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Eco-Friendly Automotive Bumper Design Using Natural Fiber Reinforced Composites

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***Abstract*— The automotive sector is increasingly being forced to minimize its effects on the environment while still being able to deliver safety and performance. The traditional car bumper made of petroleum-based polymers is a source of plastic waste and carbon emissions. The current research aims to design, manufacture, simulate, and test an eco-friendly car bumper made of hybrid natural fiber-reinforced composites. Banana, jute, bamboo, and cotton fibers with a small amount of glass fibers and an epoxy matrix were used and manufactured by the hand lay-up method. Mechanical properties were tested according to ASTM procedures, and impact resistance was analyzed by FEA simulation according to FMVSS standards. The results clearly indicate that hybrid composites possess better strength-to-weight ratio, improved energy absorption capacity, and acceptable deformation as it poses 19.12 mm where the existing material poses 12.60 mm, poisson ratio of hybrid is also perfect where it poses 0.41 and the existing poses 0.40 and are more sustainable and economical compared to the conventional synthetic materials**

Keywords - *Natural fiber composites, Hybrid composites, Automotive bumper, Banana fiber, Jute fiber, Sustainability, Impact analysis*

I. INTRODUCTION

Automotive bumpers are critical safety components designed to absorb impact energy during low-speed collisions, thereby protecting vehicle occupants and essential components such as headlights, radiators, and structural members. Modern bumper systems must satisfy safety regulations while also meeting requirements related to aesthetics, aerodynamics, pedestrian protection, and cost Conventional bumpers are primarily manufactured from petroleum-based plastics such as polypropylene (PP), ABS, and polycarbonate blends. Although these materials provide good impact resistance and manufacturability, they are non-biodegradable and contribute significantly to environmental pollution. In 2022 alone, the European automotive industry generated approximately 1.6 million tonnes of plastic waste, with recycling rates below 19%. Additionally, the manufacture and disposal of plastic bumpers result in high carbon emissions.

Natural fiber–reinforced composites have emerged as sustainable alternatives due to their low density, renewability, biodegradability, and reduced carbon footprint. However, single natural fiber composites often suffer from lower mechanical properties and moisture sensitivity. To overcome these limitations, hybridization of natural fibers with other natural or minimal synthetic fibers has been proposed. This research focuses on developing and evaluating a hybrid natural fiber composite bumper that achieves improved mechanical performance while maintaining low cost and sustainability.

II. MATERIALS SELECTION AND NATURAL FIBERS USED

A. Banana Fiber

Banana fiber is derived from the agricultural waste of banana pseudo-stems, making it a sustainable and eco-friendly reinforcement material. Additionally, banana fibers have been observed to have a relatively lower density of 1.35 to 1.5 g/cm³. Banana fibers have been found to have relatively higher strength, with a tensile strength ranging from 355 to 500 MPa [5], along with a Young's modulus of about 20 to 32 GPa. Moreover, the elongation at break of banana fibers has been found to be 3 to 10%. On the other hand, the banana fibers have been observed to have relatively higher absorption of impact energy. The banana fibers are easily available at a relatively lower cost. All the above factors have been helpful in making the banana fibers suitable for automotive products..

B. Jute Fiber

Jute is one of the most versatile and heavily used natural fibers due to its low cost, biodegradability, and ease of availability. The density of jute varies from 1.3 to 1.46 g/cm³, which helps in creating composite materials of low weight. Jute fibers show an ultimate tensile strength of 393 to 773 MPa[4], and their Young's modulus lies within the range of 20 to 30 GPa, signifying good stiffness and integrity of fibers. The total deformation was **2.123 mm [8].** Jute fibers used in composite materials made from polymers show

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improved material stiffness, carrying capacity, and dimensional stability. Jute also stands for impact properties and bonding characteristics, making it best used for vehicles and articles of semi-load carrying capacity.

C. Bamboo Fiber

The mechanical properties, that is, high specific strength, as well as significant value of rigidity, may be attributed to the special microstructure found in bamboo as well as to cellulose in particular. Besides, it has a low density that ranges from 1.2 to 1.5 g/cm³. The bamboo fibers are known to possess tensile properties that range from 500 to 900 MPa, while the young's modulus is around 30 to 40 GPa, signifying high rigidity. Bamboo fibre carried the highest stress (0.55 MPa) and the highest deformation (0.81 mm)[2].The use of bamboo fibers within a composite material points to an improvement in terms of rigidity, as well as the stiffness, of a given composite material. Besides, bamboo is a material that is highly eco-friendly owing to features that include a quick growth rate as well as renewability.

D. Glass Fiber (Limited Use)

A limited amount of E-glass fiber was included in the core layers to improve the impact strength of the composite material. This has led to overall improvement in the integrity of the composite material while maintaining the overall notion of natural fiber reinforcement as the dominant material property within the composite system. E-glass fiber has a density value of around 2.5–2.6 g/cm³; it exhibits a high value of tensile strength between 2000 to 3500 MPa; its Young's modulus value ranges between 70 to 76 GPa. The proportion of E-glass fiber that was included in the core layer was limited to ensure that the composite material achieved the required balance between sustainability and overall material integrity while meeting the impact strength necessary for use in the automotive industry.

III. HYBRID COMPOSITE DESIGN AND STACKING SEQUENCE

The Idea of Hybrid composition was taken from the paper [1][10] where they used **the Flax and Kenaf Fiber**. The thickness of the hybrid composite was made to be 5 mm, and the volume fraction was between 40%-50%. The standard stacking sequence used:

- **Jute / Glass / Banana / Bamboo / Glass / Jute**

This process provides a range of natural fibers on the surfaces for sustainable aspects coupled with aesthetic effects, in addition to glass fibers integrated within the core for impact properties together with strength.

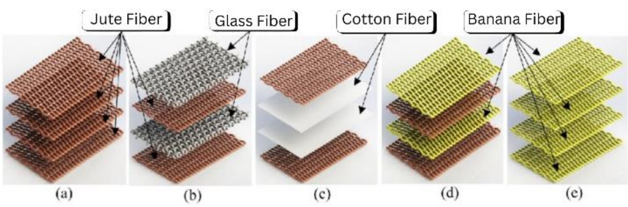

FIG 1 : LAYERS [11]

Properties	*Polypropylene*	*Reinforced Hybrid Fiber*
Density (kg/m³)	900	1250 – 1350
Young's Modulus (Gpa)	1.3 – 1.8	2.5-3.2
Poisson's Ratio	0.42	0.32 – 0.36
Bulk Modulus (GPa)	1.6	2.1
Shear Modulus (GPa)	0.46	1.0 – 1.2
Tensile Ultimate Strength (MPa)	35	70 – 110
Water Absorpyion (%)	<0.05	3 – 6

TABLE I. MECHANICAL PROPERTIES

IV. SPECIMEN PREPARATION & MANUFACTURING PROCESS

In the manufacturing process, we have adopted hand lay-up method with epoxy resin and hardener.

Epoxy resin [3] is a thermoset polymer characterized by its impressive properties, such as good adhesion, toughness, and chemical as well as heat resistance. It has low shrinkage as a thermoset, which makes it useful as a coating, in composites, and as an adhesive. The hardener/curing agent combines chemically with epoxy resin to activate a chemical cross-linking action, thereby curing the material. The amount of hardener used and curing mainly influence the final properties as well as curing time.

A. Hand Lay-Up Technique

The reason for choosing the "hand lay-up" technique [9] was the ease of use associated with it, making it a less expensive technique that is also suitable for prototyping. The fibers were placed in a woven or mat format, with the epoxy resin being evenly distributed for proper wetting.

FIG 2 : HAND LAY-UP METHOD

V. TESTING STANDARDS

The composite specimens were tested for structural behaviors based on ASTM standards for assessing the reliability and consistency of the results obtained. The

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specimens were tested for tensile strength according to ASTM D3039 standards and for flexural bending behaviors according to ASTM D790 standards. The impact strength of the specimens was obtained from ASTM D256 standards for the use of the Izod impact test and ASTM D6110 standards for the use of the Charpy impact test. Speeds at which the bumpers were tested:

- full front/rear tests ≈ 6 mph (≈10 km/h
- corner tests ≈ 3 mph (≈5 km/h) Examples of IIHS protocol tests used to assess damage and repair cost.

The low speed of ~5-10 mph is employed since, at improper engagement or height difference between bumpers, there can be an undesirable transfer of energy to lights, hood, grille, and structure, which can cause repair costs to rise from a few hundred to thousands.

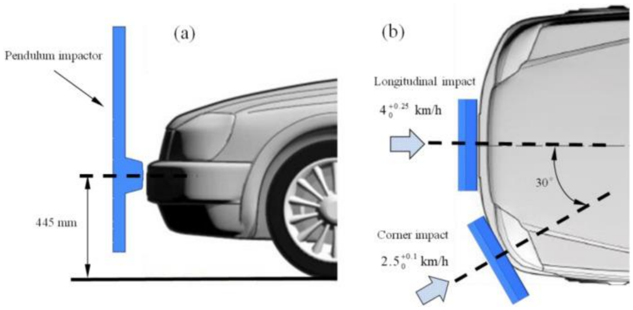

FIG 3 : TESTING CONDITION [11]

VI. DESIGN AND SIMULATION ANALYSIS

A. *CAD Modeling*

A conceptual front bumper design was created based on the Renault Kwid model, considering practical geometry and mounting requirements.

Parameters	*Dimensions (mm)*
Length	1500
Height	205
Hole Diameter	100
Center Cut	80*40

TABLE II. MECHANICAL DIMENSIONS

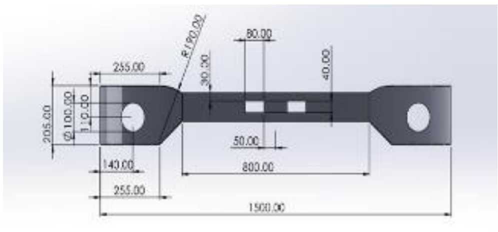

FIG 4 : CAD DESIGN

B. *Finite Element Analysis (FEA)*

Simulations were performed based on FMVSS low-speed impact conditions (2.5-5 mph). Deformation, stress, strain, energy absorption, and factors of safety were the parameters analyzed.

Parameters	*PolyPropylene*	*Reinforced Hybrid Fiber*
Stress	94.60	233.82
Strain	0	0
Factor of Safety	15	15

TABLE III. ANALYSIS RESULTS

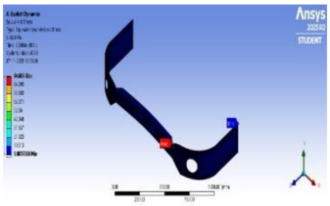

FIG 5 : STRESS – PP

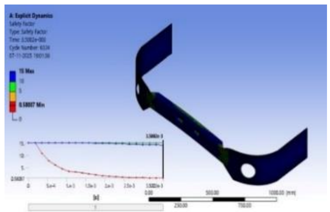

FIG 6 : STRESS – HYBRID

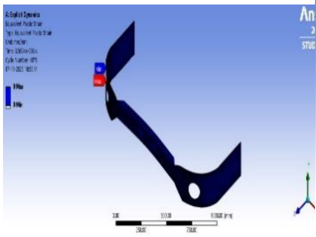

FIG 7 : STRAIN – PP

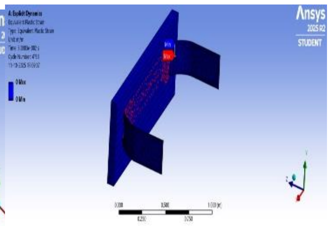

FIG 8 : STRAIN – HYBRID

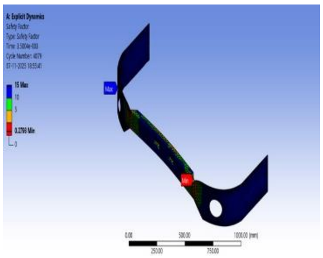

FIG 9 : FOS – PP

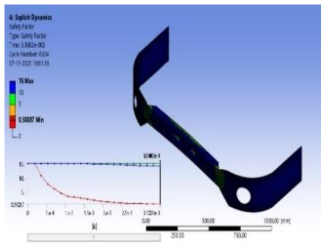

FIG 10 : FOS – HYBRID

C. *Simulation Results*

The hybrid fiber bumper designs showed lower deformation and greater energy absorption than banana-based composites. Deformation was within acceptable limits (<20 mm) for low-speed impacts, with a greater factor of safety than polypropylene.

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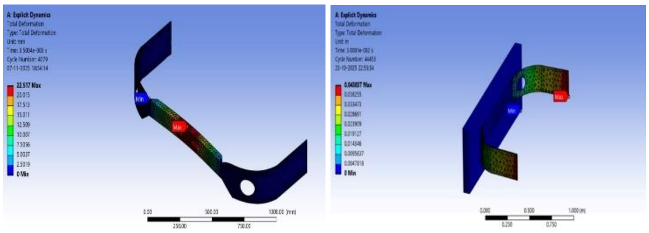

FIG 11 : DEFORMATION OF PP & HYBRID

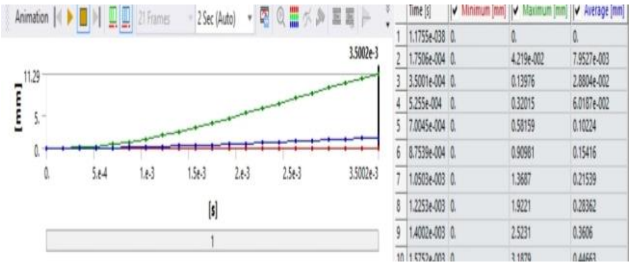

FIG 12 : DEFORMATION OF HYBRID

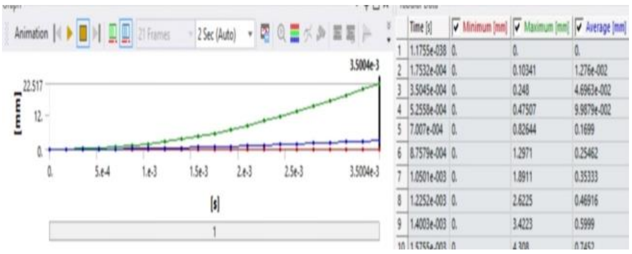

FIG 13 : DEFORMATION OF PP

VII. COST AND SUSTAINABILITY ASSESSMENT

Natural fibers play an important role in reducing the cost of the materials used and carbon footprint. Banana and jute fibers are from agricultural waste materials; they contribute to sustainable development by the concept of the circular economy. Hybrid composites aid the reduction of synthetic plastics used while maintaining their mechanical properties.

VIII. RESULTS AND DISCUSSION

A. Tensile Test

The tensile strength of the hybrid banana-jute glass composites ranged between 9.38 KN, which satisfied the minimum requirement for the automotive bumper face sheets. The hybridization process resulted in improved tensile strength compared to the use of individual composites from natural fibers.

Material	***Sample 1***	***In Mpa***
Glass Fiber	7.2 kN	64 Mpa
Hybrid Fiber	5.92 kN	53 Mpa
Natural Fiber	4.3 kN	38 Mpa

TABLE IV. TENSILE TEST RESULTS

B. Flexural Test

The flexural test results showed improved bending strength and rigidity because of the synergistic interaction of hybrid fibers. The hybrid laminate showed higher resistance to crack initiation and propagation.

Material	***Sample 1***	***In Mpa***
Glass Fiber	10 Kg	15.3 Mpa
Hybrid Fiber	30 Kg	46 Mpa
Natural Fiber	20 Kg	31 Mpa

TABLE V. FLEXURAL TEST RESULTS

C. Impact Strength Test

The impact test results indicated the superior energy absorption potential of hybrid composites. The enhancement of resistance to sudden impact by the addition of layers of glass fibers made it a suitable candidate for low-speed crash application.

Material	***Sample 1***
Glass Fiber	8.00 J
Hybrid Fiber	4.03 J
Natural Fiber	7.68 J

TABLE VI. IMPACT TEST RESULTS

IX. CONCLUSION

The present study verifies the possibility of creating an eco-friendly car bumper using a hybrid composite material composed of banana, jute, bamboo, and a small amount of E-glass fibers in an epoxy resin using the hand-layup method. The composite material was planned to have a thickness of 5 mm with a fiber volume fraction ranging from 40 to 50%. The FE analysis was carried out using the low-speed impact test as per FMVSS norms, with impact velocities ranging from 2.5 to 5 mph. It was found that the deformation was minimized to

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19.12 mm compared to 20.00 mm in the case of polypropylene, with a maintained factor of safety of 1.5, which indicates good impact characteristics. The tensile properties were also tested experimentally according to the ASTM D3039 protocol, which found that the hybrid composite can withstand a load of 5.92 kN at a pressure of 53 MPa, compared to 7.2 kN (64 MPa) for glass fiber and 4.3 kN (38 MPa) for natural fiber alone, which indicates a good balance and sustainability. The hybrid composite also offers good flexural properties compared to natural fiber and glass fiber, as found in the experimental study done according to the ASTM D790 protocol, which found that the hybrid composite can withstand a pressure of 46 MPa, compared to 31 MPa for natural fiber and 15.3 MPa for glass fiber, which indicates good sustainability and a better alternative to natural fiber and glass fiber. The hybrid composite also offers good impact characteristics, as found in the experimental study done according to the ASTM D256/D6110 protocol, which found that the hybrid composite can withstand an energy absorption of 4.03 J, compared to 8.00 J for glass fiber and 7.68 J for natural fiber, which indicates good sustainability and a better alternative to natural fiber and glass fiber.

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