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Design And Analysis Of Envirinmental Friendly Natural Fiber Composite For Car Front Bumper

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Abstract—As the automotive industry aggressively looking to adopt sustainable materials, the design and analysis of environmentally friendly natural fiber composites is one of the promising solutions for reducing environmental impact. This study focuses on the development of a composite material derived from natural fibers (jute, hemp, sisal), specifically targeting its application in car front bumper beam. Static analysis was conducted using an ANSYS 21 to assess the tensile strength. Design of bumper beam created with the assistance of CATIA V5 R21. Finite element analysis (FEA) was employed to simulate the performance of the composite analyzing stress distribution and deformation under load. Conduct experiment using a Universal Testing Machine (UTM) and compare the FEA predictions to experimental predictions.

Keyword: Car front bumper, strength optimization, Natural composite material, Analysis, UTM.

1. Introduction

Road traffic accidents have become a critical global concern, claiming thousands of lives and injuring millions annually. In India alone, nearly 10,000 fatalities and over a million injuries are reported each year due to vehicular crashes, highlighting the urgent need for enhanced automotive safety systems. Among various protective components in passenger vehicles, the bumper beam plays a pivotal role in absorbing collision energy and minimizing damage to both the vehicle structure and its occupants. Positioned at the front and rear ends of vehicles, bumper beams act as the first line of defense in collisions, effectively reducing the severity of impact forces transmitted to the passenger cabin [2-5].

In parallel with rising safety concerns, the automotive bumper market has notable growth. Valued at $ 10.1 billion in 2022, and projected to reach $ 16.7 billion by 2032, driven by a compound annual growth rate of 5.76%. Key factors fueling this expansion include the demand for lightweight bumpers, the incorporation of crash-absorbing thermoplastic olefins, advancements in material technologies, and stringent regulatory safety standards. Furthermore, shifting consumer preferences toward vehicle customization, aerodynamics, and aesthetics have reinforced the importance of bumper design as both a functional and stylistic feature.

From a technical standpoint, crashworthiness remains central to bumper beam development. Advanced design strategies focus on mitigating the effects of abrupt accelerations during collisions, ensuring that human tolerance thresholds are not exceeded. Generally, steel has the regular material for bumper beam owing to its durability. Its high density contributes to increased vehicle weight and fuel consumption, which contradicts the industry's current focus on lightweight and environment-friendly designs. Consequently, research has pointed toward alternative materials such as Al alloys and polymer. These materials not only achieve weight reduction but also provide superior energy absorption, corrosion resistance, and formability, enabling complex aerodynamic designs[6-8].

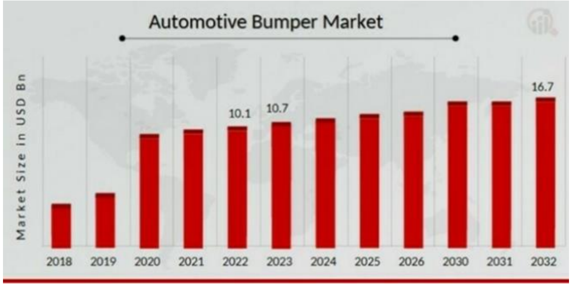


Fig 1. Automotive bumper market

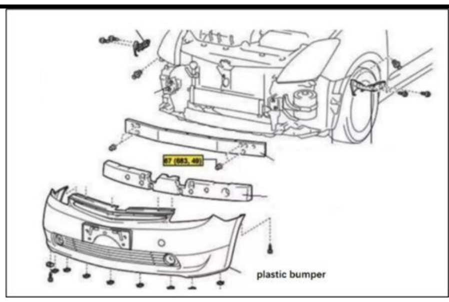


Fig 2. Front Bumper Assembly

In light of these considerations, this research seeks to investigate advanced material alternatives and design approaches for automotive bumper beams, with a focus on enhancing crashworthiness while ensuring weight reduction, cost-effectiveness, and compliance with safety regulations[5].

2. LITERATURE REVIEW

1. Vipul Jain et al.
This research incorporates an examination of the environmental concerns and weight restrictions of aluminum and steel bumpers. A composite material with glass and pineapple leaf fibers was selected as an alternative for the bumpers of an ambassador vehicle. The bumper was designed using CATIA and ANSYS was utilized for testing. The initial and final designs results indicated the geometric optimizations made along with the strategic placement of ribs and thickness variations made considerable progress in increasing the strength of the bumper. The hybrid bio-composite was superior in strength while maintaining moderate weight, and withstanding greater deformation. This composite will fit the automotive lightweight structures.

2. N. Murugu Nachippan et al.
The research looks at what natural fiber reinforced composites do to reduce bumper weight and improve biodegradability. We did finite element analysis of bumpers which we modeled with glass fiber and hybrid glass natural fiber composites. We looked at static parameters which include deformation, von Mises stress, and strain. We found that which glass treated hemp fiber composites had the least deformation thus very appropriate for automotive bumper applications.

3. Shada Bennbaia et al.
It identifies the bumper as the main energy-absorbing part and develops a composite–plastic hybrid design to be manufactured through 3D printing. It optimizes the spiral energy absorber structure by comparing various diameters under low-impact conditions. Variations tested include pure thermoplastic, Kevlar-reinforced composite, and thermoplastic filled with foam. Four more spirals added to the existing five offering the maximum energy absorption as well as controlled failure clearly indicate suitability in crash energy management applications.

4. Sai Kiran Sidde et al.
The study investigates the use of natural fiber composites as a sustainable alternative to plastic in car bumpers. Jute fiber composites were modeled and compared with plastic bumpers using finite element analysis under identical impact conditions. Results showed that jute fiber exhibited lower equivalent stress, higher yield limit, and reduced deformation (2.1 mm compared to 11.7 mm in plastic). These findings demonstrate that jute fiber composites can effectively replace plastic bumpers while minimizing environmental impact.

5. Hossein Mohammadi et al.
The paper highlights the importance of lightweight materials for fuel efficiency and emission reduction in automobiles. Fiber-reinforced plastics (FRPs) were studied as replacements for steel and cast iron in bumper beams, with glass fibers providing superior reinforcement. The focus was on the mechanical performance and manufacturing methods of glass fiber–reinforced polymer bumpers. The findings suggest that glass fiber composites offer higher crashworthiness and impact resistance compared to traditional materials, making them promising for automotive use.

6. Dil Jan et al.
This review evaluates bumper beams under crash conditions, focusing on energy absorption, pedestrian safety, and weight reduction. Traditional high-strength steel bumpers were identified as heavy, whereas composite materials provide lightweight and crashworthy alternatives. The study analyzed parameters influencing bumper design and manufacturing processes, alongside comparisons between experimental and numerical

modeling approaches. It concludes that numerical models are effective tools for designing optimized, high-performance bumper beam systems.

7. Neraj Natarajan et al.
The paper investigates bumper performance under low-speed impacts, often overlooked in bumper design. Using finite element analysis, five design variations were evaluated by altering bumper thickness and shape for both central and corner impacts. The best performance was achieved with the modified profile featuring increased thickness, which absorbed the most energy. The study highlights that vehicle damage can be reduced with proper stiffness linings on metal bumpers.

8. V. Sathish Kannan et al.
This paper presents the crash analysis of ABS material bumpers considered for designs toward passenger safety. Three models of luxury car bumpers were designed in CATIA and analyzed using ANSYS under explicit dynamic conditions, keeping a constant thickness of 5 mm for the bumper. Factors considered include equivalent stress, deformation, and plastic strain. The study came out with that design which was optimized most to withstand the forces that would act upon it during collisions.

9. Laxmikant G. Keni et al.
The study stresses the importance of bumper beams in absorbing crash energy to improve passenger safety. Using comparative analysis, bumper beams with honeycomb structures of 2 mm and 4 mm thickness were evaluated. The honeycomb design showed potential for improving crashworthiness while maintaining lightweight properties. The results emphasize the role of material, thickness, and geometry in achieving safer automotive bumper designs.

10. Bing Du et al.
This paper reviews bumper beam materials, contrasting traditional high-strength steel with modern composites. Steel bumpers, while strong and cost-effective, add significant weight, prompting the shift toward lightweight composites. The study includes fabrication methods, performance assessments, experimental validation, and finite element analysis of bumper beams. Optimization approaches are also discussed, underlining composites as the future of lightweight and high-performance bumper systems.

3. Novelty of work

1friendly alternative to conventional material such as steel, aluminum, and plastics. While past studies have investigated various synthetic and hybrid composites, this project emphasizes the exclusive use of sustainable natural fibers, ensuring biodegradability and reduced environmental impact. Furthermore, the work integrates finite element analysis (FEA) for static and impact loading conditions to assess crashworthiness, enabling a direct performance comparison with traditional bumper materials. Unlike existing approaches, this study not only focuses on weight reduction and strength enhancement but also establishes a sustainable pathway for green automotive components, making the bumper both structurally efficient and environmentally responsible.

4. Problem Statement

a. Automobile components are typically comprised of steel and its alloy resulting in increased fuel consumption

b. Thermoplastic bumpers are utilized by the majority of vehicles due to the fact that they are less expensive to produce and they absorb more energy when impacted.

c. In order to overcome certain drawbacks of bumpers made from different materials, natural fiber composites are highly suggested.

d. Therefore, it has to shift toward a light, green, and sustainable material that can take over the present ones.

5. Objectives

The main objective of this research is to design and develop automotive bumper using natural fibers. Following are the objectives of the project;

a. To Identify and select appropriate natural fibers (jute, hemp, sisal) for bumper.

b. Perform static analysis using FEA to evaluate the mechanical properties of the natural fiber composite under static load conditions.

c. Develop a specimen of selected material by using suitable method for physical analysis.

d. Conduct experimental analysis using a Universal Testing Machine (UTM)

e. Compare the performance of the natural fiber composite with conventional materials used in automotive applications.

6. Research Methodlogy

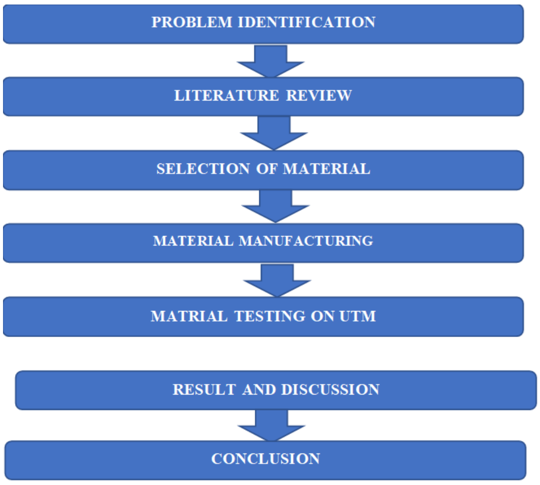


Fig 3. Research Methodology

7. Finite Element Analysis

FEA solution of engineering problems, such as finding deflections and stresses in a structure, requires three steps:

1. Pre-processing, 2. Solution, 3. Post processing

A brief description of each of these steps follows

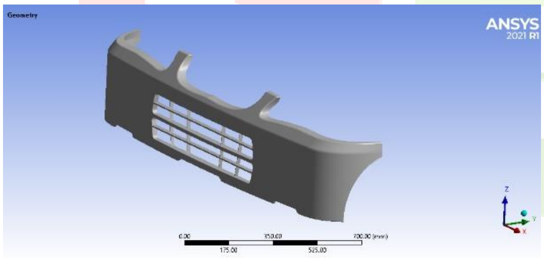
In this study, ANSYS Workbench 21.0 is used for the analysis. The general workflow of FEM in ANSYS includes:

1. Model geometry creation, 2. Mesh generation, 3. Applying boundary conditions and loads, 4. Solving the system equations, 5. Evaluating and interpreting results[3]

8. Fea Of Front Bumper Abs Material

ANSYS Workbench serves as an integrated CAE platform supporting simulations across structural, fluid, thermal, and electromagnetic domains, featuring a user-friendly interface and comprehensive pre- and post-processing tools.

Font Bumper geometry and ABS Material properties:



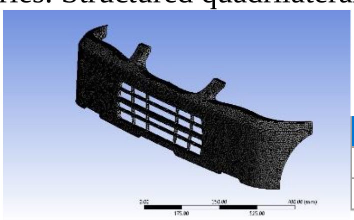
Properties of Outline Row 3: ABS

	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	1080	kg m^-3
4	Isotropic Elasticity		
5	Derive from	Young's Modulu...	
6	Young's Modulus	2.06E+09	Pa
7	Poisson's Ratio	0.45	
8	Bulk Modulus	6.8667E+09	Pa
9	Shear Modulus	7.1034E+08	Pa
10	Bilinear Isotropic Hardening		
11	Yield Strength	3.8E+07	Pa
12	Tangent Modulus	8.9E+08	Pa
13	Tensile Yield Strength	3.8E+07	Pa
14	Tensile Ultimate Strength	4.5E+07	Pa

Fig 4. Front bumper geometry and Engineering data (Material)

Meshing:

Simple geometries: Structured quadrilateral or hexahedral meshes are adequate.



Statistics	
Nodes	114036
Elements	55778

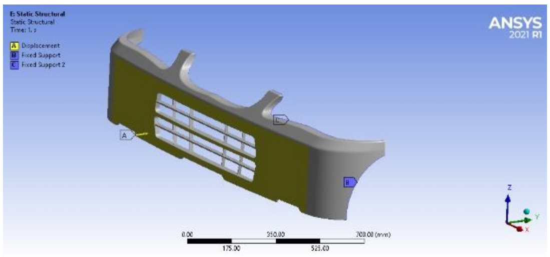
Type	Element Size
Element Size	10.0 mm

Fig 5. Finite element mesh model of existing car front bumper

Final existing car front bumper mesh model, it contains 114036 nodes and 55778 elements. Element size was 10 mm

Boundary condition:

As shown in below image 'A' shows displacement, 'B & C' shows fix support as boundary condition. Applied displacement of 2mm in the direction of Y or normal to the bumper.



Type	Displacement
Define By	Components
Coordinate System	Global Coordinate System
X Component	Free
Y Component	2. mm (ramped)
Z Component	Free

Fig 6. Boundary condition of existing car front bumper

Results:

Equivalent Stress, Equivalent Elastic strain and Maximum Principal Stress

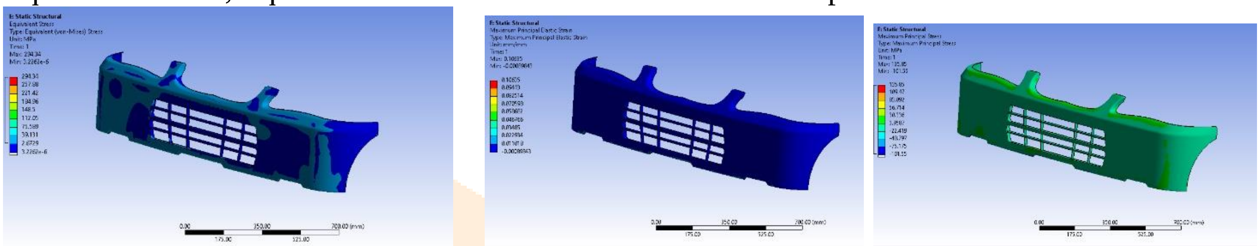
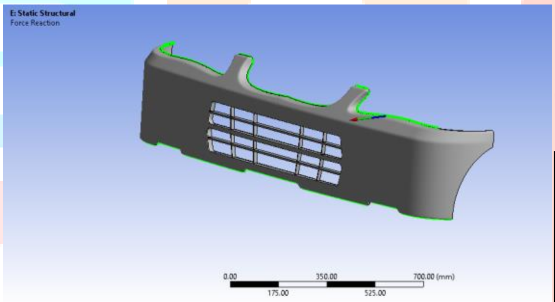


Fig 7 Equivalent Stress, Equivalent Elastic strain and Maximum Principal Stress of car front bumper

Force Reaction:

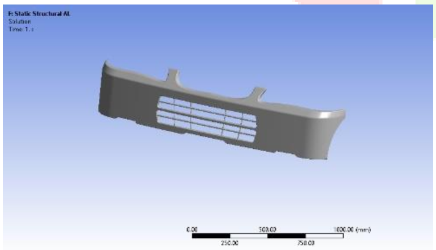


Results	
Maximum Value Over Time	
X Axis	-7.8357 N
Y Axis	-616.52 N
Z Axis	-136.9 N
Total	3157.5 N

Fig 8. Maximum Force Reaction of car front bumper

9. FEA OF CAR FRONT BUMPER WITH AL ALLOY MATERIAL

Font Bumper geometry and AL Alloy Material properties:

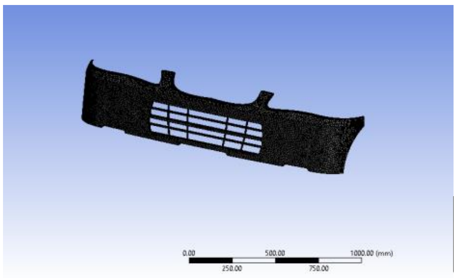


Properties of Outline Row 4: Aluminum Alloy

	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	2770	kg m^-3
4	Isotropic Secant Coefficient of Thermal Expansion		
5	Coefficient of Thermal Expansion	2.3E-05	C^-1
6	Isotropic Elasticity		
7	Derive from	Young's Modu...	
8	Young's Modulus	7.1E+10	Pa
9	Poisson's Ratio	0.33	
10	Bulk Modulus	6.9608E+10	Pa
11	Shear Modulus	2.6692E+10	Pa
12	S-N Curve	Tabular	
16	Tensile Yield Strength	2.8E+08	Pa
17	Compressive Yield Strength	2.8E+08	Pa

Fig 9. Geometry and Engineering data (Material)

Meshing:



Statistics	
Nodes	114036
Elements	55778

Type	Element Size
Element Size	10.0 mm

Fig 12. Finite element mesh model of existing car front bumper

Final existing car front bumper mesh model contains 114036 nodes and 55778 elements. Element size was 10 mm

Boundary conditions:

As shown in below image 'A' shows displacement, 'B & C' shows fix support as boundary condition. Applied displacement of 2mm in the direction of Y or normal to the bumper.

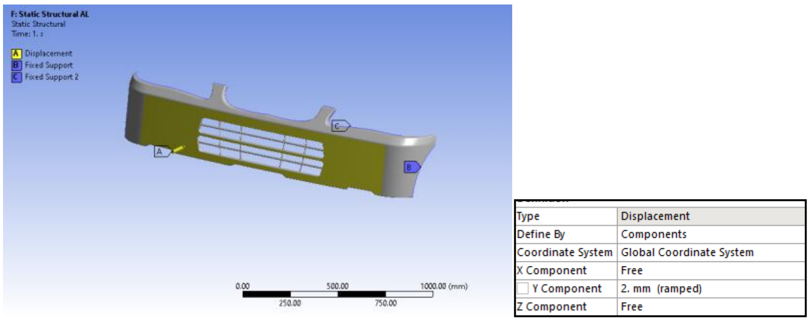


Fig 13. Boundary condition of existing car front bumper

Results:

Equivalent Stress, Equivalent Elastic strain, Maximum Principal Stress:

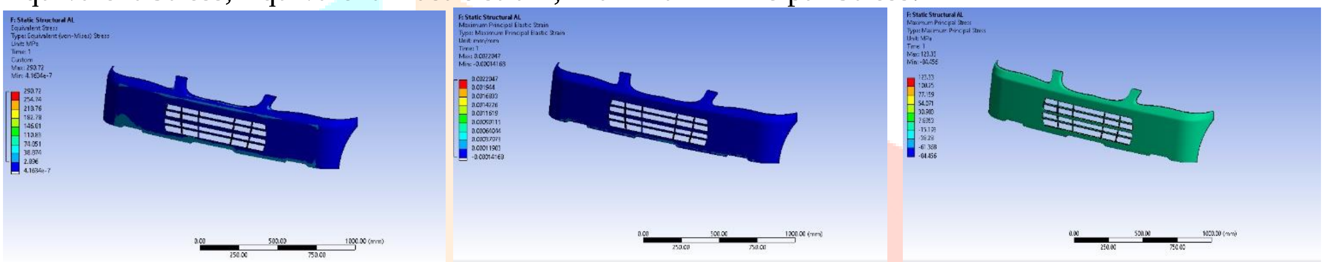


Fig 14 Equivalent Stress, Equivalent Elastic strain, Maximum Principal Stress:

Force Reaction:

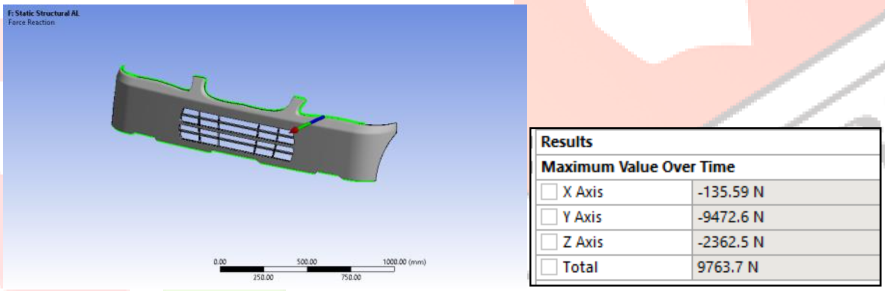


Fig 15. Maximum Force Reaction of car front bumperFEA results

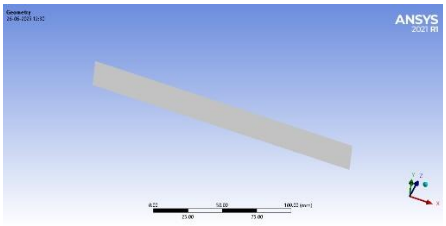
10. Comparison Table for FEA Results of ABS and AL Alloy Front Bumper

SR NO	COMPONENT	EQUIVALENT STRESS (MPa)	MAX PRINCIPAL STRESS (MPa)	FORCE REACTION (N)
1	ABS car front bumper	294.34 MPa	135.85	3157
2	Aluminum car front bumper	290.72 MPa	123.33	9763

Table 1. Comparison of FEA result of AL alloy & ABS

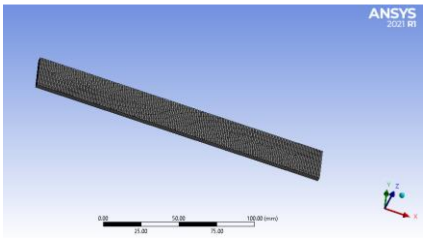
11. FEA OF ALUMINUM AND JUTE FIBER SPECIMEN

Geometry, Jute fiber Material properties and Meshing:



Properties of Outline Row 5: JUTE

	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	1.5	g cm^-3
4	Isotropic Elasticity		
5	Derive from	Young's Modulu...	
6	Young's Modulus	38	GPa
7	Poisson's Ratio	0.38	
8	Bulk Modulus	5.2778E+10	Pa
9	Shear Modulus	1.3768E+10	Pa
10	Tensile Yield Strength	800	MPa



Statistics	
Nodes	4699
Elements	4503

Type	Element Size
Element Size	1.0 mm

Fig 16. Geometry, Jute fiber Material properties and Meshing of Jute fiber specimen.

Finite mesh model contains 4699 nodes and 4503 elements. The size of elements is 1 mm

Boundary conditions:

As shown in the image 'A' is the displacement and 'B' is the fix support boundary condition.

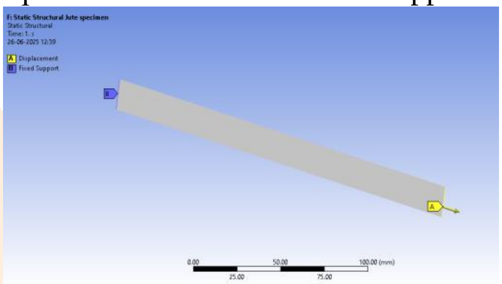
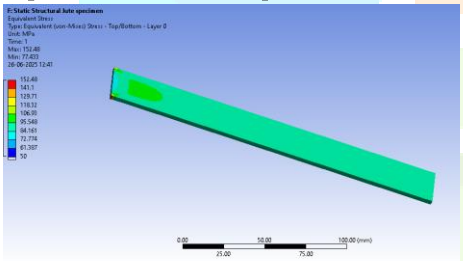
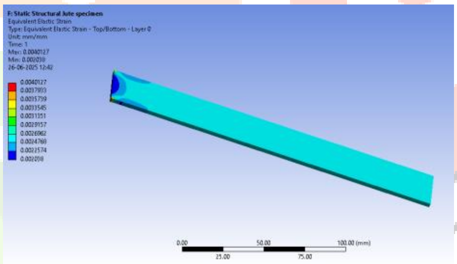


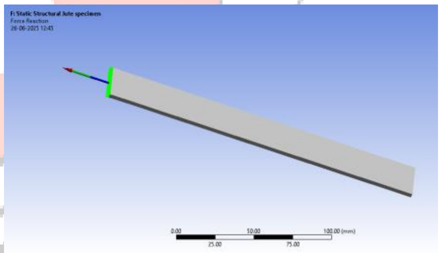
Fig 17. Boundary condition of aluminum and Jute fiber specimen

Result

Equivalent stress, Equivalent elastic strain and Force reaction of aluminum and Jute fiber specimen







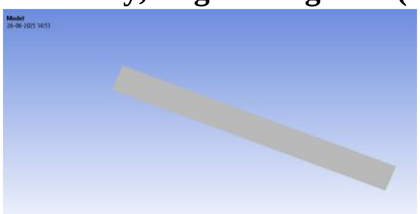
Results

Maximum Value Over Time	
X Axis	-7142.5 N
Y Axis	8.2413e-010 N
Z Axis	-2.7278e-027 N
Total	7142.5 N

Fig 18. Equivalent stress, Equivalent elastic strain and Force of reaction of aluminum and Jute fiber specimen

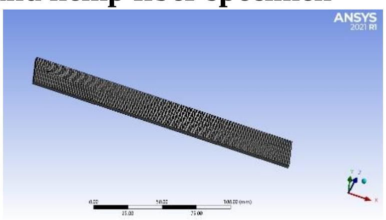
12. FEA OF ALUMINUM AND HEMP FIBER SPECIMEN

Geometry, Engineering data (Material) and mesh model of aluminum and hemp fiber specimen



Properties of Outline Row 4: HEMP

	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	1.4	g cm^-3
4	Isotropic Elasticity		
5	Derive from	Young's Modulu...	
6	Young's Modulus	70	GPa
7	Poisson's Ratio	0.15	
8	Bulk Modulus	3.3333E+10	Pa
9	Shear Modulus	3.0435E+10	Pa
10	Tensile Yield Strength	900	MPa



Statistics	
Nodes	4699
Elements	4503

Type	Element Size
Element Size	1.0 mm

Fig 19. Geometry, Engineering data (Material) and mesh model of aluminum and hemp fiber specimen

Finite mesh model contains 4699 nodes and 4503 elements. The size of elements is 1 mm.

Boundary conditions:

As shown in the image 'A' is the displacement and 'B' is the fix support boundary condition.

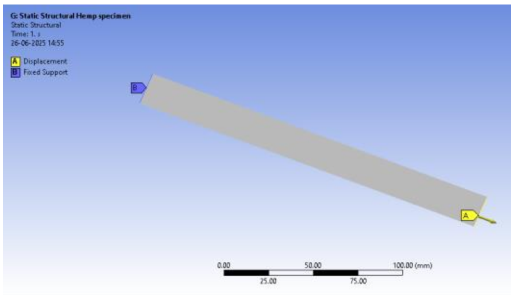
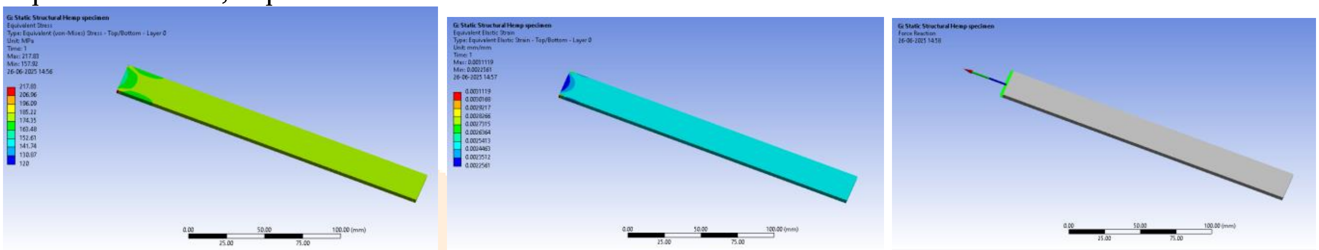


Fig 20. Boundary condition of aluminum and hemp fiber specimen

Result

Equivalent stress, Equivalent elastic strain and reaction force:

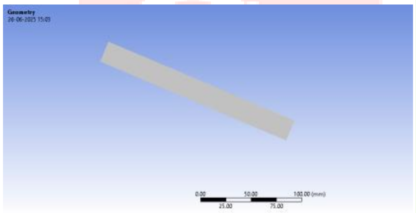


Results	
Maximum Value Over Time	
X Axis	-13130 N
Y Axis	7.2622e-010 N
Z Axis	-5.2742e-027 N
Total	13130 N

Fig 21. Equivalent stress, Equivalent elastic strain and reaction force of aluminum and hemp fiber specimen

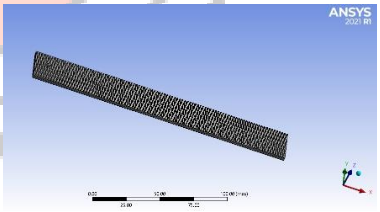
13. FEA OF ALUMINUM AND SISAL FIBER SPECIMEN

Geometry, Engineering data (Material) and Mesh model:



Properties of Outline Row 6: SISAL

	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	1.4	g cm^-3
4	Isotropic Elasticity		
5	Derive from	Young's Modulu...	
6	Young's Modulus	38	GPa
7	Poisson's Ratio	0.32	
8	Bulk Modulus	3.5185E+10	Pa
9	Shear Modulus	1.4394E+10	Pa
10	Tensile Yield Strength	700	MPa



Statistics	
Nodes	4699
Elements	4503

Type	Element Size
Element Size	1.0 mm

Fig 22. Geometry, Engineering data (Material) and Mesh model of aluminum and sisal fiber specimen

Finite mesh model contains 4699 nodes and 4503 elements. The size of elements is 1 mm

Boundary conditions:

As shown in the image 'A' is the displacement and 'B' is the fix support boundary condition.

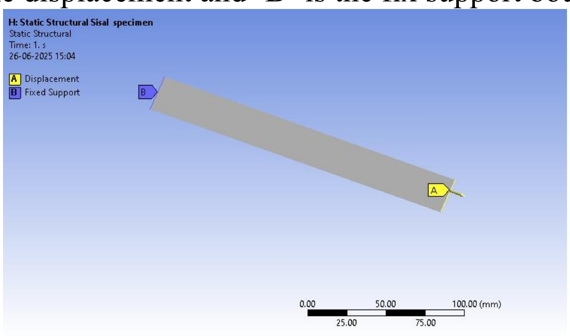
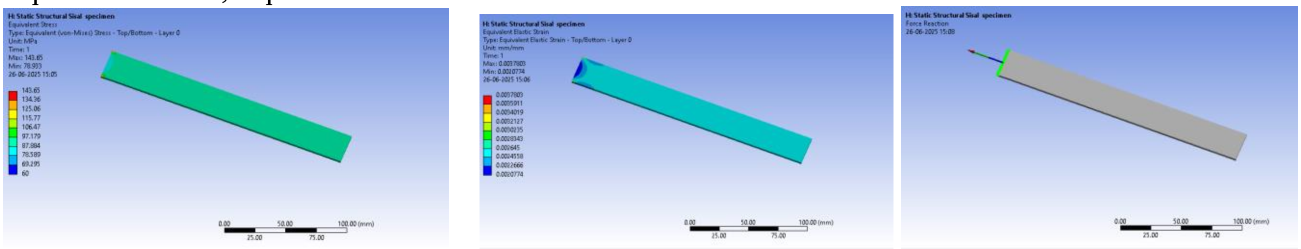


Fig 23. Boundary condition of aluminum and sisal fiber specimen

Result

Equivalent stress, Equivalent elastic strain and Reaction force:



Results

Maximum Value Over Time	
X Axis	-7137.6 N
Y Axis	3.2138e-010 N
Z Axis	1.4392e-027 N
Total	7137.6 N

Fig 24. Equivalent stress, Equivalent elastic strain and Reaction force of aluminum and sisal fiber specimen

14. FEA RESULT COMPARISON:

SR NO	COMPONENT	EQUIVALENT STRESS (MPa)	FORCE REACTION (N)
1	Aluminum and jute fiber specimen	152.48	7142.5
2	Aluminum and hemp fiber specimen	217.83	13130
3	Aluminum and sisal fiber specimen	143.65	7137.6

Table 2. FEA Result comparison between Jute, Hemp, Sisal Fiber

Based on the FEA analysis of specimen with material Jute fiber, Hemp fiber and Sisal fiber we have selected Siala fiber for manufacturing because this material having good reaction force with low internal stress.

15. MANUFACTURING OF COMPONENT

The manufacturing of the natural fiber composite bumper starts with selecting suitable fibers such as jute, hemp, and sisal. These fibers are cleaned and sometimes treated chemically to improve their bonding with the resin. After treatment, the fibers are mixed with a polymer resin, which acts as the matrix and helps in distributing stress throughout the component.

A. Classification of frp manufacturing processes:

SR NO	**Open mold processes:**	**Closed mold processes:**	**Open mold processes:**
1	Hand lay-up	Filament winding	Spray-up
2	Automated tape laying	Pultrusion processes	Compression molding
3	Compression molding	Tube rolling	Transfer molding
4	Resin transfer molding		Continuous laminating

Table 3. Classification of FRP Manufacturing

B. Open molding-hand layup method:

Hand lay-up is a type of open mold process which is used for the production of a large variety of composite products ranging from very small to very large. Hand lay-up is the most basic composites molding method which also happens to be very economical in terms of tooling, easy in terms of the processing and which also has a wide range of part size options. Also, with skilled labor design changes are very easy to make. There is low investment in equipment. With trained operators we see that good production rates and also very consistent quality is achieved (9).

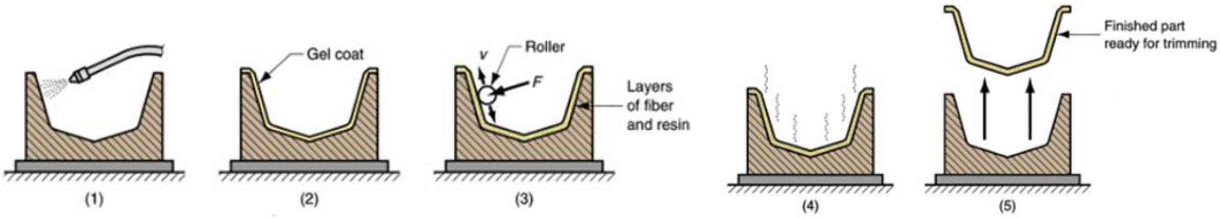


Fig. 25 Hand Layup Method

Hand lay-up: (a) mold is sprayed with mold release agent; (b) the outer surface of the mold is coated with a thin layer of gel coat (resin); (c) when the gel coat is partially set, the application of fiber and resin layers begins, the fiber; (d) air is rolled out of every layer to saturate the resin, and the fiber; (e) the part is cured; (f) the finished part is taken out of the mold after it is fully hardened(9)

Specimen manufacturing:

Fig. 26 Resin application on Specimen

Fig. 27 Sisal Fiber layup on specimen

Final Specimen:

Fig. 43 Final specimen Sisal fiber with Aluminum

16. Experimental Testing

A Universal Testing Machine (UTM) is a type of mechanical testing equipment which is used for determining mechanical properties (e.g., tensile strength, compressive strength, bending strength, and shear strength) of different materials. The UTM tests the specimen by applying a controlled tensile or compressive load and measuring its response.

The specimen is held under the UTM. As depicted in the following, tensile test is performed on the specimen(10).

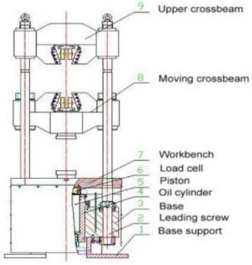


Fig. 28 Components of a UTM

The specimen is kept under the UTM. Tensile test is performed on the specimen, as shown in the following figures.

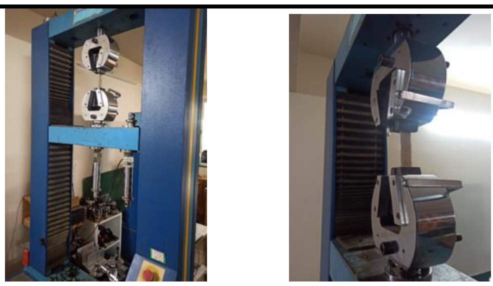


Fig. 29 Experimental Testing on specimen using UTM

The following fig. with graph of displacement v/s load for aluminum and sisal fiber specimen. Displacement is taken on Z-axis and load in N is taken on X-axis. The max force reaction 7275 N is taken by the aluminum and sisal fiber specimen under tensile loading.

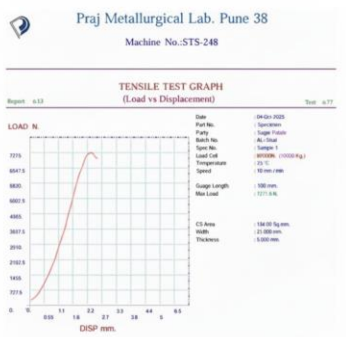


Fig. 30 Graph shows load vs displacement during tensile test

17. Results Table:

Parameter	Force reaction (N)
Tensile aluminum and sisal fiber specimen (FEA)	7137.6 N
Tensile aluminum and sisal fiber specimen (experimental/ UTM)	7271.6 N

Table 4. AL and sisal fiber specimen FEA and UTM result comparison

18. Conclusion

• The analysis comparing ABS and Aluminum car front bumpers reveals significant differences in their stress distribution and force reaction under equivalent loading conditions.

• The ABS bumper experiences higher equivalent (Von Mises) and maximum principal stresses (194.33 MPa and 112.21 MPa respectively) compared to the Aluminum bumper (152.97 MPa and 103.77 MPa), indicating that the ABS material is subjected to greater internal stresses.

• Conversely, the Aluminum bumper exhibits a substantially higher force reaction (9763 N) than the ABS bumper (3157 N). This suggests that while the Aluminum bumper can withstand and transmit a much larger force, the ABS bumper undergoes greater material stress for a given impact, likely due to differences in material stiffness, yield strength, and deformation characteristics.

• The data highlights that Aluminum demonstrates superior force absorption or distribution capabilities relative to the stresses generated within the material under the test conditions.

• The aluminum and sisal fiber specimen shows the lowest equivalent stress (143.65 MPa) and a force reaction very similar to that of the jute fiber specimen (7137.6 N vs. 7142.5 N). While its equivalent stress is the lowest, its force reaction is comparable to that of the jute and hem specimen. Aluminum and sisal fiber shows almost similar result on UTM test and found reaction force 7271.6N

• In summary, for applications requiring good strength and load-bearing capacity, the sisal fiber-reinforced aluminum composite appears to be the most promising option among the three tested configurations.

Future scope

- More types of composite combinations (like Banana fiber, Bamboo Fiber) can be tested to find an option that gives good strength at a lower cost.
- Long-term tests like vibration, fatigue, and environmental exposure can be done to check how the reinforced trim performs over years of vehicle use.
- Different manufacturing methods, can be explored to improve quality and make large-scale production easier.
- Knee form impact, NVH, Load transfer analysis can be done on this material.

19. References:

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