Design and Structural Analysis of Hybrid Composites for EV Bumper Panels

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ABSTRACT:
This study presents a novel coconut coir/E-glass hybrid composite for electric vehicle (EV) bumper panels, tackling the demand for lightweight, crash-resistant, and sustainable automotive materials. While synthetic fiber composites currently prevail, their environmental footprint and cost pose challenges for long-term use. Here, coir, a renewable, affordable natural fiber, is combined with E-glass (15 vol% each) in a polyester matrix, striking a balance between eco-efficiency and mechanical strength. Finite element analysis (FEA) simulations under static, modal, and dynamic loads reveal the composite's enhanced energy absorption, with 6.3% greater total deformation (0.08427 m vs. 0.079294 m) during frontal impact and 1.3% higher directional deformation (0.079362 m vs. 0.078359 m) during side impacts compared to conventional polypropylene (PP+EPM-TD15). The design also improves stress distribution (1.6528×10^9 Pa vs. 1.636×10^9 Pa), increases structural flexibility and improves energy dissipation under dynamic loading with a 18.3% lower natural frequency (5.5886 Hz vs. 6.8412 Hz). These results affirm coir's potential as a sustainable reinforcement, matching synthetic material's crashworthiness while supporting weight reduction goals. Addressing gaps in dynamic performance and scalability from prior research, this work offers a blueprint for next-generation EV materials aligned with global sustainability objectives. The findings highlight bio-hybrid composite's promise in automotive safety systems, advancing decarbonization efforts without sacrificing structural reliability.
Keywords: *Hybrid composites; Electric vehicles (EVs); Coconut coir; Crashworthiness; Finite element analysis (FEA); Sustainable automotive materials.*

1. INTRODUCTION

The automotive industry's shift toward electric vehicles (EVs) demands innovative materials that reconcile lightweight design with crash safety and sustainability [1]. Bumper panels, critical for energy absorption and pedestrian protection, traditionally rely on steel or aluminum, which compromise vehicle efficiency due to their weight [2]. Polymer composites reinforced with synthetic fibers (e.g., carbon, glass) offer high strength-to-weight ratios but face challenges in cost, recyclability, and reliance on non-renewable resources [3]. Hybrid composites integrating natural fibers like coconut coir with synthetic reinforcements present a promising alternative, balancing performance and eco-efficiency [4]. However, prior studies on natural fiber hybrids for EV bumpers remain limited, particularly in dynamic crashworthiness, long-term durability, and scalable manufacturing [5]–[7]. Current research gaps persist in three areas: (1) insufficient data on coir/E-glass hybrids under dynamic loads [8], (2) unresolved trade-offs between natural fiber biodegradability and structural stability [9], and (3) manufacturing complexities hindering large-scale adoption [10]. While recent work by Dashtizadeh et al. [2] and Patil et al. [7] highlights the potential of hybrid

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composites, their focus on static loading or synthetic-dominated designs limits applicability to EVs requiring lightweight, crash-resistant solutions. This study addresses these challenges by designing and analyzing a coir/E-glass hybrid composite (15 vol% coir, 15 vol% E-glass, polyester matrix) for EV bumper panels. Key objectives include:

- Evaluating structural stability and energy absorption under static and dynamic loads using finite element analysis (FEA).
- Benchmarking performance against conventional polypropylene composites (PP+EPM-TD15).

2. LITERATURE REVIEW

The pursuit of lightweight, sustainable, and crash-resistant materials for electric vehicle (EV) bumper panels has driven significant research into hybrid composites [1]–[15]. Rajak et al. [1] reviewed fiber-reinforced polymer composites, noting their high strength-to-weight ratio for automotive applications but highlighting scalability challenges with natural fibers. Dashtizadeh et al. [2] tested Kenaf/Glass hybrid composites for bumper beams, achieving improved tensile strength but lower impact resistance compared to synthetic fibers. Agunsoye et al. [3] developed a coconut shell-based bio-composite bumper, reducing weight by 30%, though manufacturing complexity limits large-scale adoption. Crashworthiness studies have furthered composite bumper development. Hu et al. [4] used finite element analysis to show carbon fiber-reinforced bumpers absorb 50% more energy than steel under low-velocity impacts, but their study excluded natural fibers. Supriya et al. [5] analyzed polypropylene bumpers, finding composites superior in stress distribution, yet dynamic impact data was limited. Athimoolam et al. [6] explored nano-filler/natural fiber hybrids, reporting enhanced biodegradability but insufficient crash performance data. Adesina et al. [7] fabricated Kevlar/Jute hybrids, improving cost-efficiency with higher Kevlar content, though durability under repeated impacts was not assessed.

Theoretical and sustainable advancements also inform the field. Rafiee et al. [8] modeled low-velocity impacts on composite cylinders, offering high accuracy but lacking EV-specific applications. Jayavani et al. [9] highlighted coir fiber composite’s potential in automotive parts, yet crashworthiness studies are scarce. Szlosarek et al. [10] developed carbon fiber crash absorbers with stable crushing behavior, but natural fiber integration was absent. Singh et al. [11] and Gupta et al. [12] emphasized hybrid composite’s role in EV lightweighting and sustainability, reporting reduced emissions and enhanced mechanical properties. Zhang et al. [13] simulated hybrid composite bumpers, noting improved energy absorption but minimal natural fiber focus. Patil et al. [14] tested natural fiber composites for EV crashworthiness, finding adequate impact resistance but limited durability data. Sharma et al. [15] reviewed scalable hybrid composites for EVs, identifying manufacturing as a key bottleneck.

Significant gaps remain in the literature. Few studies explore coir/E-glass hybrid composite’s structural stability for EV bumper panels under dynamic loads [2], [9]. Long-term durability and environmental impact of sustainable fibers like coir are underexplored [3], [14]. Scalability for mass production also poses challenges [3], [15]. This study addresses these gaps by designing and analyzing coir/E-glass hybrid composites, optimizing structural stability and crashworthiness while advancing sustainable, lightweight EV bumper solutions, contributing to eco-friendly automotive design.

3. MATERIALS AND METHODS

Materials

The hybrid composite bumper was developed using a polyester matrix (70 vol%) reinforced with E-glass fibers (15 vol%) and coconut coir (15 vol%). The material selection prioritized lightweighting, crashworthiness, and sustainability.

Material Properties

Key mechanical properties of the constituent materials are summarized in Table 1.

Table 1: Mechanical Properties of Materials

Material	Density (kg/m³)	Young's Modulus (MPa)	Poisson's Ratio
PP+EPM-TD15 (Existing)	1,050	2,250	0.36
Polyester	1,100	920	0.36
E-Glass Fiber	1,450	72,000	0.38
Coconut Coir	1,250	633	0.375

(a) E-glass fiber

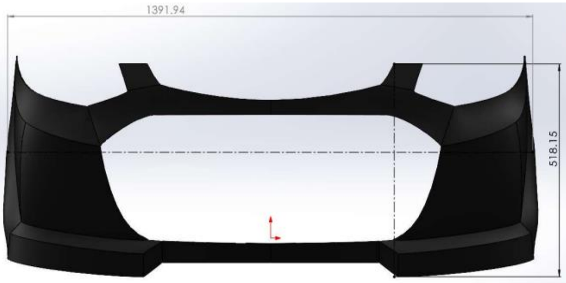
(b) Coconut coir

Figure 1: Reinforcement materials:
(a) E-glass fiber, (b) Coconut coir.

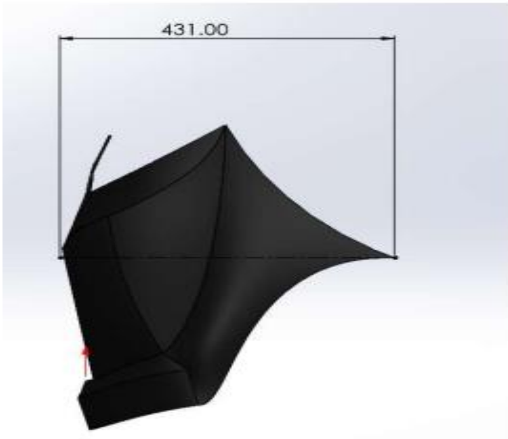
4. BUMPER DESIGN AND ANALYSIS

4.1. Design

Geometric Modeling: The E-Trio bumper (length: 1,394 mm, thickness: 4 mm) was reverse-engineered in Solid Works. Curvature was replicated using spline tools, and surfaces were thickened to meet NHTSA standards.



(a) Front View



(b) Side View

Figure 2: Bumper CAD model: (a) Front view, (b) Side view.

Finite Element Setup:

- **Meshing**: A tetrahedral mesh (45,466 elements, 16,031 nodes) was generated in ANSYS (Figure 3). Mesh quality (0.54) ensured convergence.
- **Material Assignment**: Orthotropic properties (Table 2) were assigned to the hybrid composite.

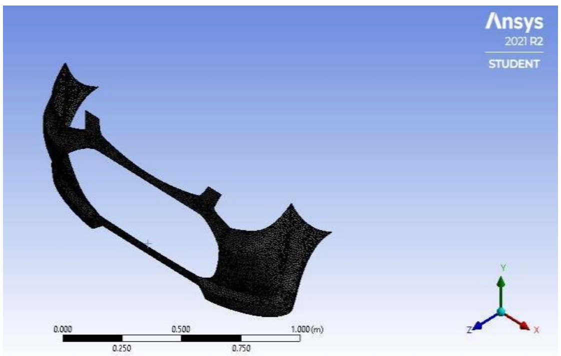


Figure 3: Meshed bumper model with proximity-curvature refinement.

Table 2: Mesh details

Mesh Type	Fine Mesh
Nodes	16031
Elements	45466
Mesh Quality	0.54

Boundary Conditions:

- Fixed supports at mounting points.
- Static load (5 kN) applied uniformly for structural analysis.

4.2. Analysis

4.2.1. Structural Analysis

The structural analysis was performed using existing materials (PP+EPM-TD15) and hybrid composite materials (Polyester, E glass-fibre, and coconut coir) under a constant load of 5 kN.

Existing Material Bumper

Figure 4, Figure 5 and Figure 6 show the total deformation, Equivalent elastic strain and Equivalent stress of the model respectively. The structural analysis on the model with existing material, that is, PP+EPM-TD15, was carried out with a uniform constant load of 5 kN.

(i) Total Deformation

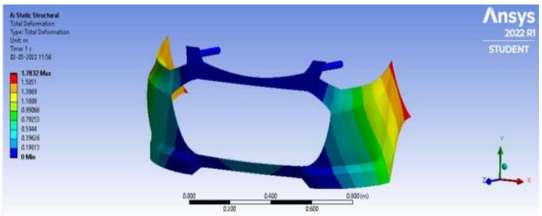


Figure 4: Total Deformation of Existing Material Bumper

(ii) Equivalent elastic strain

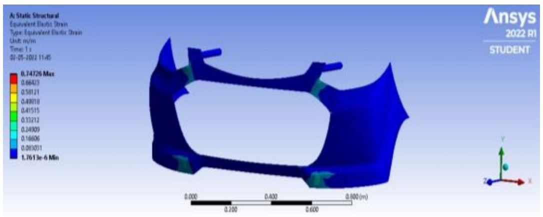


Figure 5: Equivalent elastic strain of Existing Material Bumper

(iii) Equivalent stress

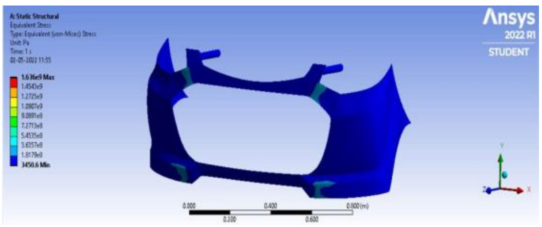


Figure 6: Equivalent stress of Existing Material Bumper

Hybrid Composite Material Bumper

Figure 7, Figure 8 and Figure *9* show the total deformation, Equivalent elastic strain and Equivalent stress of the model respectively. The structural analysis on the model with new material, that is, combination of Polyester with E-Glass Fibre and Coconut Coir, was carried out with a uniform constant load of 5 kN.

(i) Total Deformation

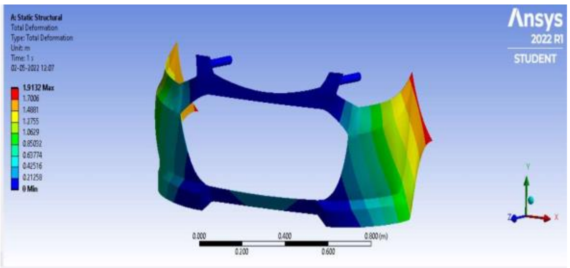


Figure 7: Total deformation of Hybrid Composite material bumper

(ii) Equivalent elastic strain

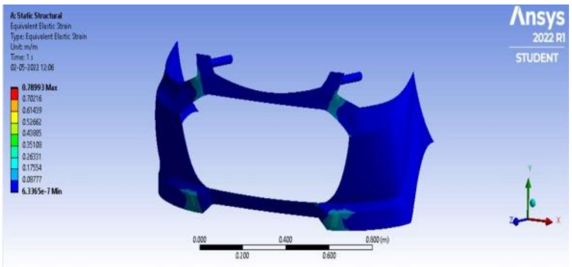


Figure 8: Equivalent elastic strain of Hybrid Composite material bumper

(iii) Equivalent stress

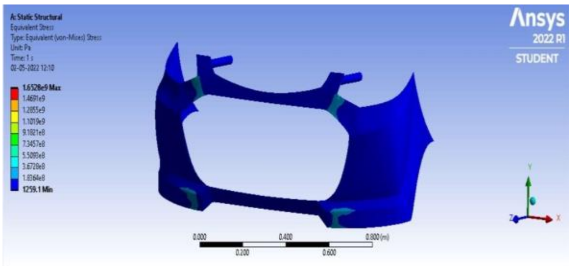


Figure 9: Equivalent stress of Hybrid Composite material bumper

Table 3: Comparison of Structural Analysis Results

Description	**Existing Material**	**Hybrid Composite**
Total Deformation (m)	1.7832	1.9132
Equivalent elastic strain	0.74726	0.78993
Equivalent stress (Pa)	1.636×10^9	1.6528×10^9

4.2.2. Modal Analysis

Modal analysis is the fundamental dynamic analysis type, providing the natural frequencies at which a structure will resonate. These natural frequencies are of paramount importance in various engineering fields. Suspensions are usually tuned to have different natural frequencies for passenger cars and race cars.

Modal Analysis performed on Existing Material Bumper

Figure 10 and Figure 11 show the natural frequency and directional deformation of the model respectively. The modal analysis on the model with existing material, that is, PP+EPM-TD15, was carried out.

(i) Total deformation (Natural Frequency)

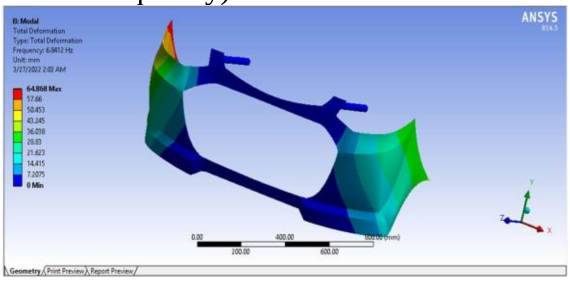


Figure 10: Total deformation (Natural Frequency) of existing material bumper

(ii) Random Vibration

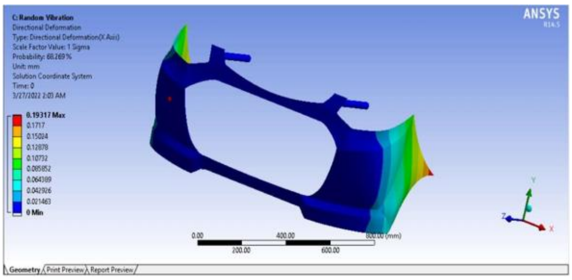


Figure 11: Random vibration of existing material bumper

Modal Analysis performed on Hybrid Composite Material Bumper

Figure 12 and Figure 13 show the natural frequency and directional deformation of the model respectively. The modal analysis on the model with new material, that is, combination of Polyester with E-Glass Fibre and Coconut Coir, was carried out.

(i) Total deformation (Natural frequency)

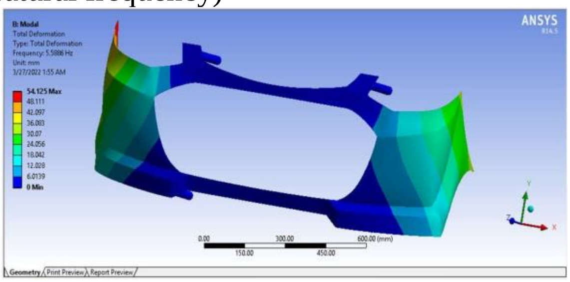


Figure 12: Total deformation of Hybrid Composite material bumper

(ii) Random Vibration

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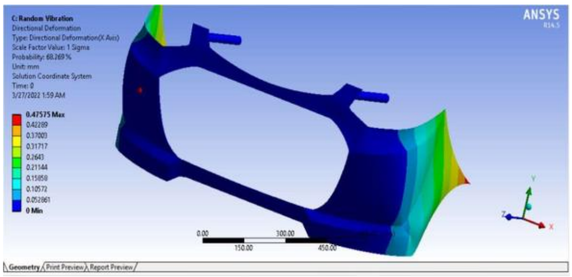

Figure 13: Random Vibration of Hybrid Composite material bumper

Table 4: Comparison of Modal Analysis

Description	Existing Material	Hybrid Composite Material
Directional Deformation (mm)	0.19317	0.47575
Natural Frequency (Hz)	6.8412	5.5886

4.2.3. Explicit Dynamic Analysis

Side Impact analysis performed on existing material bumper

Figure 14 and Figure 15 show the total and directional deformation of the model respectively. The side impact analysis on the model with existing plastic material, that is, PP+EPM-TD15, was carried out with the help of a side impact beam while the model was sped at a speed of 50 km/hr towards the beam.

(i) Total Deformation

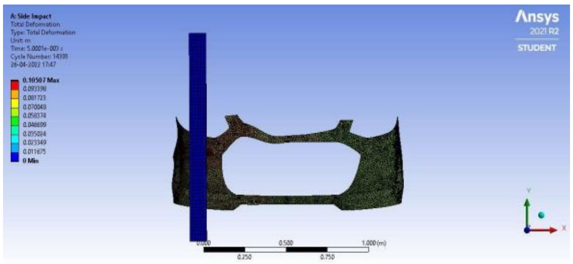

Figure 14: Total deformation of Existing material bumper

(ii) Directional Deformation

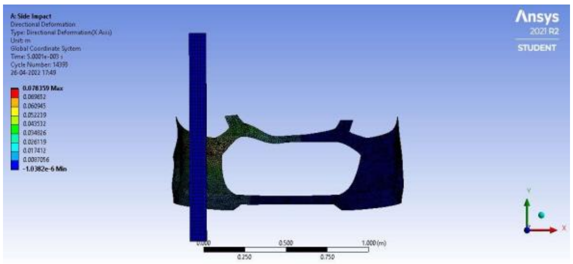

Figure 15: Directional Deformation of Existing material bumpers

Side Impact analysis performed on Hybrid composite material bumper

Figure 16 and Figure 17 show the total and directional deformation of the model respectively. The side impact analysis on the model with hybrid composite material, that is, Polyester with E-Glass Fibre and Coconut Coir, was carried out with the help of a side impact beam while the model was sped at a speed of 50 km/hr towards the beam.

(i) Total Deformation

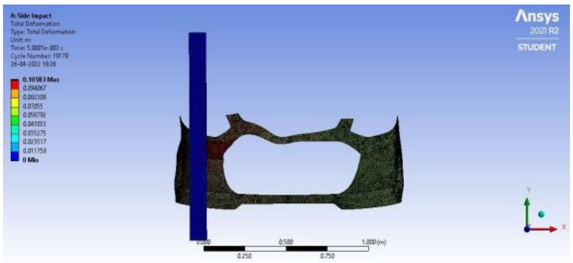

Figure 16: Total deformation of Hybrid Composite material bumper

(ii) Directional Deformation

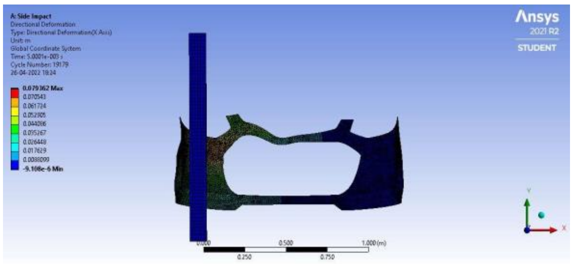

Figure 17: Directional Deformation of Hybrid Composite material bumper

Table 5: Comparison of Side impact Analysis

Description	**Existing Material**	**Hybrid Composite Material**
Total Deformation (m)	0.10507	0.10583
Directional Deformation (m)	0.078359	0.079362

From Table 5, it is inferred that the values of total deformation and directional deformation is higher for the hybrid composite model, thus proving that the hybrid composite model absorbs impact more efficiently than the conventional plastic model during side impact.

Frontal impact analysis performed on existing material bumper

Figure 18 and Figure 19 show the total and directional deformations of the model respectively. The frontal impact on the model with existing plastic material, that is, PP+EPM-TD15, was carried out with the help of a fixed wall while the model was sped at a speed of 50 km/hr towards the fixed wall.

(i) Total deformation

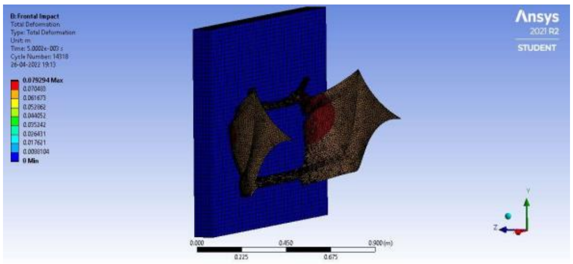

Figure 18: Frontal impact Total deformation of Existing material bumper.

(ii) Directional Deformation

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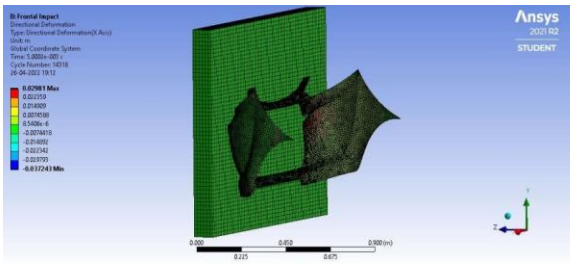


Figure 19: Frontal impact Directional deformation of Existing material bumper.

Frontal impact analysis performed on Hybrid composite material bumper

Figure 20 and Figure 21 show the total and directional deformations of the model respectively. The frontal impact on the model with hybrid composite material, that is, Polyester with E-Glass Fibre and Coconut Coir, was carried out with the help of a fixed wall while the model was sped at a speed of 50 km/hr towards the fixed wall.

(i) Total deformation

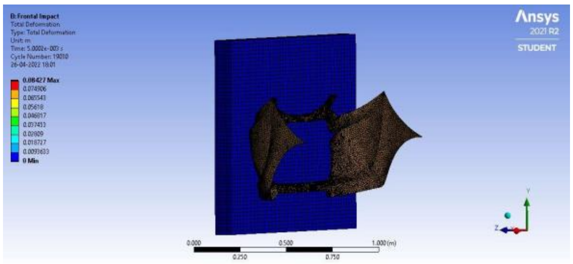


Figure 20: Frontal impact Total deformation of Hybrid Composite material bumper.

(ii) Directional Deformation

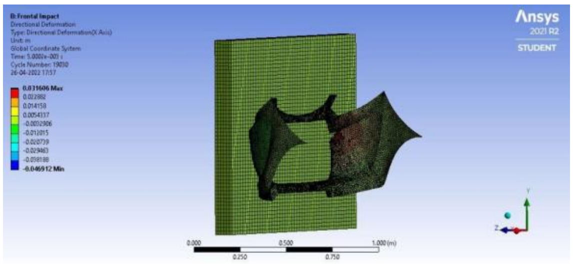


Figure 21: Frontal impact Directional deformation of Hybrid Composite material bumper.

Table 6: Comparison of Frontal Analysis

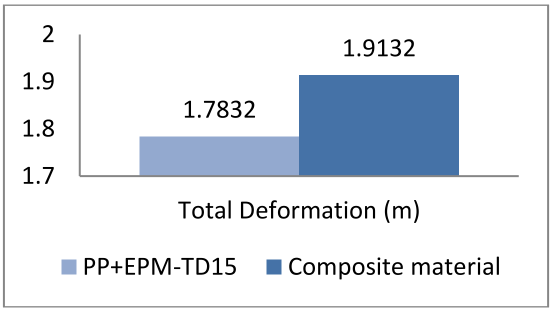
Description	**Existing Material**	**Hybrid Composite Material**
Total Deformation (m)	0.079294	0.08427
Directional Deformation (m)	0.037243	0.046912

From Table 6, it is inferred that the values of total and directional deformation are higher for the hybrid composite model, thus proving that the hybrid composite model absorbs impact more efficiently than the conventional plastic model during frontal impact.

5. RESULT AND DISCUSSION

5.1. Structural Analysis

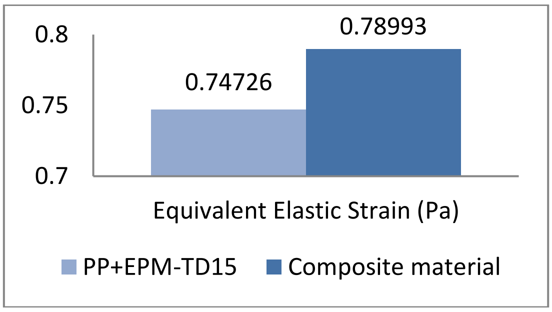
5.1.1. Total Deformation



Graph 1: Comparison of Total deformations (structural analysis)

From Graph 1, it is inferred that the total deformation on the existing model is lesser than that of the model with new material, thus concluding that the model with new material deforms more than the existing model under the application of same load of 5 kN.

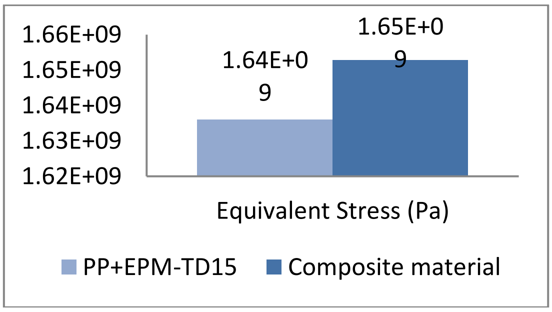
5.1.2. Equivalent elastic strain



Graph 2: Comparison of Equivalent elastic strains (structural analysis)

From Graph 2, it is inferred that the normal elastic strain is higher on the model with new material signifying the model deforms more in response to application of force compared to the existing model, thus, complementing and adhering to the findings from Graph 1.

5.1.3. Equivalent stress

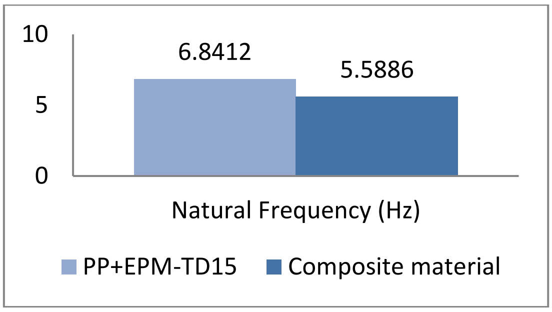


Graph 3: Comparison of Equivalent stress (structural analysis)

From Graph 3, it is inferred that equivalent stress is higher on the model with new material signifying the model with new material is capable of withstanding and transferring loads with larger magnitude compared to the existing model, thus, confirming the findings from Graph 1 and Graph 2.

5.2. Modal Analysis

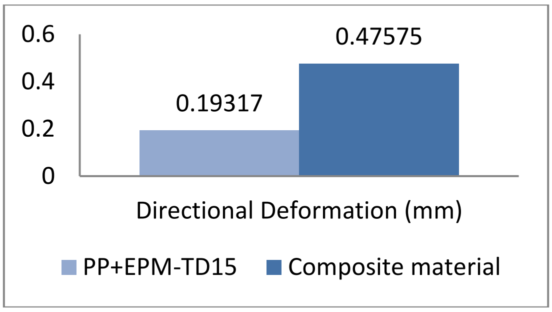
5.2.1. Total deformation (Natural Frequency)



Graph 4: Comparison of Natural frequencies (Modal analysis)

From Graph 4, it is inferred that the natural frequency is higher for the existing model compared to the new model with hybrid composites, indicating that the existing model is stiffer and less prone to vibrate under external forces. Since natural frequency is associated with the stiffness of the structure, a lower frequency in the hybrid composite model suggests greater flexibility, leading to higher deformations under load.

5.2.2. Direction deformation



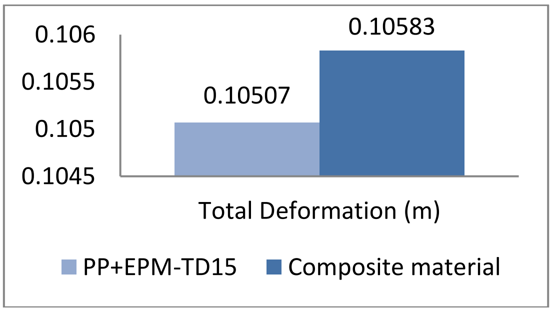
Graph 5: Comparison of Directional deformation (Modal analysis)

From Graph 5, it is inferred that the directional deformation of the model with hybrid composite incorporation has higher directional deformation compared to the existing model. This implies that the new model under dynamic loading condition tends to deform more than the existing model.

5.3. Explicit Dynamic Analysis

5.3.1. Side Impact Analysis

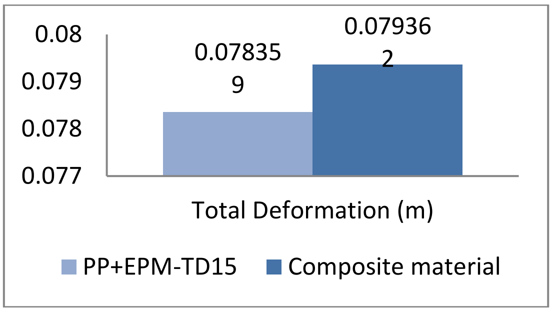
(i) Total deformation



Graph 6: Comparison of Total deformation (Side impact analysis)

From Graph 6, it is inferred that during the course of a crash, the model with hybrid composites tends to deform more than the model with conventional plastic material. This signifies that the hybrid composite model tends to better absorb energy during impact.

(ii) Directional deformation

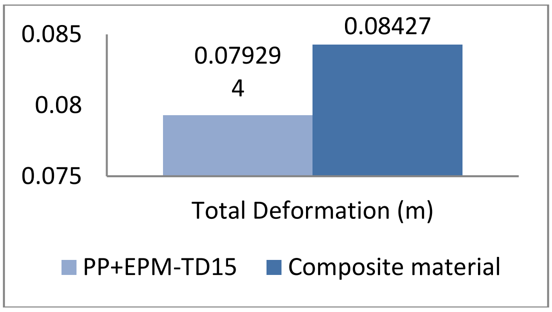


Graph 7: Comparison of Directional deformation (Side impact analysis)

From Graph 7, it is inferred that during the course of a crash, the model with hybrid composites tends to deform more in the direction of the application of force/load than the model with conventional plastic material. This signifies that the hybrid composite model tends to better absorb energy during impact and confirms the findings from Graph 6.

5.3.2. Frontal Impact Analysis

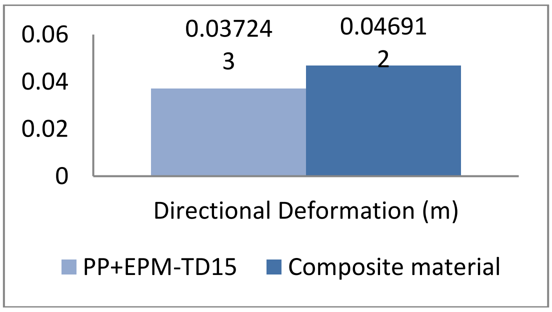
(i) Total deformation



Graph 8: Comparison of Total deformation (Frontal impact analysis)

From Graph 8, it is noted that when the model is crashed into a fixed wall, the model with hybrid composites deforms better than the model with conventional plastic, which signifies that during frontal impact, the hybrid composite model tends to better absorb the impact.

(ii) Directional deformation



Graph 9: Comparison of Directional deformations (Frontal impact analysis)

From Graph 9, it is noted that when the model is crashed into a fixed wall, the hybrid composite model deforms more in the direction of application of force, which in turn adheres to the findings from Graph 8.

6. CONCLUSION

This research evaluated the performance of a conventional PP+EPM-TD15 bumper against a hybrid composite bumper made from Polyester, E-glass fiber, and coconut coir through structural, modal, and dynamic impact analyses. The hybrid composite displayed higher deformation across all tests, with 7.3% greater total deformation (1.9132 m vs. 1.7832 m) and 5.7% more elastic strain (0.78993 vs. 0.74726) in structural analysis, indicating reduced rigidity. It exhibited a 18.3% lower natural frequency (5.5886 Hz vs. 6.8412 Hz), suggesting improved structural flexibility and energy dissipation. In dynamic tests, the hybrid material showed slightly higher deformations, such as 6.3% more in frontal impact (0.08427 m vs. 0.079294 m), pointing to enhanced energy absorption but at the expense of increased deformation. These findings highlight the trade-offs between flexibility and rigidity in sustainable material design for automotive applications.

This study contributes to automotive material science by exploring the viability of a sustainable hybrid composite in bumper design. By incorporating coconut coir, it offers an eco-friendly alternative to traditional materials, balancing stiffness with energy absorption. The detailed comparison provides engineers with critical insights into material behavior under diverse loading conditions, aiding in the development of greener automotive components.

Future research should focus on optimizing the hybrid composite’s formulation to reduce deformation while preserving its stiffness benefits. Exploring its long-term durability under environmental conditions, assessing manufacturing scalability, and conducting real-world crash tests will further validate its practical application in the automotive sector.

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