase in the maximum von-Mises stress is observed for models FB-1 and FB-2, while for models FB-3 and FB-4 it is increased by 34.96% and finally for models FB-5 and FB-6 the maximum von-Mises is increased by 41.73%. Although, all the models have the same number of Flax and Bamboo fiber layers but still the maximum von-Mises stress changed which can be attributed to the effect of lay-up sequence. Because, in models FB-1 and FB-2 the layers are placed like a sandwich structure where for model FB-1 all the stiffer layers i.e. Bamboo fiber layers are used as the face sheets and softer layers (based on the material property) i.e. Flax fiber layers are used as core. Model FB-2 is also acts as sandwich structure with softer face sheets and stiffer core. Models FB-3 to FB-6 contains alternating layers of Flax or Bamboo fiber layers (either one or two together). The location of the maximum von-Mises stress occurrence was found to be the interface layers between dissimilar material layers i.e. Flax/Bamboo interface layers.

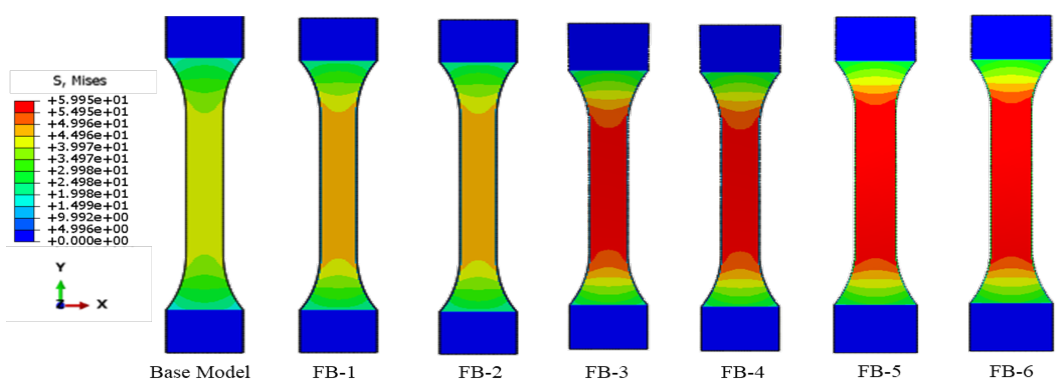

Figure 4. von-Mises stress distribution for all models

The distribution of maximum principal stress is shown in Figure 5. Similar trend like von-Mises stress is also observed in this case i.e. models FB-1 and FB-2 has lower maximum principal stress compared to other models although the lowest stress was for the base model as shown in Table 3. So, if the layers are arranged like a sandwich structure then the maximum principal stress is reduced compared to other lay-up orientations which indicates a longer service life of the composite.

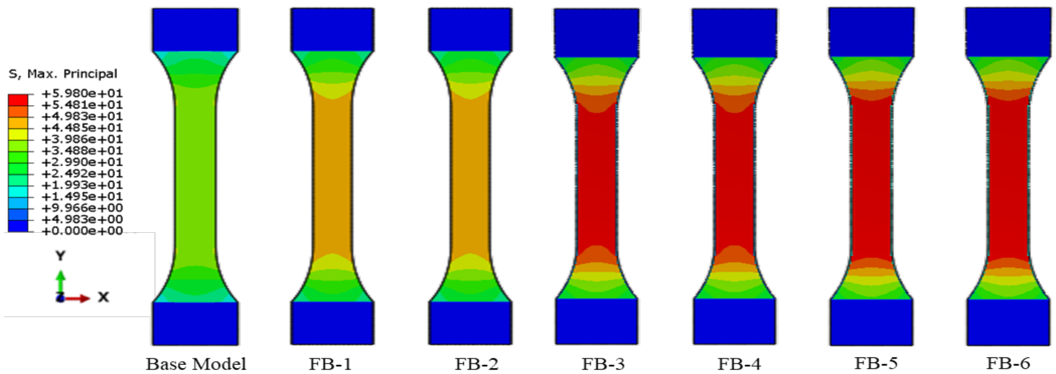

Figure 5. Maximum principal stress distribution for all models

Table 3. Comparison of maximum displacement, von-Mises stress and maximum principal stress for all models

Model	Maximum Displacement (mm)	% Change	Maximum Von-Mises Stress ((MPa)	% Change	Maximum Principal Stress (MPa)	% Change
Base Model	0.6319	--	42.30	--	40.55	--
FB-1	0.5050	-20.08	48.06	13.61	48.00	18.37
FB-2	0.5050	-20.08	48.06	13.61	48.00	18.37
FB-3	0.5162	-18.30	57.09	34.96	56.98	40.51
FB-4	0.5162	-18.30	57.09	34.96	56.98	40.51
FB-5	0.5505	-12.88	59.95	41.73	59.80	47.47
FB-6	0.5505	-12.88	59.95	41.73	59.80	47.47

Figure 6(a) shows the stress-strain diagram of all the models along with the base model. It is found from this graph that the slope of this graph for models FB-1 and FB-2 is higher compared to other models which indicates that these models have higher modulus of elasticity compared to other models which is evident in Figure 6(b) where modulus of elasticity of all the models are shown.

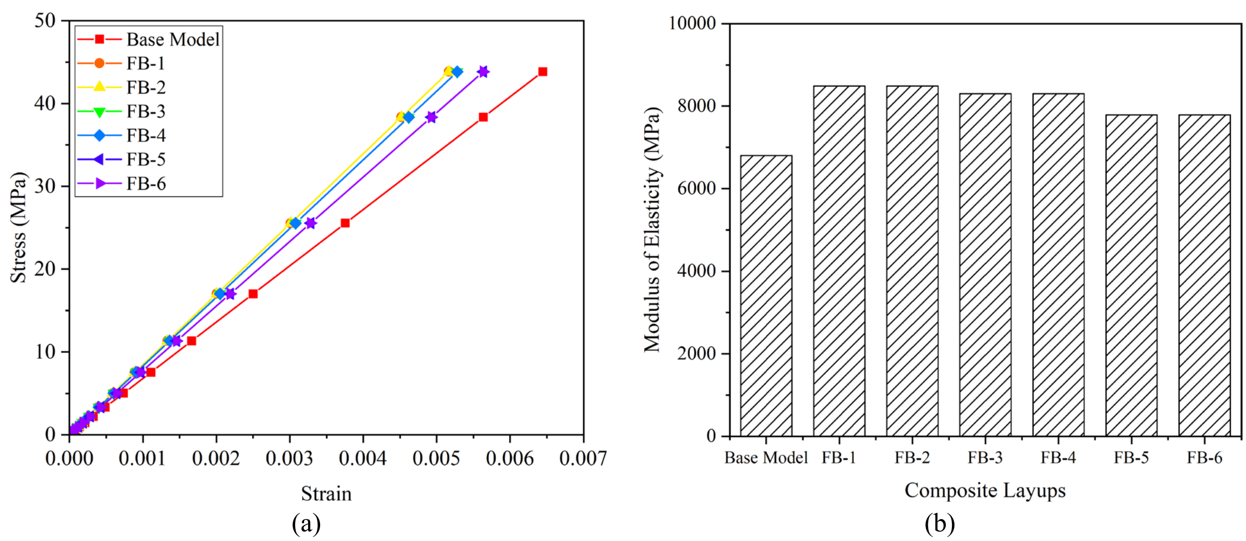

Figure 6. (a) Stress-strain response, and (b) modulus of elasticity of all models

The modulus of elasticity of the base model is 6802.89 MPa as shown in Table 4. For models FB-1 and FB-2, the modulus of elasticity is increased by 24.73% while for models FB-3 and FB-4 it is increased by 22.45% and for models FB-5 and FB-6 the modulus of elasticity is increased by 14.4% compared to the base model. Although, according to the classical laminate theory, the modulus of all the flax/bamboo/epoxy hybrid composites should be same as they all have same volume fraction (Karimzadeh et al., 2020). However, according to our findings, if the layers are oriented like a sandwich structure then the modulus of elasticity also increases provided that all the models have the same number of layers and same fiber volume fraction i.e. everything is the same except the lay-up sequence.

Table 4. Modulus of elasticity for all models

Composite layups	Modulus of Elasticity (MPa)	% Change
Base Model	6802.89	-
FB- 1	8485.80	24.73%
FB-2	8485.80	24.73%
FB-3	8300.17	22.45%
FB-4	8300.17	22.45%
FB-5	7787.95	14.4%
FB-6	7787.95	14.4%

5.0 Conclusions

The key findings of this research can be summarized as-

- Maximum deformation is reduced by 20.08% and modulus of elasticity is increased by 24.73% for Models FB-1 and FB-2 which suggests that if the hybrid composite is designed like a sandwich structure then the structural stiffness as well as modulus of elasticity are increased.
- The maximum von-Mises stress and maximum principal stress for Flax/Bamboo fiber reinforced hybrid composite is higher compared to Flax/Glass fiber reinforced composite which is due to the stiffness of the Bamboo fiber. However, minimum increase is observed for Models FB-1 and FB-2.
- Bamboo fiber has the potential of replacing glass fiber as all the hybrid composites with bamboo fibers exhibit better mechanical properties in tensile test.

References

Anwar, U., Paridah, M., Hamdan, H., Sapuan, S. M., & Bakar, E., Effect of curing time on physical and mechanical properties of phenolic-treated bamboo strips. *industrial crops and products*, *29*(1), 214-219, 2009.

Asif, M., Rahman, K. A., Faisal, M. O., & Islam, M. S., Comparative study on mechanical properties of bamboo and bamboo-glass fiber reinforced hybrid composites. *Journal of Engineering Advancements*, *1*(01), 06-10, 2020.

Belal, S. M., Anwar, M. S., Islam, M. S., Arifuzzaman, M., & Al Bari, M. A., Numerical study on the design of flax/bamboo fiber reinforced hybrid composites under bending load. *Hybrid Advances*, 100112, 2023.

Cerbu, C., & Botiș, M., Numerical modeling of the flax/glass/epoxy hybrid composite materials in bending. *Procedia Engineering*, *181*, 308-315, 2017.

Chakrabarti, D., Islam, M. S., Jubair, K., & Sarker, M. R. H., Effect of chemical treatment on the mechanical properties of luffa fiber reinforced epoxy composite. *Journal of Engineering Advancements*, *1*(02), 37-42, 2020.

Gu, F., Zheng, Y., Zhang, W., Yao, X., Pan, D., Wong, A. S. M., Guo, J., Hall, P., & Sharmin, N., Can bamboo fibres be an alternative to flax fibres as materials for plastic reinforcement? A comparative life cycle study on polypropylene/flax/bamboo laminates. *industrial crops and products*, *121*, 372-387, 2018.

Islam, M. S., Azmy, S., & Almamun, A., Comparative study on mechanical properties of banana and rattan fiber reinforced epoxy composites. *American Journal of Engineering Research (AJER)*, *8*(2), 1-6, 2019.

ISO, B., Plastics–determination of tensile properties. *British Standard, Germany*, 1997.

Jubair, K., Islam, M. S., & Chakraborty, D., Investigation of Mechanical Properties of Banana-Glass Fiber Reinforced Hybrid Composites. *Journal of Engineering Advancements*, *2*(04), 175-179, 2021.

Karimzadeh, A., Yahya, M., Abdullah, M., & Wong, K., Effect of stacking sequence on mechanical properties and moisture absorption characteristic of hybrid PALF/glass fiber composites. *Fibers and Polymers*, *21*, 1583-1593, 2020.

Khalil, H. A., Bhat, I., Jawaid, M., Zaidon, A., Hermawan, D., & Hadi, Y., Bamboo fibre reinforced biocomposites: A review. *Materials & Design*, *42*, 353-368, 2012.

Khan, Z., Yousif, B., & Islam, M., Fracture behaviour of bamboo fiber reinforced epoxy composites. *Composites Part B: Engineering*, *116*, 186-199, 2017.

Lu, H., Lian, H., Xu, J., Ma, N., Zhou, Z., Song, Y., Yu, Y., & Zhang, X., Study on the Variation Pattern and Influencing Factors of Poisson's Ratio of Bamboo. *Frontiers in Materials*, *9*, 896756, 2022.

Moudood, A., Rahman, A., Öchsner, A., Islam, M., & Francucci, G., Flax fiber and its composites: An overview of water and moisture absorption impact on their performance. *Journal of Reinforced Plastics and Composites*, *38*(7), 323-339, 2019.

Xu, D., Cerbu, C., Wang, H., & Rosca, I. C., Analysis of the hybrid composite materials reinforced with natural fibers considering digital image correlation (DIC) measurements. *Mechanics of Materials*, *135*, 46-56, 2019.

Biographies

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