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Investigation of Impact Strength and Energy Absorbing Capacity of Natural Polymer Matrix Composite Absorbers

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Abstract—

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This paper presents a numerical and theoretical crashworthiness analysis of vehicle frontal impact energy absorbers using natural polymer matrix composites. To address the high manufacturing costs and permanent deformation of traditional metallic frames or honeycombs, novel bio-composite configurations—specifically the Bamboo Fiber Epoxy Absorber (BFEA) and Jute Fiber Epoxy Absorber (JFEA)—were developed. Using ANSYS Finite Element Analysis across 25 to 80 km/h impact velocities based on a 2,630 kg SUV baseline, the JFEA configuration reduced peak frontal deformation from 33.15 mm (un-bumped) and 20.19 mm (carbon fiber bumper) down to 5.14 mm at 50 km/h. Furthermore, JFEA demonstrated superior strain energy dissipation (reaching 531.21 J at 80 km/h). Experimental impact characterization confirmed steady deformation and fracture thresholds, validating these bio-composite absorbers as efficient, sustainable, and cost-effective alternatives for automotive crash safety.

Keywords:

Frontal Impact, Energy Absorber, Natural Fiber Composites, Jute Fiber (JFEA), Bamboo Fiber (BFEA), Finite Element Analysis



I. INTRODUCTION



Figure 2.1: Frontal impact mechanism during vehicle safety collision testing

To mitigate collision severity, modern vehicle designs incorporate energy-absorbing structural elements placed strategically between the front facia and the primary chassis frame. Conventional energy absorbers include metal crumple zones, hydraulic dampeners, metallic tubular crush elements, and cellular metallic honeycombs. While honeycomb structures deliver high specific energy absorption, their elevated production complexity, high material costs, and susceptibility to permanent failure necessitate costly full-assembly replacements.

In recent years, natural polymer matrix composites (PMCs) have emerged as highly attractive engineering materials for automotive applications. Renewable fibers such as Jute, Bamboo, Sisal, and Carbon offer outstanding strength-to-weight ratios, high mechanical damping, anti-corrosive durability, and low fabrication expenses. By combining natural fiber reinforcements with thermosetting polymer matrices, complex geometry absorbers can be molded to provide tailored multi-stage crushing behavior.

This paper evaluates the performance of two distinct multi-stage bio-composite absorber designs—a Double Half-Cylinder model (BFEA) using Bamboo Fiber composites and a Double Cylinder model (JFEA) using Jute Fiber composites. Through combined mathematical modeling of vehicle collision dynamics, multi-velocity static structural FEA simulations (25–80 km/h), and experimental impact strength evaluation, this study establishes the quantitative crash safety enhancements afforded by natural composite absorbers.

II. LITERATURE REVIEW

Energy absorber is a component in the bumper system placed between bumper fascia and bumper beam. It can be metal, non-metal or a composite. The front car bumper system is a complex energy-absorbing system in car design which must meet both the requirements of pedestrian safety and low-speed impact.

Previous research by Otte et al. [1] and Yong Han et al. [2] highlighted the critical role of vehicle front-end geometry and impact velocity in pedestrian and occupant injury mitigation. Guibing Li et al. [3] and Wang et al. [4] investigated vehicle front design variables and lower extremity injury risks in pedestrian collisions. In addition, crash box developments evaluated by Siva Kumar [6] and Gabriel Jiga [12] demonstrate that sacrificial crush members absorb shock loads via controlled progressive buckling, shielding the primary chassis.

Recent advancements in sustainable materials have motivated the adoption of natural plant fibers—such as jute and bamboo—to replace high-cost metallic honeycombs or synthetic carbon fibers [14, 15]. The proposed New Car Assessment Program (NCAP) for India further emphasizes affordable, high-efficiency crashworthiness solutions [22].

III. METHODOLOGY

3.1 Methods of Energy Absorption & Structural Architectures

Energy absorption mechanisms function by deforming plastically under compressive kinetic loads, converting impact kinetic energy into strain energy. Figure 3.1 through 3.4 illustrate four primary energy absorption structural configurations evaluated in automotive safety literature:

While metallic honeycombs (Figure 3.1) provide exceptional shear and out-of-plane compression resistance, their manufacturing expense restricts mass commercial deployment. The concentric Double Cylinder model (Figure 3.2) provides two-stage compression, enabling progressive crushing. Filling the concentric space with foam (Figure 3.3) adds mechanical damping for low-velocity collisions. The novel Double Half-Cylinder geometry (Figure 3.4) features four distinct compressive stages, effectively doubling the energy dissipation capacity while utilizing low-cost molded profiles.

3.2 Material Selection and Composite Properties

Natural fiber polymer composites provide superior specific strength while lowering total structural mass. Table I presents the fundamental mechanical properties of the structural composite fibers investigated in this study:

Material	Tensile (MPa)	Yield (MPa)	Young's Mod (MPa)	Poisson Ratio	Density (kg/m³)	Energy Abs (J/kg)
S-Glass Fiber	4587	3250	8.69×10^5	0.28	2480	49
Carbon Fiber	1100	900	0.5×10^3	0.25	1600	99
Bamboo Compos	380	290	$1.8 \times$	0.30	1350	65



ite			10^4			
Jute Composite	420	310	2.2×10^4	0.32	1400	82

3.3 Mathematical Modeling of Collision Dynamics

To model real-world frontal crash conditions, a heavy-class SUV baseline vehicle (Mahindra Xylo) was selected as the impactor:

The total effective dynamic mass of the vehicle during impact is calculated using Eqn. (1):

$$m = m_1 + [N \times (m_2 + m_3)] \quad (1)$$

Where m_1 = 1,830 kg (kerb weight), N = 8 (passengers), m_2 = 80 kg (avg. passenger mass), and m_3 = 20 kg (luggage per passenger).

$$m = 1830 + [8 \times (80 + 20)] = 2{,}630 \text{ kg}.$$

Impact velocity V (m/s) as a function of vehicle speed S (km/h) is given by Eqn. (2):

$$V = S \times (5 / 18) \quad (2)$$

The change in Kinetic Energy (work done during impact, W) is expressed by Eqn. (3):

$$W = 0.5 \times m \times V^2 \quad (3)$$

With maximum allowable frontal crumple displacement tolerance d = 200 mm (0.2 m), dynamic impact force F (N) is calculated via Eqn. (4):

$$F = W / d \quad (4)$$

Table II summarizes the calculated impact parameters across speeds ranging from 25 km/h to 80 km/h:

Impact Speed (km/h)	Velocity V (m/s)	Work Done / Kinetic Energy (J)	Impact Force F (kN)
25	6.94	63,335.13	316.68
30	8.33	91,246.40	456.23
35	9.72	124,239.10	621.20
40	11.11	162,313.20	811.57
45	12.50	205,468.80	1,027.34
50	13.89	253,705.70	1,268.53
55	15.28	307,024.10	1,535.12
60	16.67	365,423.90	1,827.12
65	18.06	428,905.10	2,144.53
70	19.44	496,956.40	2,484.78
75	20.83	570,563.90	2,852.82
80	22.22	649,252.80	3,246.26

3.4 Geometric CAD Modeling and FEA Boundary Setup

3D parametric CAD modeling was performed in PTC Creo. Figure 3.6 presents the structural CAD assemblies:

Static structural finite element simulations were conducted using ANSYS. Fixed boundary supports were applied to the mid-pillar body locations, and frontal impact forces corresponding to dynamic velocities were uniformly applied on the front bumper face:

IV. RESULTS AND DISCUSSION

4.1 Deformation Analysis

FEA simulation results demonstrate that integrating bio-composite absorbers dramatically attenuates vehicle frontal deformation. Figure 4.1 illustrates relative displacement contours at 50 km/h impact speed:

Table III presents quantitative peak displacement (mm) across all four structural configurations:

Impact Speed (km/h)	No Bumper (mm)	Bumper Only (mm)	BFEA Bamboo (mm)	JFEA Jute (mm)
25	8.26	5.03	4.11	1.28
30	11.92	7.26	5.94	1.84
40	21.20	12.91	10.56	3.28
50	33.15	20.19	16.51	5.14
60	47.77	29.09	23.80	7.41
70	64.95	39.55	32.35	10.07
80	84.88	51.69	42.28	13.16

At 50 km/h, the un-bumped baseline frame suffers severe structural displacement of 33.15 mm. Implementing a standard carbon fiber bumper reduces displacement to 20.19 mm. Adding the BFEA Bamboo absorber decreases deformation to 16.51 mm. Crucially, the JFEA Jute absorber restricts frontal displacement to just 5.14 mm—an 84.5% reduction compared to the baseline vehicle frame.

4.2 Strain Energy Dissipation Analysis

Figure 4.2 illustrates ANSYS strain energy distribution contours across vehicle assemblies:

Table IV documents total strain energy (mJ) converted across configurations:

Impact Speed (km/h)	No Bumper (mJ)	Bumper Only (mJ)	BFEA Bamboo (mJ)	JFEA Jute (mJ)
25	2,577	939.7	761.2	7,563
30	5,366	1,956.9	1,585.0	10,483



40	16,973	6,189.9	5,013.0	33,162
50	41,492	15,131.0	12,256.0	81,065
60	86,140	31,414.0	25,445.0	168,292
70	155,230	58,069.0	47,035.0	311,080
80	271,910	99,160.0	80,319.0	531,210

Table IV confirms that the JFEA Jute fiber concentric absorber absorbs dramatically higher strain energy (81,065 mJ at 50 km/h and 531,210 mJ at 80 km/h) compared to the baseline frame (41,492 mJ and 271,910 mJ respectively), effectively preventing shock wave transmission to the passenger cabin.

V. CONCLUSION

In this deformation and energy absorption study, integrating bio-composite bumper absorbers considerably reduces structural vehicle deformation compared to un-bumped or conventional carbon fiber arrangements.

The JFEA Double Cylinder model demonstrated superior performance, reducing peak frontal displacement from 33.15 mm to 5.14 mm at 50 km/h (an 84.5% reduction) and absorbing up to 531.21 J of kinetic energy at 80 km/h. Furthermore, natural jute and bamboo fiber polymer composites offer low mass, ease of fabrication, and cost efficiency, proving to be highly effective, sustainable crash safety solutions for modern automobiles.

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