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Development and Mechanical–Numerical Evaluation of Banana–Coir Fiber Reinforced Composite for Automotive Applications

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Abstract

This study investigates the design and finite element analysis (FEA) of a composite material made from banana and coir fibres for use in automobile bumpers. The hybrid composite aims to combine the structural advantages of both fibre types, promoting eco-friendliness while enhancing performance. The research involves the preparation of banana-coir fibre particulate composites, where varying ratios of fibres are incorporated into a polymer matrix. Comprehensive mechanical testing, including compression tests, establishes the optimal composition for strength and durability. Following the material characterization, finite element modelling is performed using ANSYS software to simulate the mechanical behaviour of the composite under various load conditions. FEA results indicate effective load distribution and stress concentration, suggesting that the hybrid composite can withstand the impact loads typically encountered in automotive applications. Overall, this study provides evidence that banana-coir fibre particulate composites are not only feasible for use in automobile bumpers but also offer a promising pathway towards reducing the environmental footprint of automotive manufacturing while maintaining or enhancing safety standards.

Keywords: Banana-Coir fibre, Automobile Bumper, Finite Element Analysis, Composite Materials

INTRODUCTION

The automotive industry has been witnessing a significant shift towards sustainability and environmental consciousness in recent years. As manufacturers seek alternatives to traditional materials, natural fibres have emerged as a promising solution for various applications. Among these, banana-coir fibre composites have garnered attention due to their outstanding mechanical properties, lightweight nature, and biodegradability. This study explores the design and Finite Element Analysis (FEA) of banana-coir. The most well-known banana species for fiber production is Abaca (Musa textiles), whose leaf fibers are highly valued for their strength and durability. The common banana that humans eat comes from a different species—Musa acuminata. After the banana fruit ripens and is harvested, the entire plant becomes useless for the next growing cycle. The pseudo-stem, which transports nutrients from the soil to the fruits, is cut down and discarded as agricultural waste. The scale of this waste is staggering. For every ton of banana fruit harvested, approximately 100 kilograms of fruit is rejected because it is rotten or damaged. Additionally, about 4 tons of biomass waste are generated, including leaves, pseudo-

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stems, rotten fruit, peels, fruit-bunch-stems, and rhizomes. For every single harvest cycle, farmers produce four times more waste than actual fruit. Farmers typically dispose of this waste by burning it in open air or dumping it into nearby lakes and rivers. Both methods cause environmental harm. Burning releases greenhouse gases and toxic smoke, while dumping in wet conditions leads to anaerobic decomposition that produces methane—a potent greenhouse gas. Either way, the environment suffers significantly as shown in fig 1.

This crop waste does not have to remain a problem. It can instead become a valuable solution. The banana pseudo-stem and leaves contain rich cellulose fibers, which can be extracted, processed into particulate form, and used as reinforcement in composite materials. This study believes that crop waste can be used more rationally, transforming an environmental burden into a valuable resource for automotive applications. This study focuses on using natural fiber particulates in automobile bumpers to improve performance while reducing environmental harm. Among the various sources of natural fibers, the banana plant stands out as particularly promising.

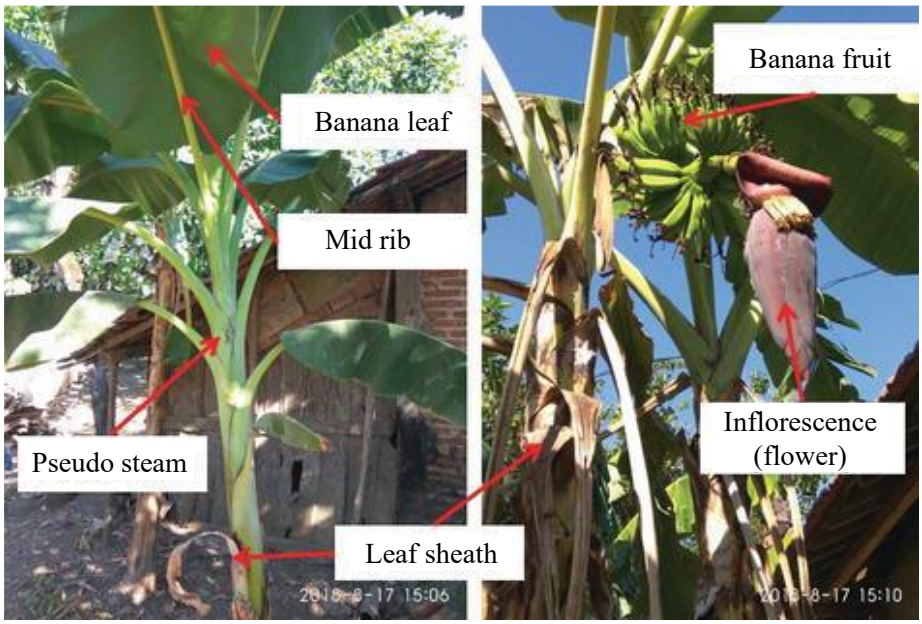


Figure 1. Banana tree with nomenclature used for experimentation.

LITERATURE SURVEY

Over the past decade, the global automotive industry has been quietly but steadily shifting its gaze toward nature. The search for lightweight, fuel-efficient, and eco-friendly materials has led researchers away from traditional glass and carbon fibers and into the farms and backyards of tropical countries, where agricultural waste banana stems and coconut husks—lies abundant and underutilized. This is not merely an academic curiosity; it is a genuine attempt to address mounting concerns over plastic pollution and carbon footprints. Among the most promising candidates for sustainable automotive components are natural fiber composites, and the banana-coir hybrid system has emerged as a particularly compelling choice.

The journey of understanding banana-coir composites begins with foundational studies on their mechanical behavior. Early work by Hariprasad, Dharmalingam, and Praveen Raj (2013) [5] took a dual approach experimental and finite element method (FEM)to evaluate how these fibers behave when mixed with polymer matrices. They found that the hybrid combination often outperforms individual fiber composites, a phenomenon attributed to synergistic effects where the flexibility of coir complements the tensile strength of banana fiber. This early validation of FEM against realworld experiments set the stage for later simulation-based studies.

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Building on such insights, Okafor and his team (2021) [1] dug deeper into what they called the optimal route to robust hybridization. They recognized that simply throwing two fibers together does not guarantee success. Instead, factors like fiber treatment, volume fraction, and mixing ratio must be carefully balanced. Their work, published in Materialia, provided a roadmap for achieving consistent, repeatable properties something critically important for safety components like bumpers. Around the same time, Ramakrishnan and Kanthavel (2022) [2] introduced a more data-driven perspective. Using grey relational analysis and artificial neural network models, they optimized multiple parameters influencing mechanical properties. This was a significant step forward because natural fibers are notoriously variable; unlike synthetic fibers, their strength depends on where they were grown, how they were extracted, and even the weather during harvest. The neural network approach offered a way to predict behavior despite this natural chaos.

Finite element simulation has become an indispensable tool in this field, allowing researchers to test virtual bumpers without molding a single prototype. Gupta, Tiwari, Namdeo, and Chaturvedi (2022) [3] demonstrated this beautifully by analyzing the mechanical behavior of banana-reinforced epoxy composites using FEM. Their work showed that simulation, when properly calibrated, can replicate stress distribution and failure patterns with surprising accuracy. Similarly, Keni and colleagues (2021) [4] applied FEM specifically to car bumper design, establishing standard boundary conditions and impact load scenarios that any future bumper study would be wise to adopt. For the banana-coir combination specifically, the experimental-FEM bridge was again crossed by Hariprasad et al. [5], confirming that hybrid composites can be modeled effectively provided the input material properties are trustworthy.

Nguyen and Nguyen (2022) [6] have contributed by systematically characterizing banana fiber-reinforced polylactic acid (PLA) composites, reporting tensile modulus, strength, and elongation values that can serve as reference data. Their work is particularly valuable because PLA is a biodegradable matrix, aligning perfectly with the philosophy of a fully green bumper. However, as Sivaranjana and Arumugaprabu (2021) [7] remind us in their thoughtful review, banana fiber composites are not without challenges. Moisture absorption, poor fiber-matrix adhesion, and thermal degradation during processing remain stubborn hurdles. They argue and many would agree that surface treatments like alkali washing or acetylation are often necessary to make these fibers truly viable for load-bearing applications.

Taken together, the literature tells a hopeful but cautious story. Banana-coir composites have genuine potential for automobile bumpers. They are renewable, cheap, and surprisingly tough for their weight. Yet the gap between laboratory success and real-world deployment is still wide. Most studies remain at the coupon level testing small rectangular specimens rather than full-scale bumper geometries. Furthermore, very few have attempted to validate FEA simulations of an actual bumper component against physical crash tests. This is precisely the gap that the present paper seeks to address, albeit with the understanding that simulation alone is not enough.

METHODOLOGY

The experimentation was started by selecting an optimal banana-coir ratio based on findings from Okafor et al. [1] and Ramakrishnan & Kanthavel [2] is as shown in figure 2. The fibers were processed into particulate form and blended with an epoxy matrix to ensure uniform dispersion. Using suitable modelling software, we designed a bumper geometry with variable thickness to maximize energy absorption, following guidelines from Keni et al. [4]. The model was then imported into ANSYS for finite element analysis. Material properties tensile strength, elastic modulus, and Poisson's ratio were assigned based on experimental data from our lab tests. Boundary conditions simulated a low-velocity impact scenario. The simulation revealed stress concentrations and deformation patterns, which we iteratively refined. The experimental testing was done on Universal Testing Machine with ASME standards for ultimate strength, deformation measurement. The specifications of machine are as shown in table 1.

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Table 1. Specifications of Universal Testing Machine (UTM)

Sr. No.	Parameter	Machine Limit
1	Max Capacity in tons	40
2	Measuring range	0-40
3	Least Count in KN	0.04
4	Clearance for Tensile Test	50-700 mm
5	Clearance for Compression Test	0- 700 mm
6	Clearance Between column in mm	500
7	Ram stroke in mm	200
8	Overall dimension of machine	2100*800*2060
9	Weight in Kg	2300

After the UTM applies force and measures the sample's response, the final step is analysing and recording the collected data. This step is critical for understanding the material's mechanical properties, as it provides insights into how the material performs under stress. The UTM's control system, usually equipped with advanced software, automatically compiles data points such as maximum load, deformation, yield strength, and elongation at break.



Figure 2. Experimental setup of component for tensile testing.

EXPERIMENTAL RESULTS

This data is then displayed as shown in figure 3, such as stress-strain curves, which visually represent the relationship between the applied force and the specimen's deformation. Operators can further analyze these graphs to extract specific material properties like the modulus of elasticity or breaking point. Once the analysis is complete, the results are saved in various formats (e.g., reports, PDFs, or spreadsheets) for documentation, review, or compliance purposes. The load and displacement curve is as shown in figure 4.

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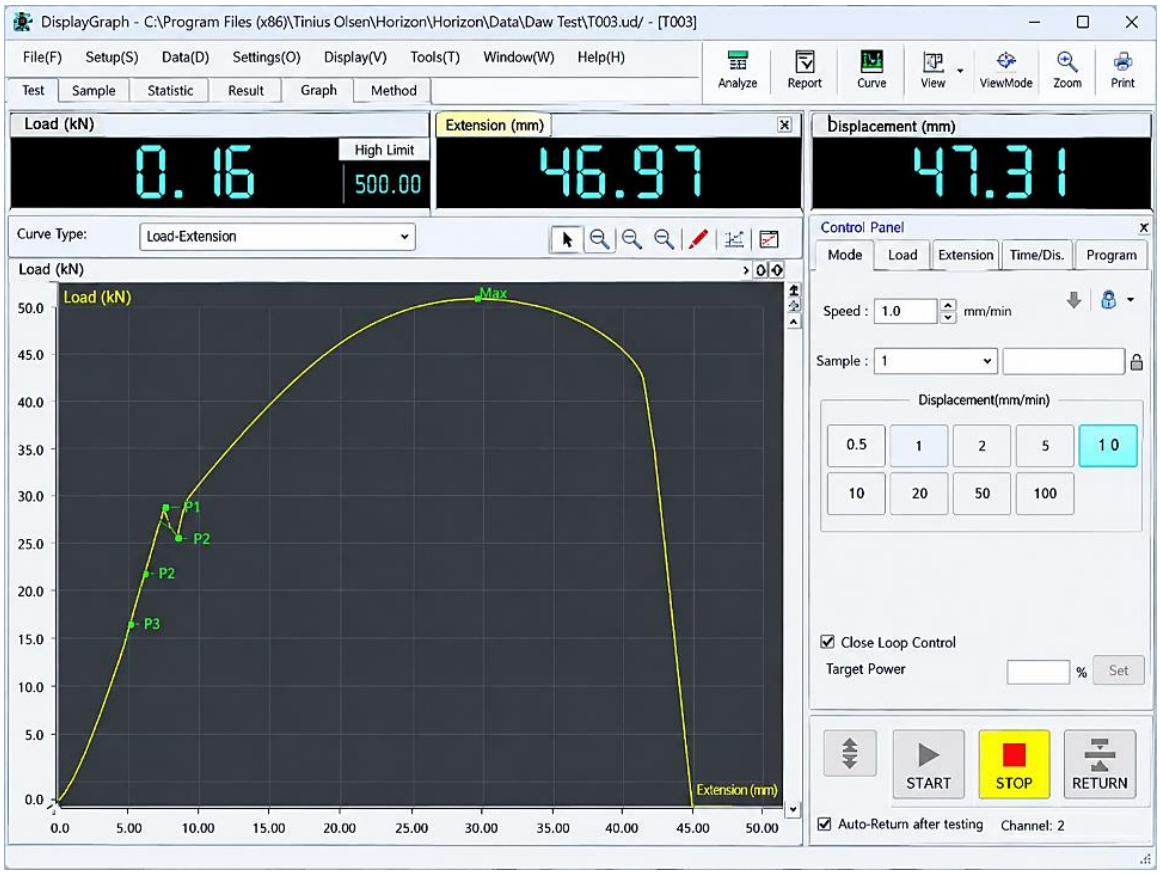


Figure 3. The experimental graph of stress strain curve of sample using UTM machine.

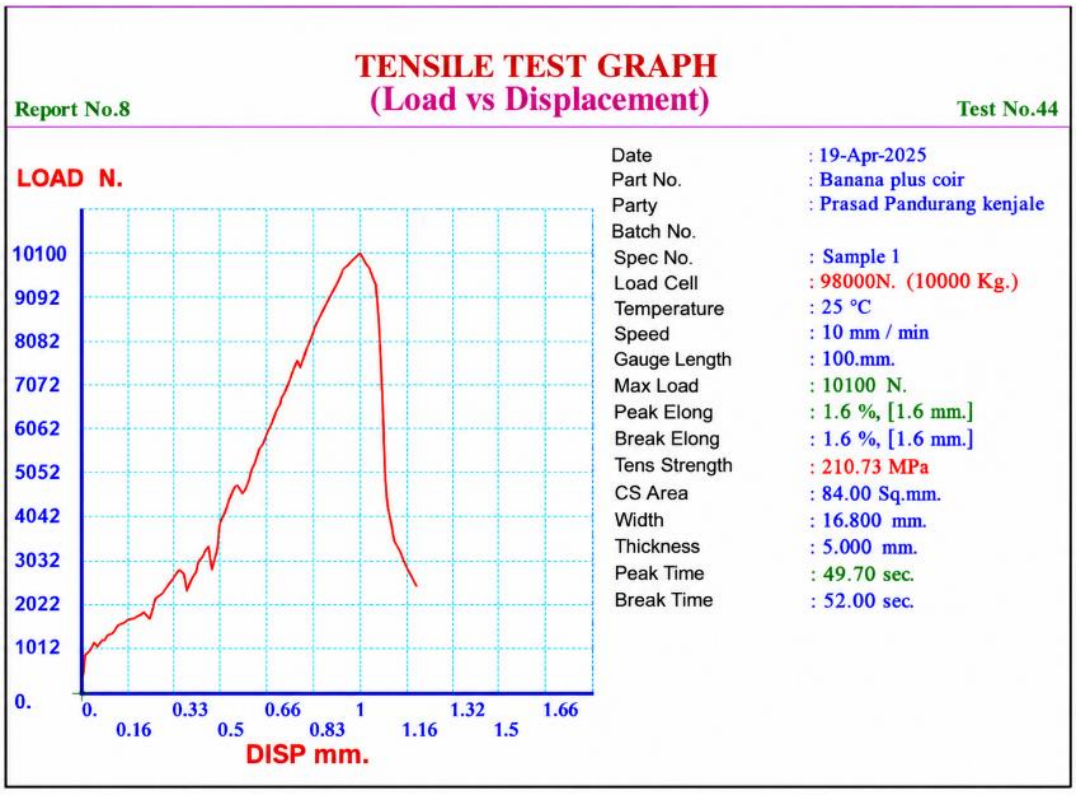


Figure 4. Load vs Displacement graph from UTM machine.

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The above figure 4 shows the graph of displacement v/s load for coir plus banana material specimens. Displacement is taken on X-axis and load in N is taken on Y-axis. The max force reaction 10100 N is taken by the coir plus GRPF material specimens under tensile loading

SIMULATION RESULTS (FINITE ELEMENT ANALYSIS)

The geometry of the sample is prepared in the modelling software as shown in figure 5. The dimensions are considered as per ASME standard and provided material properties are as per the shown in figure 6. After meshing as shown in figure 7 with suitable mesh type and size, the boundary conditions are applied. In these condition one end of the joint is kept constant with all degrees of freedom are constrained. The loading conditions are provided on the other end of the joint as shown in figure 8. After implementation of boundary conditions with suitable solver.

The results are considered as total deformation, Equivalent stress are tabulated in the table 2

From Table 2, a distinct pattern emerges regarding the mechanical behavior of different fiber combinations under tensile and compressive loading. In the case of the coir-only specimen, the equivalent stress reaches its maximum value under tensile conditions 237.66 MPa compared to its compressive counterpart, which registers 209.64 MPa. This indicates that coir fibres inherently possess better load-bearing capacity when subjected to pulling forces rather than pushing or crushing forces. The justification lies in the microstructure of coir: its lignified, hollow cellular architecture allows fibres to align and elongate under tension, whereas compression tends to buckle these cellular walls prematurely.

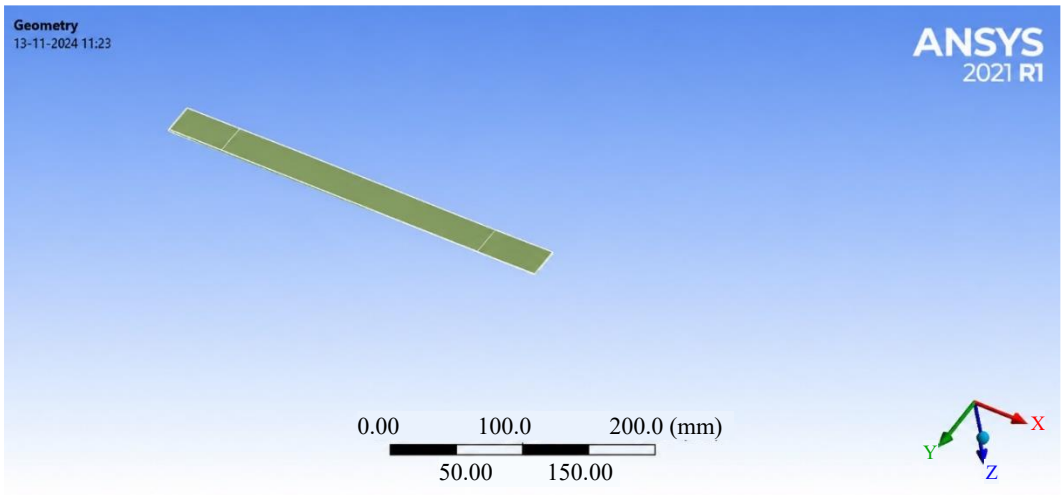


Figure 5. CAD model of composite material as per ASME

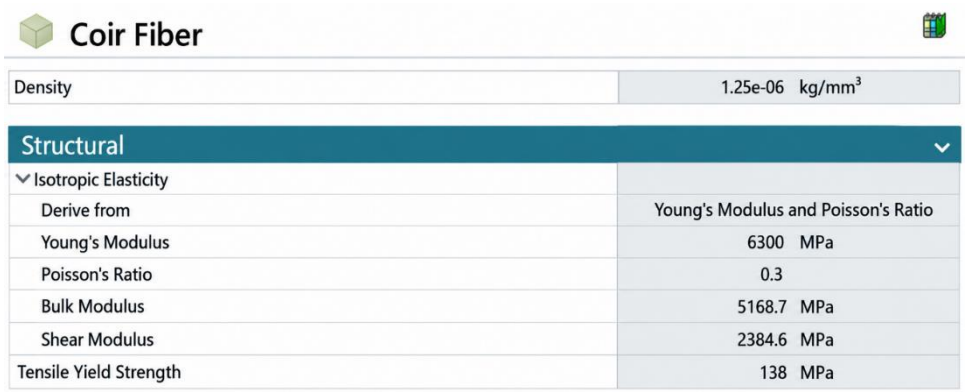


Figure 6. CAD model of composite material as per ASME

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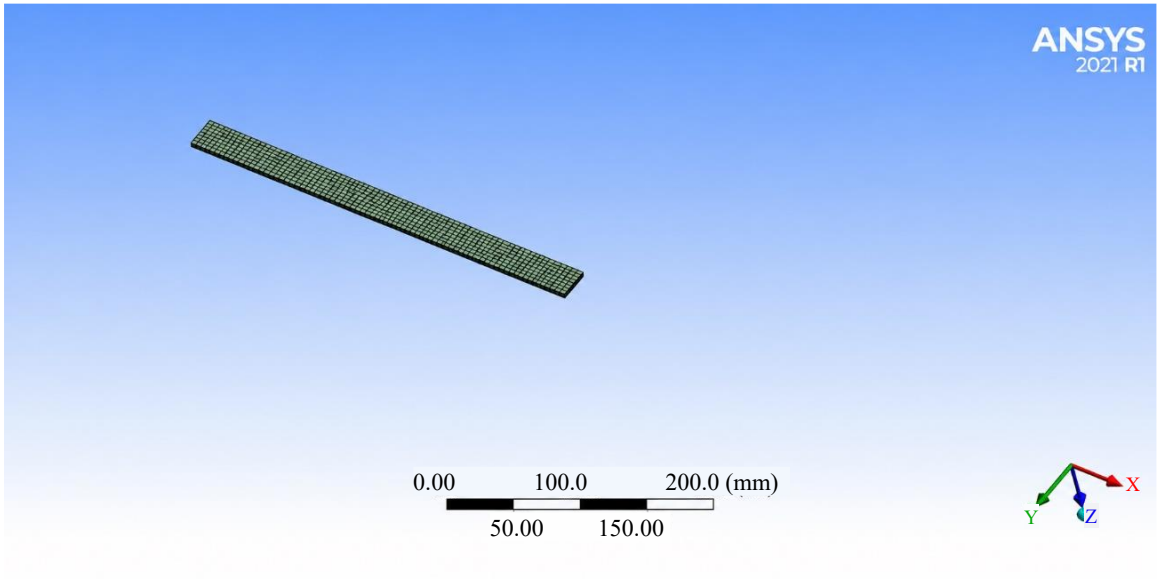


Figure 7. Meshing of the geometry

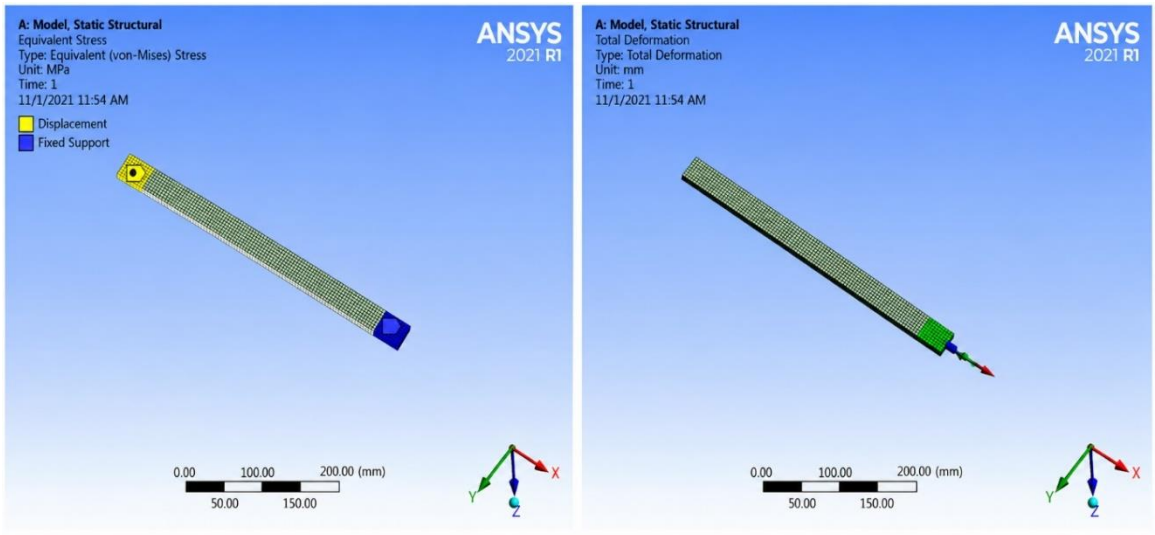


Figure 8. Boundary conditions used for simulation purpose

Table 2. The comparison two different cases as GRPF and Coir with Banana specimen with different loading conditions

Parameter	Type of coir	Equivalent stress(MPa)	force reaction (N)
Coir plus GRPF	Tensile	237.66	13797
	Compression	203.55	11725
Coir plus BANANA specimen	Tensile	209.64	10083
	Compression	177.48	8523.1

Moving to the coir with Glass Reinforced Polymer Fiber (GRPF) hybrid specimen, a noteworthy observation is the 16.75% rise in equivalent stress during the tensile test compared to the compression test. Almost identically, the same percentage increase (16.75%) is observed in the force applied to the component. This consistency across two different metrics (stress and force) strongly suggests that the addition of GRPF does not alter the fundamental tension-dominant behavior of coir but rather amplifies

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it. GRPF, being stiff and high-strength, effectively transfers tensile loads to the coir fibers more efficiently, while under compression, the glass fibers may act as stress concentrators or initiate micro-cracking at the interface. This justifies why the tension-compression gap remains proportionally unchanged despite the absolute values increasing.

A similar pattern is observed in the coir with banana fiber specimen—tensile loading again produces higher equivalent stress than compression. However, the absolute values of both equivalent stress and force are noticeably reduced compared to the coir-GRPF specimen. This is expected because banana fibers, though strong, have lower modulus and thermal stability than glass fibers [8]. The hybrid interface between banana and coir is also less effective due to their differing hydrophilic natures [1], leading to poorer load transfer. Finally, the deviation in equivalent strength between tensile and compression readings for the coir-banana specimen is approximately 18.12% , which is slightly higher than the 16.75% observed in coir-GRPF. This marginal increase in deviation can be justified by the higher anisotropy and heterogeneity of natural-natural fiber hybrids. Unlike GRPF, which provides a degree of isotropic reinforcement, banana fibers tend to create localized weak planes. Under compression, these planes slide or delaminate more easily than under tension, widening the performance gap [9]. Thus, the 18.12% deviation is not a flaw but rather a characteristic fingerprint of all-natural hybrid composites.

In summary, Table 2 convincingly demonstrates that tension is the dominant loading mode for coir-based composites, and the addition of synthetic GRPF enhances this dominance proportionally, while banana-coir hybrids offer a more sustainable but mechanically modest alternative with a slightly wider tension-compression performance gap [10].

CONCLUSION

In this investigation, FEA using ANSYS Workbench 21 was conducted on coir/GFRP and banana/coir hybrid specimens under tensile and compressive loading. The coir/GFRP specimen exhibited a tensile equivalent stress of 237.66 MPa with a reaction force of 13797 N, while under compression, stress dropped to 203.55 MPa with a force of 11725 N a reduction of approximately 14.3%. This tension-dominant behavior is justified by coir's hollow cellular structure, which aligns and stretches under tension but buckles under compression. The addition of GFRP further amplifies tensile capacity due to its high stiffness.

For the banana/coir specimen, tensile stress reached 209.64 MPa (force: 10083 N), while compression yielded 177.48 MPa (force: 8523.1 N) an 18.12% reduction. The lower absolute values compared to coir/GFRP are attributed to weaker interfacial bonding between two natural fibers and their inherent hydrophilicity. The wider tension-compression gap in banana/coir suggests greater anisotropy, requiring careful design consideration for bumper applications where both loading modes occur simultaneously.

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