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Developing an alternative crossbar material from jute/E-glass fiber hybrid reinforced polymer matrix composite

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Abstract. Over the last three decades, the use of hybrid reinforced fiber composite materials for structural applications has increased. Minimizing the weight of vehicle components has been considered an important solution for improving fuel economy, increasing technical benefits, and reducing harmful emissions. This study used jute and E-glass fiber with a polyester matrix to develop the hybrid composite. Hand layups were employed for sample preparation of 40% fiber and 60% of the polyester matrix with four different stacking sequences. The mechanical property and water absorption test were influenced by fiber stacking sequences and jute fiber treatment. In this investigation, the result shows that the hybrid G-J-J-G hybrid of NaOH-treated jute fiber exhibited higher strength than a hybrid containing jute fiber at their outer layer and a hybrid of the same stacking sequence with untreated jute fibers. A hybrid with a G-J-J-G arrangement was used to develop alternative crossbar members by size optimization with a genetic algorithm. The sizing optimization of crossbar member results shows that the weight of the hybrid composite crossbar can be reduced by 46.47%, from 9.765 kg to 5.227 kg per single component of crossbar member, and comparatively, an average of 0.00544 L per 100 km of fuel was enabled to be saved. Thus, jute/E-glass hybrid reinforced polyester composite can effectively be an alternative to the current steel structure without compromising their application.

Keywords: Jute/E-glass fiber / mechanical properties / stacking sequence / crossbar member

1 Introduction

Nowadays, a growing concern over fuel consumption and pollution caused by the increasing number of automobiles, and the automotive industry is under great pressure to reduce fuel consumption and emissions. Weight reduction of individual components of the car can be a solution to these problems [1]. As a result, composite material is recently used widely in aerospace and automotive industries, with much focus on renewable energy and the economic advantages of being a better alternative over the traditional way [2,3].

In the automotive manufacturing industry weight reduction has been the main concern to conserve resources and economize energy [4]. Weight reduction of the vehicle can be scaled by using light materials and design optimization for the production of spare parts of the vehicle. Hence, lightweight vehicles with better mechanical performance in automotive industries may be compromised by using reinforced composite material combined with other materials such as metal and plastic. The design of a cost-effective lightweight vehicle's complex cross-section and a thin-walled structural beam of multi-material construction can get high strength-to-weight and stiffness-to-weight ratios. Comparatively, the strength and stiffness factors are why composites are currently used in aerospace applications, which also require an extremely light material, and compared to single-layered steel in cars, multiple-layer composite laminates can be designed to absorb more energy in a crash than the current metal materials used in the automotive industries.

All mentioned studies have assisted engineers with the design and efficient usage of natural fibers [5]. The various advantages of natural fibers are low density, low cost, low energy inputs, and comparable mechanical and better elasticity of polymer composite reinforced with natural fibers, especially when modified with synthetic glass fibers [4,6]. In this work, the jute fiber was used as natural fiber and hybridized with the glass fiber for enhancing the mechanical properties. The cross-bar member 436 ccs light weight loading vehicles is the simple structure and convenient member; that holds a distribute load. Thus, hybrid composite plays a major role in the automotive field

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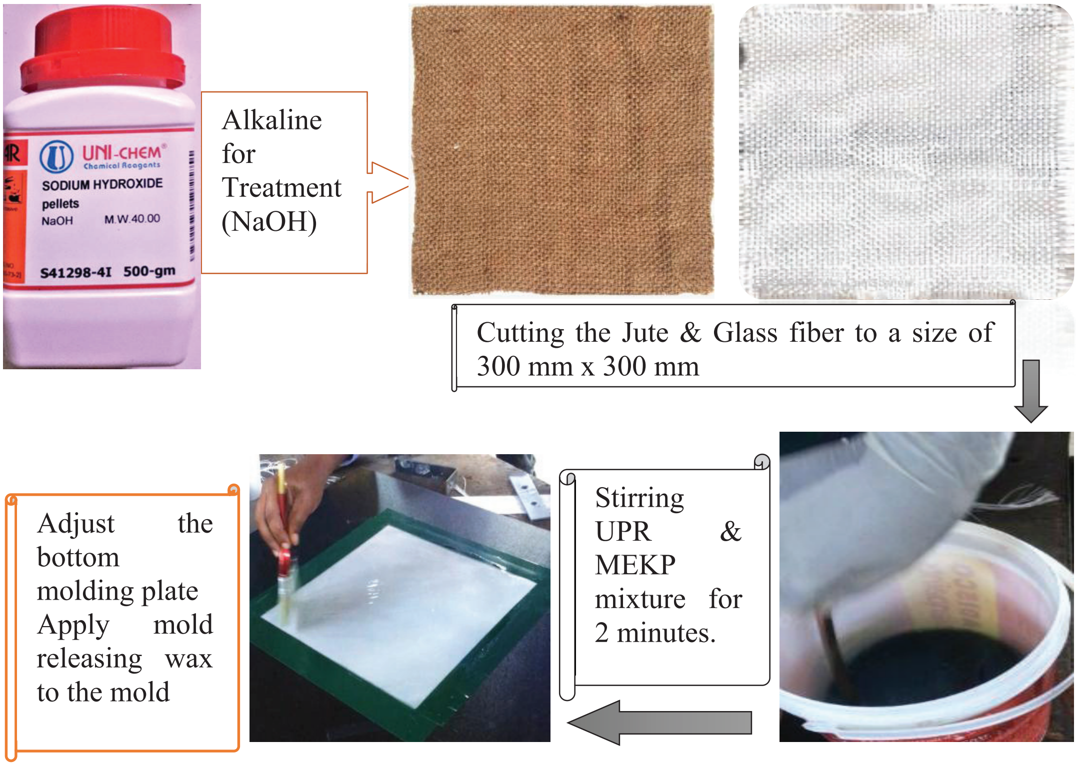


Fig. 1. Raw material preparation.

due to their mechanical and physical properties to balance the strength-to-weight ratio without scarifying its strength.

2 Material and method

2.1 Raw materials

In these studies, the specimens were prepared using Jute fiber, E-glass fiber, Unsaturated Polyester Matrix, Sodium Hydroxide, and Hardener (MEKP/Butanox M50). Thus, raw materials such as Fiber E-glass, Hardener (MEKP), and Unsaturated Polyester Resin were purchased from Polar Fiber E-glass PLC in Addis Ababa, while Jute fiber was purchased from a construction equipment retailer shop in Hawassa, Ethiopia. The jute and E-glass fiber is durable and lightweight materials used as a reinforcement and serve to strengthen the composites laminate. Sodium hydroxide is used as a chemical treatment agent to improve the mechanical properties of the fiber. The woven E-glass fiber used in this investigation has a density of 2.6 g/cm^3 [3].

2.2 Sample fabrication procedures

In this study, the sample fabrication process was started by cutting the E-glass fibers, alkaline treated and untreated jute fiber to a size of 300 mm × 300 mm per the size of the mold Figure 1. Then the mixture (for every 1 kg of polyester resin 20 ml of MEKP M50 was added) was gently stirred for about 2 min before being applied to the composite fiber in the mold, Figure 1. The unsaturated polyester resin (UPR 1003) was used as a binder, and the hardener (MEKP/butanox M50) was used as a curing agent. Hand layup was used to fabricate the samples Figure 2.

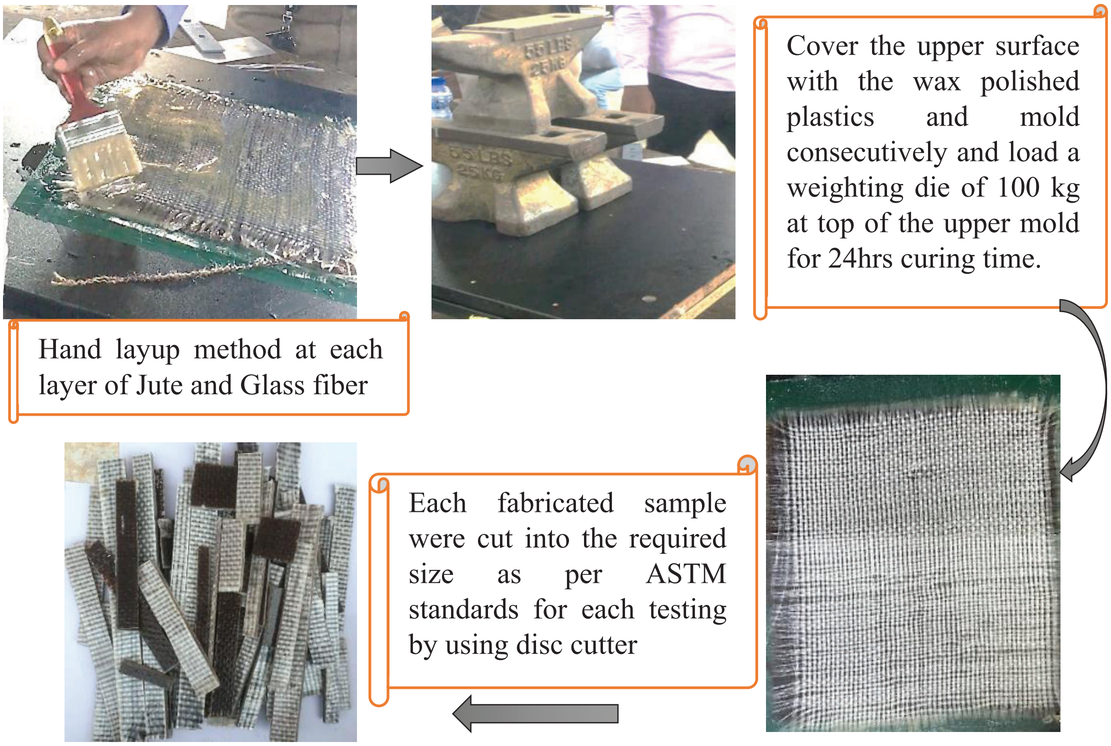
2.3 Apparatus

To fabricate the laminated composite material, a caliper, scissor cutter, disc cutter, supporting table, pressing dies, electronic balance, brush, and molding carpet were used.

2.4 Laminate preparation

The physical and mechanical properties of the composite were studied in this research work by preparing different arrangements of jute and E-glass fibers to conduct the experiment and reach a conclusion. To characterize the mechanical properties of the specimen, alkaline treated and untreated jute fiber hybridized with an E-glass fiber were designed and fabricated according to ASTM standards.

The fabrication of jute/E-glass fiber hybrid reinforced polyester composite was designed with the stacking sequences G-J-J-G, G-J-G-J, and J-G-G-J containing alkaline-treated jute fiber lamina and G-J-J-G containing untreated jute fiber. For each stacking sequence, the composites were reinforced with a jute/E-glass fiber [0^0,0^0] orientation [7,8]. Before reinforcement of jute fiber was treated with NaOH to enhance its properties. The fiber volume fraction and matrix volume fraction of the hybrid composite are determined.



Hand layup method at each layer of Jute and Glass fiber

Cover the upper surface with the wax polished plastics and mold consecutively and load a weighting die of 100 kg at top of the upper mold for 24hrs curing time.

Each fabricated sample were cut into the required size as per ASTM standards for each testing by using disc cutter

Fig. 2. Hybrid composite sample manufacturing process.

In the experiment, the composite was prepared using jute and E-glass fiber as reinforcement and general polyester resin as a binder Figure 1. To achieve a good surface finish on the product and prevent polyester from adhering to the mold surface, a release wax was applied on thin plastic sheets used at the top and bottom of the mold plate Figure 1. The process was repeated for each sample of jute and E-glass fiber as per the orientation of the designed layers [6,9].

2.5 Determining the applied load of existing crossbar member

Weight distribution analysis in the chassis involves determining the proper distribution of payload weight about the frame's crossbar member. The input data acquired from the Mahindra Alfa company websites and the importing company, Hora trade PLC Adama, were used to determine the applied load to the cross-bar frame.

2.6 The load applied to the crossbar member frame of 436 ccs

The loading condition of the structure 436 cc of three-wheel vehicle includes loading a maximum of 505 kg and supporting self-weight of 490 kg. The cross member is supposed to carry the gross vehicle load and attached it to the chassis. The mass of the cargo bed will be 120.31 kg (including the bolts, estimated loading equipment, and calculated values using sizes and density of cargo-bed material; mild steel), and the weight of the cross single C-shape crossbar was 9.765 kg.

The analysis of the laminated structural cross-bars using the Tsai-Wu failure theory and the findings of the various tests carried out during the experiment. The input data from the experiment were the guiding principles for the design of laminated composite cross-bar members. Hence, the results are presented and discussed as follows.

3 Result and discussion

3.1 Introduction

The analysis of the laminated structural cross-bars using the Tsai-Wu failure theory and the findings of the various tests carried out during the experiment. The input data from the experiment were the guiding principles for the design of laminated composite cross-bar members. Hence, the results are presented and discussed as follows.

3.2 Physical property

3.2.1 Density

The density of each specimen was determined based on the procedures mentioned in the materials and methods section of this paper. Thus, the measured densities along with the corresponding hybrid sample of jute/E-glass reinforced hybrid composite material are presented in Table 1.

Table 1. Density of the fabricated specimen.

Composite type	Stacking sequences	Weight of E-glass fibers (g)	Weight of jute fiber E-glass (g)	Matrix weight (g)	Composite weight (g)	Actual density (g/cm^3)
Hybrid 1	G-J-J-G (UJF)	198.3	97.8	444.15	740.25	1.448
Hybrid 2	J-G-G-J	197.8	87.6	428.1	713.5	1.431
Hybrid 3	G-J-J-G	196.7	88.4	427.65	712.75	1.438
Hybrid 4	G-J-G-J	197.9	86.8	427.05	711.75	1.404

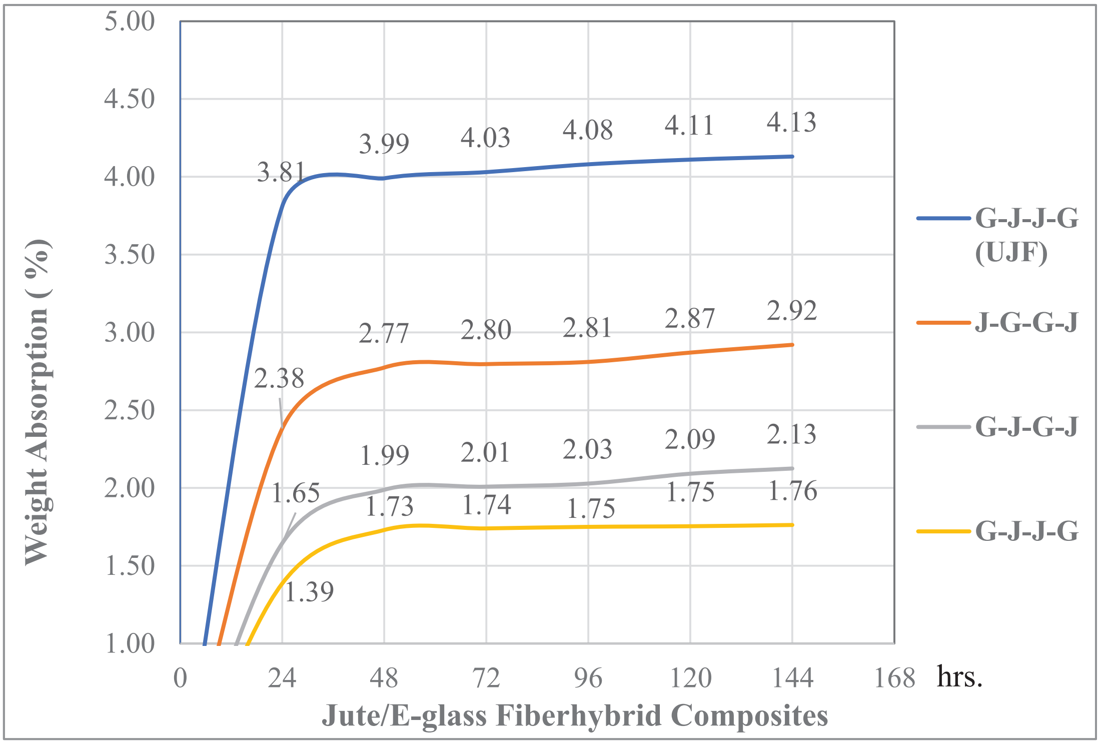


Fig. 3. Water absorption results diagram.

In general, the actual density of each specimen was determined as per the ASTM D792 method, and the average density of the sample was 1.430 g/cm^3.

3.2.2 Water absorption test

In this study, hybrid composite samples were immersed fully in the rainwater according to the ASTM standard and the weight percentage was calculated. As shown in Figure 3, the minimum amount of water absorbed is shown in a Jute/E-glass fiber reinforced composite of G-J-J-G, which is 1.76% per 144 hrs. of immersed in the rainwater, and the maximum amount of water absorbed in the hybrid composite of the same sequences but contained untreated jute fiber, which is 4.13% per 144 hrs Figure 3.

Comparatively, the outer E-glass fiber has a significant effect, while laminated at the outer surfaces of the hybrid composites decreases the water absorption of jute fiber, which is 4.13%, 2.92%, 2.13%, and 1.76% of G-J-J-G, G-J-G-J, and J-G-G-J, respectively.

3.3 Mechanical properties

3.3.1 Tensile strength test

The tensile testing experiment was conducted for each fabricated jute-E-glass hybrid reinforced composite materials specimen. The experimental results of the composites of different stacking sequences and the average ultimate tensile strength are illustrated in Figure 4. The composites of G-J-J-G with alkaline-treated jute fiber have the highest ultimate tensile strength, 89.66 MPa of all tested specimens, while the composites of J-G-G-J have the lowest ultimate tensile strength, 53.34 MPa. Tensile strength differs significantly between hybrid 1 (G-J-J-G UJF) and hybrid 3 (G-J-J-G) with the ultimate tensile strength of 59.12 MPa and 89.66 MPa, respectively as shown in Figure 4. The jute fibers in the outer layer of the specimens could not handle significant loads, causing the E-glass fibers to withstand the majority of the stress. Thus, the alkaline treated jute fiber handles significant stress than untreated jute fiber in the composites of the same stacking sequences.

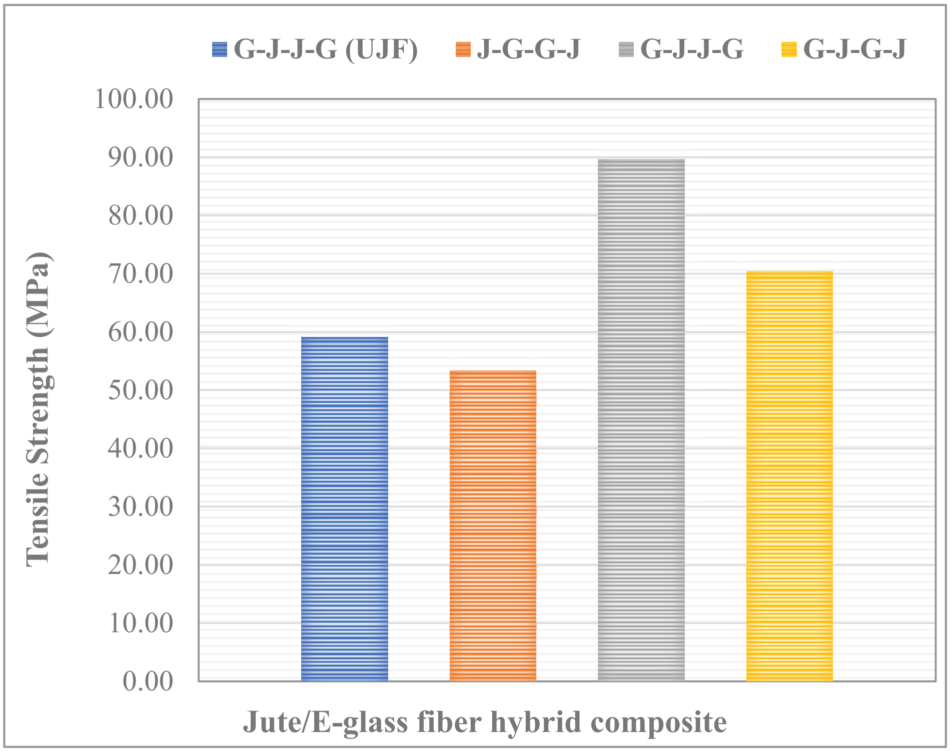


Fig. 4. Mean tensile strength of hybrid composites.

The hybrid of samples with the outer E-glass fiber arrangement shows better mechanical strength in the fabricated specimen of jute/E-glass reinforced hybrid polyester composites, for example, the ultimate tensile strength of the hybrid 4 (G-J-G-J) specimen is 70.45 MPa, which is greater than the hybrid 2 (J-G-G-J) specimen of 53.34 MPa. E-glass fibers were certainly more efficient at resisting heavy loads before applied loads were transferred to jute fibers. Furthermore, the specimen with an alkaline treated jute fiber containing an E-glass fiber at the outer sequences has a higher ultimate tensile strength than a hybrid of untreated jute fiber in the G-J-J-G sequences. Thus, hybrid 1 and hybrid 4 have ultimate tensile strengths of 59.12 MPa and 70.45 MPa, respectively.

3.3.2 Compression strength test

The compressive strengths of the composite specimens were also assessed using the axial compression test, and the test average results for the various layer notation composites. It was observed that the J-G-G-J hybrid reinforced fiber specimen has a low mean compressive strength of 61.08 MPa, whereas the hybrid specimen with the G-J-J-G specimen has a maximum strength of 132.65 MPa Figure 5.

The compressive strength of alkaline-treated jute fiber of the G-J-J-G hybrid specimen increased by 30.5% compared to untreated jute fiber in the same sequences. However, as shown in Figure 5, untreated jute fiber in the G-J-J-G has a better compressive strength of J-G-G-J hybrid composites by 39.8% and is lower than the G-J-G-J hybrid composite by 1.5%. this show that the outer E-glass fiber sequences made a significant increase in the compressive strength of the hybrid. This suggests that the outer layered E-glass fiber arrangement enhances the composites' mechanical properties as well as alkaline treatment jute fiber.

3.3.3 Flexural strength

The flexural test of three-point bending of the comparison of the composite results among the composite. All the composite showed good flexural strength, both treated and untreated jute fiber reinforced with the same E-glass fiber and matrix. Hybrid 3 of the G-J-J-G stacking sequence shows good flexural strength than all the hybrid composites, two layers of alkaline-treated jute fiber complimented with an E-glass fiber sequenced on the outer layers. The alkaline treatment of jute fiber increases the flexural strength of the composite of the same stacking sequences from 211.4 MPa (G-J-J-G UJF) to 261.8 MPa (G-J-J-G). It can be observed that the stacking sequence has a significant effect on the properties of hybrid composites. The flexural strength was observed higher when the E-glass fibers were used as outer layers, G-J-J-G, G-J-G-J, and J-G-G-J. In all hybrid composites of the result in Figure 6, the average flexural strength fluctuated between hybrid 3 (261.8 MPa) and hybrid 2 (112.2 MPa). The hybrid 1 (G-J-J-G UJF) composite results from better flexural strength than both alkaline-treated jute fiber complement in hybrid 2 (J-G-G-J) and hybrid 4 (G-J-G-J).

3.3.4 Impact strength

The impact energy and toughness values of the jute/E-glass fiber hybrid reinforced composites of various stacking arrangements. As observed from the experiment results

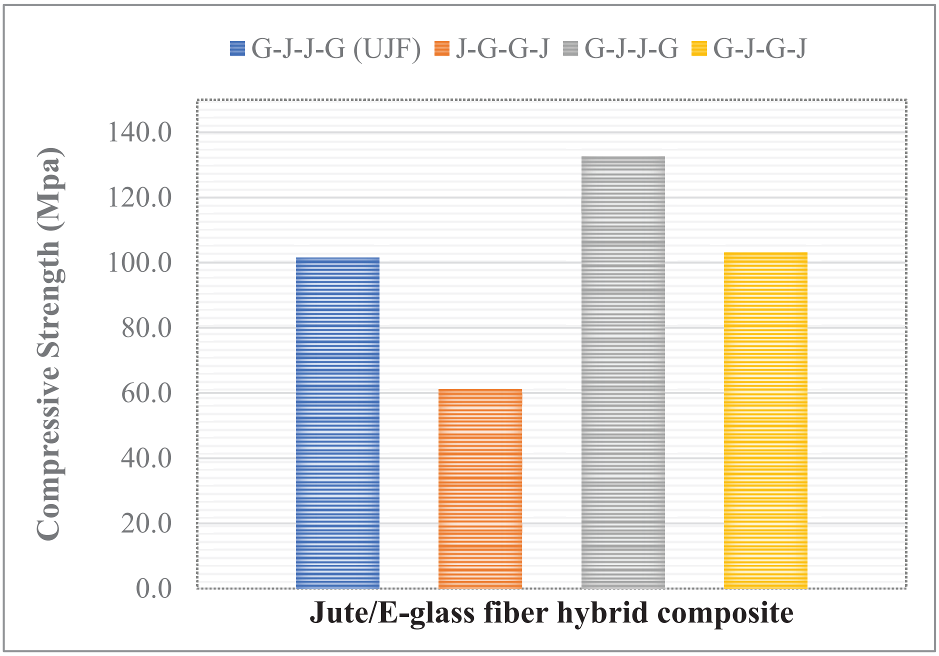


Fig. 5. Compressive strength.

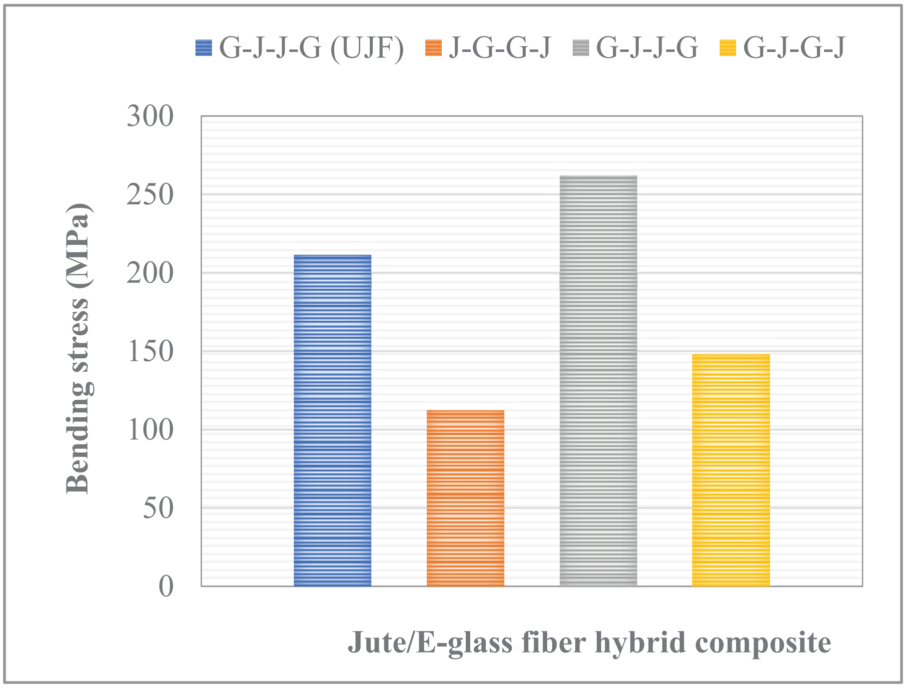


Fig. 6. Flexural strength (three-point bending stress).

shown in Figure 7, alkaline-treated jute fiber hybridized with the E-glass fiber shows greater strength than the untreated jute fiber combination. Thus, the untreated jute fibers of G-J-J-G composites result in 134.8 MPa, which is less than the same stacking sequences of the composite but alkaline-treated jute fiber at a maximum impact energy of 176.2 MPa. Because the alkaline treatments improved the mechanical properties of jute fiber hybridized with the synthetic jute fiber and matrix. Furthermore, the impact strength of alkaline treated jute fiber of an outer layered in hybridized composites was lower than that of E-glass fiber outer arranged. The maximum impact strength of the G-J-G-J composite becomes 151.8 MPa, which is less than the 176.2 MPa of the G-J-J-G composites but greater than the 136.2 MPa of the J-G-G-J composites, as shown in Figure 7.

The reason for this was that outer-layered E-glass fiber absorbed more impact energy than outer-layered jute fiber. In comparison, the maximum impact strength of the

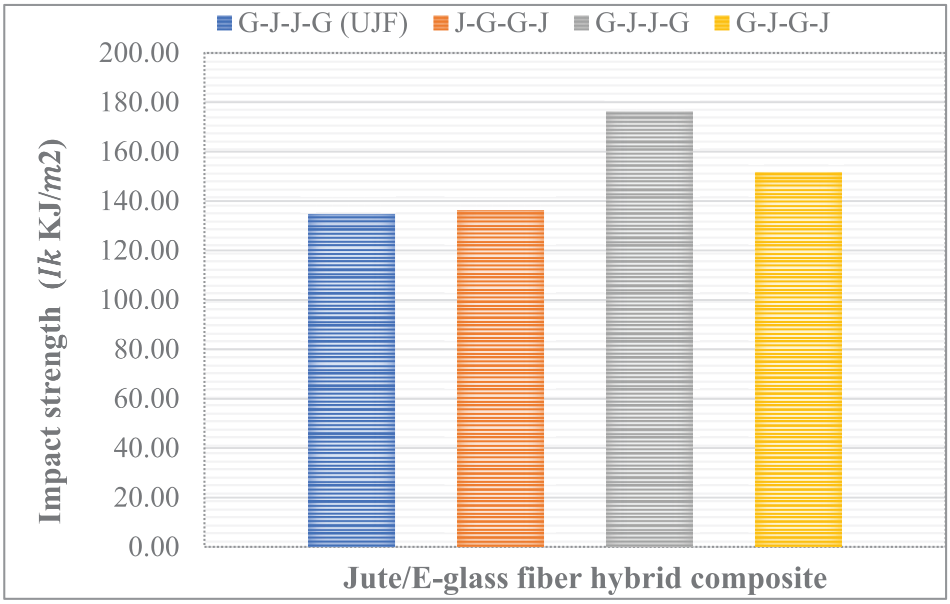


Fig. 7. Impact strength.

jute/E-glass hybrid composite was 176.2 KJ/m^2. The positioning of E-glass fibers on the surface of hybrid composites with the same number of plies of jute/E-glass and different stacking sequences could improve the composite's impact strength and toughness.

3.4 Sizing optimization using genetic algorithm

To achieve a significant weight reduction and cross-bar quality improvement, the optimization tools must be extended to determine the best structure dimension.

3.4.1 Constraints

3.4.1.1 Tsai-Wu failure theory

Constraints represent the functional relationships between design variables and other design parameters that satisfy certain physical phenomena and resource limitations.

The Tsai-Wu failure theory was used as a constraint throughout analysis cross-bar frame size optimization. Tsai-Wu failure theory is based on the total strain energy failure theory to lamina in the plane stress and the lamina is failed if (1) is violated [7,8].

$$g(u) = F_1\sigma_1 + F_2\sigma_2 + F_6\sigma_{12} + F_{11}{\sigma_1}^2 + F_{22}{\sigma_2}^2 + F_{66}{\sigma_{12}}^2 + F_{12}\sigma_1\sigma_2 < 1, \tag{1}$$

where, F_1, F_2, F_6, F_{11}, F_{22}, F_{66} and F_{12} were the components of the failure theory parameters of unidirectional lamina.

3.4.2 Strength ratio

If $SR > 1$ then the lamina is safe and the applied stress can be increased by a factor of SR. If the $SR < 1$ the lamina is unsafe and the applied stress needs to be reduced by a factor of SR.

$$SR = \frac{\text{Ultimate stress}}{\text{Applied stress}} > 1.$$

The laminate is composed of even number of orthographic layers made of different materials (jute/polyester and E-glass/polyester. The surface layers of made of a composite with high high-stiffness reinforcements (E-glass fiber polyester reinforced) and the core layer of composite with low-stiffness reinforcement (jute fiber polyester reinforced).

3.4.2 Design of laminate for flexural responses

For a rectangular laminate plate of under in the plane compressive the strength constraint become important, hence; the size of the plate is larger than the thickness the vibration has to be considered. Each ply has a constant ply orientation of 0-degree kept constant, and thickness of each layer of composite $\{t_i\}_i^n$ ply thickness and lw web length. As a result, the following natural frequencies of a symmetrically laminated simply supported composite beam given by [7];

$$f(m,n) = \left(\frac{\pi^4}{\rho}\left[D_{11}\left(\frac{m}{L}\right)^4 + 2\left((D_{12}+D_{66}) * \left(\frac{m}{L}\right)^2 * \left(\frac{n}{b}\right)^2\right) + D_{22} * (n/b)^4\right]\right)^{\frac{1}{2}}. \tag{2}$$

The fundamental frequency is obtained when m and n were both one. The higher order frequency f_l, $l \geq 2$ were obtained by minimizing the Eigen frequency $f(m,n)$ over the nodes numbers (m,n) subjected to condition $f_l$and $(m,\ n) \neq (m_{l-1},\ n_{l-1})$, where m_{l-1} and $n_{l-1})$ Eigen mode of the frequency f_{l-1}. Thus f_l, $l \geq 2$ is given by

$$f_l = min f(m,n), l = 2, 3, \ldots$$

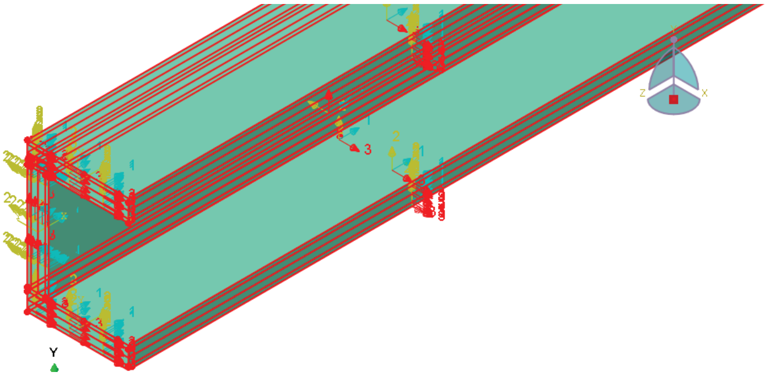


Fig. 8. Assigning the material properties and orientation to each ply.

Subject to $f(m, n) \geq f_{l-1}$ and $m \neq m_{l-1}$, and *or* $n \neq n_{l-1}$. The dimension of the $l\,th$ order frequency ω_l is defined as

$$\omega_l = f_l\left({}^{b^2}\!\Big/_{h}\right) * \left({}^{\rho_o}\!\big/_{E_O}\right)^{\frac{1}{2}}.$$

Whereas; σ_0 density of the and E_0 young modulus hybrid composite material. In general, the new jute/E-glass fiber hybrid reinforced polyester composite subjected to the following constraints;

$$g(u) \leq 1, \text{Tsai} - \text{Wu failure constraint}$$

$$SR > 1, \text{Strength Ratio}$$

$$f_l \geq f_{\text{steel crossbar}}, \text{fundamental frequency}$$

$$4 * (t_G + t_J) + l_w = H_{\text{web steel}}, \text{steel web length.} \qquad (3)$$

To determine the possible ply thickness that could hold the function of the streel crossbar member the hybrid composite has to designed with a frequency greater than the steel structure. Since the laminate is symmetric, the matrix [B] is zero for both flange and web of the crossbar frame, which bending stiffness from axial ones.

3.4.3 Design variables

Design variables were parameters that can be changed to achieve the best possible design configuration. It could be size, pattern repetition frequency, material characteristics, load, spring stiffness, etc. Both continuous and discrete variables have a defined range of possible values. Continuous variables can have any value between a specified minimum and maximum.

$$t_G, t_J \text{ and } l_w, \text{Design Vairables},$$

where, t_G is the thickness of the E-glass fiber, t_J is the thickness of the jute fiber and l_w is the length of the web.

In general, from the above analysis, the possible minimum weight and the geometric variables were determined. The result indicates that the optimized mass was 5.2269 kg and thickness of E-glass fiber 1.5 mm, the jute fiber thickness 3 mm and the web height 44.50 mm of the laminated cross bar optimum composites material. Considering the volume of the given geometrical dimension the current steel crossbar structural weight of 9.765 kg. Therefore, the optimization of the crossbar member resulted in a total mass saving of 46.47%. The maximum stress was 26.49 MPa for the optimized geometric dimension of the hybrid crossbar. The failure criteria of the laminate composite were found to be the limiting factor for the required parametric dimensions. Brandenburger's research paper shows that the fuel consumption in order to move mass 100 kg over 100 km was figured that 0.12 L for a desiel based on New European driving cycles assuming that the difference between road resistance and vehicle curb weight measured before and after reduced mass [10,11]. Thus, the theoretical fuel reduction for a single crossbar member of the 436 cc loading vehicle can be expressed as;

Average fuel saving = (0.12 iter ★ reduced mass)/(100 km ★ 100 kg),

$$\text{Average fuel saving} = (0.00544\text{liter})/(100\text{km}).$$

An average fuel reduction become 0.00544 L per 100 km was achieved per single crossbar member of the loading vehicle of 436 cc.

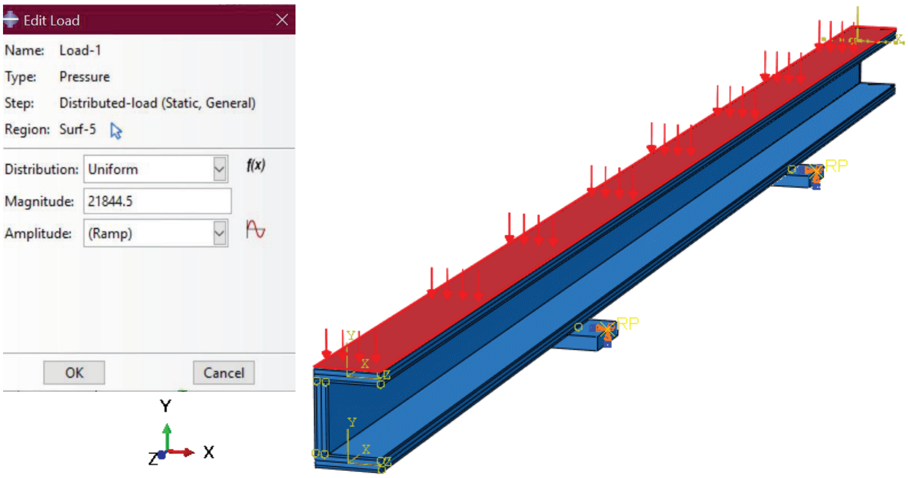
3.5 Validation of the result using Abaqus software

In order to confirm the result, the optimized crossbar was analyzed by using ABAQUS for validation purpose.

3.5.1 Modeling and defining the applied load

Figure 8 shows the structural shape of the 3D model of the jute/E-glass fiber hybrid composite to the designed dimension optimized by GA. Assigning the material properties, element thickness and Orientation of the Jute/E-glass Fiber Hybrid Reinforced Polyester Composite as per the optimized thickness and web length as shown in Figure 8.

The existing crossbar frame supports a distributed load of 1,327.68 N per the area of the upper flange surfaces, which was 21,844.5 N/m^2.



Edit Load

Name: Load-1

Type: Pressure

Step: Distributed-load (Static, General)

Region: Surf-5

Distribution: Uniform

Magnitude: 21844.5

Amplitude: (Ramp)

Fig. 9. Apply the distributed load.

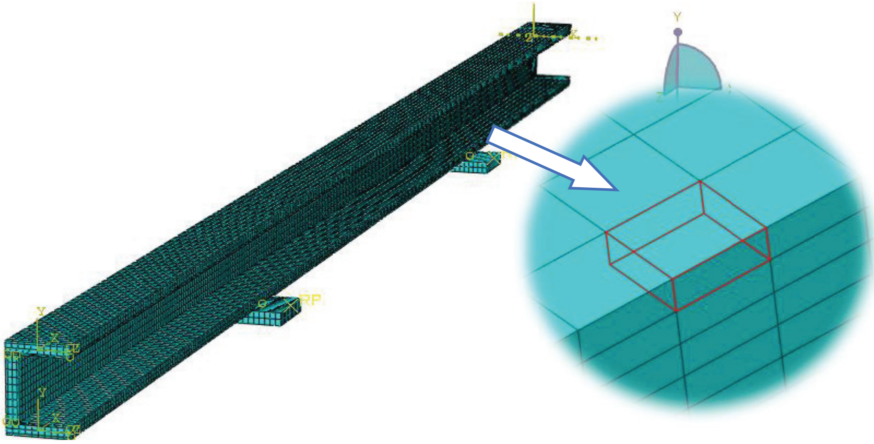


Fig. 10. Meshing the modeled hybrid crossbar.

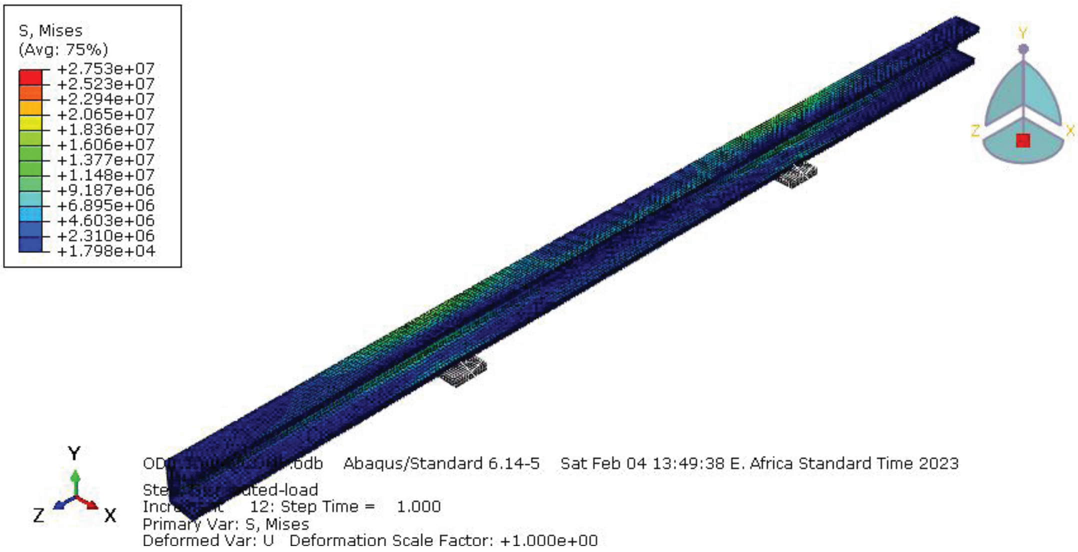


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Fig. 11. Maximum stress developed in the hybrid Jute/E-glass composite.

Through the ABAQUS steps the applied load and the constraints were defined for the position that the vehicle chassis support the crossbar Figure 9.

The crossbar member frame model was solved with a reasonable degree of mesh (4 mm size) Figure 10, refinement as the local deformation was interpolated from the global deformation.

3.6 Finite element analysis result

The contour plot of Von Mises Stress for the cross member under uniformly distributed payload and self-weight was shown in Figure 11. The maximum von misses was 27.53 MPa and accordingly, those were loaded that indicate unrealistically high stresses which result from singularity stress concentration at the middle where hybrid composite components were mounted with the chassis frame of the vehicle.

The maximum stress result from the MATLAB was 26.49 MPa. The difference of the stress using the MATLAB Analysis and FEM was 3.93%. From the ABAQUS explicit model analysis, the maximum stress induced in the developed hybrid jute/E-glass fiber was less than the experimentally observed G-J-J-G of the same sequences of 89.66 MPa. In addition, the maximum deflection (U-Magnitude) was 3.14 mm, which was observed at the contact edge points of the members of the bottom outer layer (layer-4 of the flange) of the laminate.

4 Conclusion

This research study focused on the fabrication and characterization of jute/E-Glass fiber hybrid reinforced polyester composites as well as the development of alternative crossbar components for loading vehicle components. The conclusions drawn herein were based on the results of the experimental investigation and development of the crossbar frame components. Two categories of jute fiber composition, i.e., alkaline treated and untreated, of composites samples were manufactured by hand layup method and all tests were performed according to ASTM standards.

- The Jute/E-glass hybrid reinforced polyester composites were successfully manufactured using a hand lay-up technique.
- The experimental results showed that the alkali treatment and fiber orientation affect the composite's tensile, compression, flexural, and impact properties.
- Alkaline treatment of jute fiber decreases the moisture absorption and increases the mechanical properties of the hybrid reinforced polyester composites.
- The tensile strength of an alkaline treated and E-glass fiber lamina at the outer layer (G-J-J-G) results in improved mechanical and physical properties when compared to any other stacking sequence.
- The elastic Young's modulus of the hybrid composites was proportional to the fiber stacking order in the hybrid and alkaline treatments of natural fiber.
- The weight of the hybrid composite cross bar was reduced by 46.47%, from 9.765 kg to 5.227 kg.
- A fuel savings of 0.00544 L per 100 kilometers would be achievable per single crossbar-bar member of the 436 cc loading vehicle. Thus, it can be applicable to the various suitable structure for design and development.
- The jute/E-glass hybrid polyester composite can be an alternative for a lightweight vehicle with 436 cc of steel crossbar members, without compromising carrying capacity.

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