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Static Structural and Steady-State Thermal Analysis of Stringer Using Composite Material

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Abstract

The increasing focus on sustainable materials for aerospace, this field has gained global interest. This research enquires whether sisal fibers and coconut coir are possible alternatives to carbon fiber composite materials used in aircraft components. They have high specific strength and low weight, while also being renewable sources. They thus have excellent potential as a gentle spoken out of term by their presence and for the planet. In this research, epoxy carbon UD prepreg composite laminates were produced and evaluated using ANSYS ACP (Pre) to determine their structural and thermal behavior. The findings reveal that reinforcement enhances tensile strength and dynamic properties. Besides, natural fiber composites exhibit lower drift in deformation and minimal temperature variation. The results bring out the potential for non-critical aerospace applications of the material, which is sustainable and economic besides not compromising on performance in any way.

1. Introduction

The demand for lightweight yet durable materials has seen a huge boost across sectors, most prominently in construction and engineering, triggered by the effects of industrialization and population increase. Consequently, there is a heightened demand for sustainable substitutes. [1] Composite materials are gaining popularity in numerous engineering fields, including aerospace, automotive, marine, robotics, construction, sporting goods, and electronics, due to their superior strength-to-weight and stiffness-to-weight ratios and their better corrosion resistance, enhanced damping, and improved fatigue behavior. [2]. The application of natural composite materials in aircraft manufacturing is picking up pace continuously as manufacturers pursue environmentally friendly solutions to conventional synthetic composites. Natural fiber-reinforced composites (NFRCs) integrate natural fibers like flax, hemp, and bamboo with bio-based resins to produce materials with high strength-to-weight ratios, increased damping characteristics, and better fatigue resistance. [1&2] NFRCs offer a light, eco-friendly alternative that satisfies the demanding needs of aerospace applications while also lowering the carbon footprint of aircraft manufacturing. In addition, they provide outstanding insulation and vibration-damping properties, contributing to enhanced passenger comfort. Natural fiber cultivation promotes agricultural economies and less dependency on petrochemical resources, in line with the sustainability goals of the industry. With the use of NFRCs, the aerospace industry can maximize environmental efficiency without sacrificing performance, making them a viable choice for the design of future aircraft with a concern to environmental stewardship and resource conservation. [5-7] Sisal fiber and coconut coir emerge as "green" reinforcements for aerospace composites because they are lightweight, biodegradable, inexpensive, and have desirable mechanical properties. [2&16] Coconut coir, which comes from the husk of coconuts and has historically found application in ropes and brushes, provides increased impact resistance, vibration damping, and toughness to polymer composites, helping to reduce weight and enhance fuel efficiency in aircraft. [11,13] In the same way, sisal fiber, which is derived from the leaves of Agave sisalana, has a high strength-to-weight ratio and is economical, thus applicable for non-critical aerospace parts like interior panels and flooring. [15] Upon incorporation into composites, sisal increases impact toughness, flexibility, and vibration damping, and helps in reducing emissions and improving fuel efficiency. In addition to these naturally occurring alternatives, carbon fiber continues to be a mainstay in aerospace engineering as it boasts an outstanding strength-to-weight ratio, corrosion resistance, and fatigue life, which qualify it for structural pieces such as fuselages, wings, and engine nacelles. [17] Epoxy resin, a matrix used in fiber-reinforced composites, also enhances these characteristics by providing excellent bonding, durability, and resistance to the environment. Mixing epoxy with natural fibers such as sisal and coconut coir offers a green alternative to conventional carbon composites, providing lighter, cheaper materials with enhanced tensile strength, stiffness, and thermal resistance. [9&12] The hybrid composites offer potential for application in lightweight, high-performance aircraft structures, meeting the industry's objectives of performance improvement and environmental sustainability.

1.1. Motivation and Objectives

The research seeks to investigate the possibilities of natural and synthetic fibers in improving the mechanical properties of composite materials in engineering uses. Some of the main objectives are:

- Examining natural fiber composites as eco-friendly substitutes for synthetic materials without any loss of performance.
- Maximizing fiber content, treatment process, and hybridization methods to improve strength, durability, and water resistance.
- Developing high-performance composite materials for aerospace and other industrial use.

Table 1. shows, mechanical and thermal properties of Coconut Coir, Sisal Fiber, Carbon Fiber, and Epoxy Carbon Resin are compared in the table. Carbon-based composites exhibit greater strength and stiffness, while natural fibers provide sustainability. These differences decide their use in aerospace, automotive, and structural applications. [1-5]

Table 1 Mechanical and Thermal Properties of Composite Materials

Material	Coconut Coir	Sisal Fiber	Carbon Fiber	Epoxy carbon resin
Young’s modulus (GPa)	5	23	130	121
Poisson’s ratio	0.3	0.4	0.25	0.4
Shear strength (MPa)	15	30	100	80
Shear Modulus (GPa)	1.9231	8.2143	52	4.7
Isentropic thermal conductivity (W/MK)	0.04	0.148	12	78.8
Tensile Strength (MPa)	200	700	6000	230,000
Yield Strength (MPa)	20	400	4000	1500

2. Literature Review

Natural fiber composites (NFCs) like coir, sisal, palmyra, and kenaf are gaining popularity for being environmentally friendly and have strong features. These materials are particularly interesting for the aerospace industry. [3] When these natural fibers are combined with substances like epoxy or polyester, they become more robust and water-resistant. While treatments and mixing with other materials can enhance their qualities, challenges such as moisture absorption and fiber bonding remain. Fiber metal laminates (FMLs) are known for their strength and resistance to moisture, which makes them suitable for aircraft use. [4] However, they come with high costs and are challenging to produce. On the other hand, sisal fiber composites are light and affordable but not as strong compared to synthetic materials. Kenaf and coconut coir composites provide good reinforcement and resist moisture well. [16] Carbon fiber-reinforced polymers (CFRPs) continue to be widely used in the aerospace industry, but they face issues related to recycling and automation. To improve composite structures, Finite Element Modeling (FEM) is utilized, though more research is needed to enhance their durability. Innovations in fiber treatments, nanomaterials, and recycling have the potential to broaden the use of NFCs in aviation, promoting environmental sustainability. [14 &15]

3. Methodology

This study investigates the strength and heat resistance of natural fiber composites mixed with epoxy carbon resin using ANSYS software. The research uses coconut coir and sisal fibers, which are prepared and combined with epoxy carbon resin to create test samples. Data was collected from the reviewed articles, these sources provided mechanical, thermal, and durability of both natural fibers (coconut coir, sisal fiber) and synthetic fiber (carbon fiber). The composite material is laminated with different orientation and three different cases are performed to analyze the results for both natural and synthetic fiber. The sample is created with different thickness for all the cases. [10] The natural fiber and synthetic fiber (carbon fiber) mixed with epoxy resin in the ANSYS for the simulation. Coconut coir and sisal fiber are mixed and combine with the epoxy resin to create a test sample. The research conducts a static structural analysis to test the strength of these composites. A 200 N force is applied to the wing support along the Z-axis to see how the materials handle stress, bending, stretching, and overall strength. Additionally, a thermal analysis is conducted to simulate conditions during flight to evaluate heat transfer and how well the materials resist high temperatures. [6] The fiber properties were analyzed on a comparative matrix based on tensile strength, stiffness, thermal conductivity, biodegradability, and cost-effectiveness. Where also FEM data were analyzed to determine the performance of natural fiber composites in high-stress applications. Several case studies within the automotive or aerospace sector were reviewed to learn from different applications of natural fiber-reinforced composites in prototypes. The results from these reviews were integrated to identify the strengths and weaknesses of natural fibers as alternative materials in dam structural engineering applications. [6-10]

4. Design and Analysis

ANSYS ACP (Pre), a software tool for simulation of complex composite lay-up, was used to model and analyze the composite structure. The Forma module allows for accurate definition of layer stacking order, fiber directions, and material properties, which is essential for optimizing strength and stiffness in aerospace applications. Modeling 1: I made the stringer geometry in the Space Claim, and the dimensions were designed as below (L: 1000 mm, W: 1.2 mm, D: 9 mm). It is composed of 9 mm thick composite layers with the fibers oriented in multiple directions, allowing for improved mechanical performance under various loading conditions. The FEA meshing was performed with grid refinement of 1 mm element size with refinement level 3. This high-resolution mesh is particularly beneficial for highly stressed areas that are modeled more accurately to be more precise in stress concentration. One of the important processes in FEA is the meshing, which divides the 3D geometry into smaller elements that are subjected to stress-strain conditions to investigate stress-strain states globally. This kind of modeling is a good basis for assessment of the structural stiffness and performance of composite aerospace structures.

4.1. Set Up and Orientation

In ANSYS ACP (Pre), the setup phase is crucial for accurately modeling composite materials. This step involves determining material properties, how the layers are stacked, the orientation of fibers, and the thickness of each ply. A proper setup leads to accurate analysis of stress, deformation, and behavior in different directions. Figure 1 shows Internal Structure of the Wing

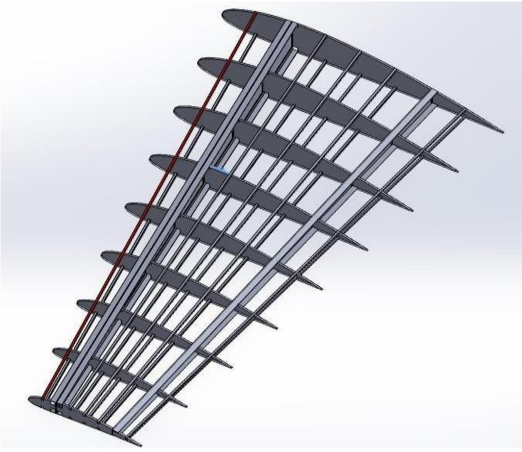


Figure 1 Internal Structure of the Wing

From Table 2., Six composite cases were developed to assess the influence of various material combinations, fiber orientations, and stacking sequences on mechanical performance. Case 1: Hybrid composite was prepared with epoxy carbon unidirectional (UD) fiber-reinforced coconut coir and sisal fiber (the orientation of the coir and sisal fibers at 45° and the epoxy UD layer at 90°). The total thickness was 1 mm, and the stacking sequence was coir-resin-sisal. An epoxy UD at 90° with 1.8 mm of thickness and different orientations of the natural fibers at 0° formed part of Case 2, which also used the same materials and the same coir-resin-sisal stacking. In case 3, the 45° coir and sisal and 90° epoxy UD were maintained, however, a layered structure was applied, with fiber layers of 0.5 mm thickness and resin layers of 1 mm thickness, which allowed a more complex coir-resin- sisal-resin configuration. In contrast, Cases 4, 5, and 6 used only carbon fiber and epoxy carbon UD. For Case 4, layer of 1 mm of 45° carbon fiber (on the left-hand side) and 90° epoxy UD (on the right-hand side) with the stacking order of carbon-resin-carbon-resin. Similarly, Case 5 used the same materials and stack as 4; however, the carbon fibers orientation changed to (0°) and total thickness increased to (1.8 mm). Figure 2 shows 2-D Sketch of the Stringer and The Dimensions Are in Millimetre's Figure 3 shows Refined Mesh of the Stringer [11-15]

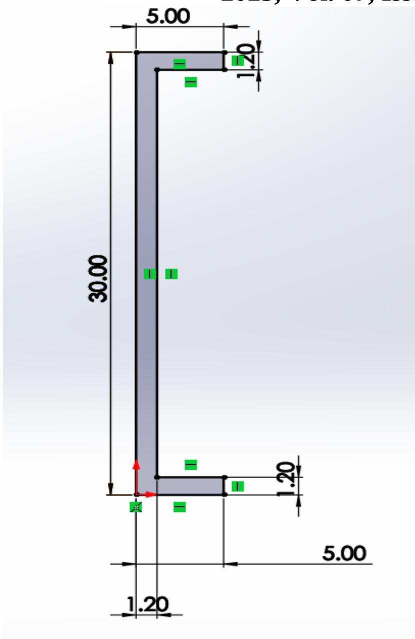


Figure 2 2-D Sketch of the Stringer and The Dimensions Are in Millimetre's

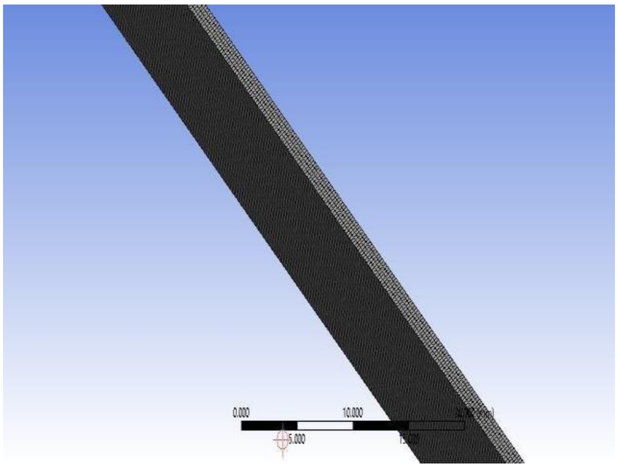


Figure 3 Refined Mesh of the Stringer

Case 6 was like Case 4 (carbon at 45°, epoxy UD at 90°) with the only difference being the layer thickness (0.5 mm for fibers and 1 mm for resin). The different configurations enabled a detailed comparison of both natural and synthetic fibers while keeping the simulation conditions identical. Table 2 shows Stacking Order and Fibre Orientation of Different Composite Case made the stringer geometry in the Space Claim, and the dimensions were designed as below (L: 1000 mm, W: 1.2 mm, D: 9 mm). It is composed of 9 mm thick composite layers with the fibers oriented in multiple directions, allowing for improved mechanical performance under various loading conditions. The FEA meshing was performed with grid

Table 2 Stacking Order and Fibre Orientation of Different Composite Case

Cases	Materials Used	Fiber Orientation	Thickness	Stacking Order
Case1	Coconut coir, sisal Fiber, epoxy carbon UD (230 GPa)	Coir & sisal: 45°, Epoxy UD: 90°	1mm	Coir-resin-sisal
Case2	Coconut coir, sisal fiber, epoxy carbon UD (230 GPa)	Coir & sisal: 0°, Epoxy UD: 90°	1.8mm	Coir-resin-sisal
Case3	Coconut coir, sisal fiber, epoxy carbon UD (230 GPa)	Coir & sisal: 45°, Epoxy UD: 90°	0.5mm (fiber), 1mm (resin)	Coir-resin-sisal-resin
Case4	Carbon fiber, epoxy carbon UD (230 GPa)	Carbon: 45°, Epoxy UD: 90°	1mm	Carbon-resin-carbon-resin
Case5	Carbon fiber, epoxy carbon UD (230 GPa)	Carbon: 0°, Epoxy UD: 90°	1.8mm	Carbon-resin-carbon-resin
Case6	Carbon fiber, epoxy carbon UD (230 GPa)	Carbon: 45°, Epoxy UD: 90°	0.5mm (fiber), 1mm (resin)	Carbon-resin-carbon-resin

5. Results and Discussion

5.1. Static Structural Analysis

ANSYS Static Structural Analysis looks at how composite stringers handle different forces. It uses supports that doesn't move and applies a force of 200N along the Z-axis. This process checks how much the structure bends and how stress spreads. It helps to make sure that the structure is strong and dependable.

5.2. Supports and Loading Conditions

The stringer is modeled with both ends fixed, simulating real-world constraints. Due to varying orientations and thicknesses, deformation responses differ, aiding in assessing load-bearing capacity and structural performance. As the below Figure 3. shows ends are fixed as of simply supported beam and load is acting downwards on the top surface in x-axis direction. Figure 4 shows Static Structural Deformation of Stringer

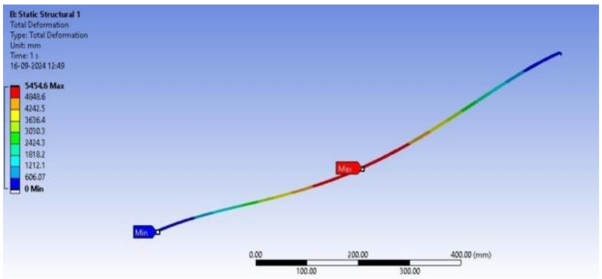


Figure 4 Static Structural Deformation of Stringer

5.3. Steady-State Thermal Analysis

Steady-state thermal analysis in ANSYS looks at how heat moves through the composite stringer, helping to pinpoint temperature distribution and any hotspots. By using convection coefficients, we can maintain stability, avoid degradation, and enhance the durability of aerospace components. Figure 4. shows the heat flow acting across the beam with maximum temperature acting in the middle (308K). Figure 4 Shows Steady State-Thermal Analysis of Stringer

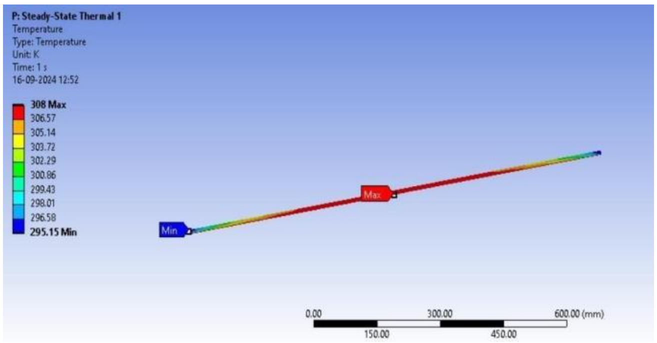
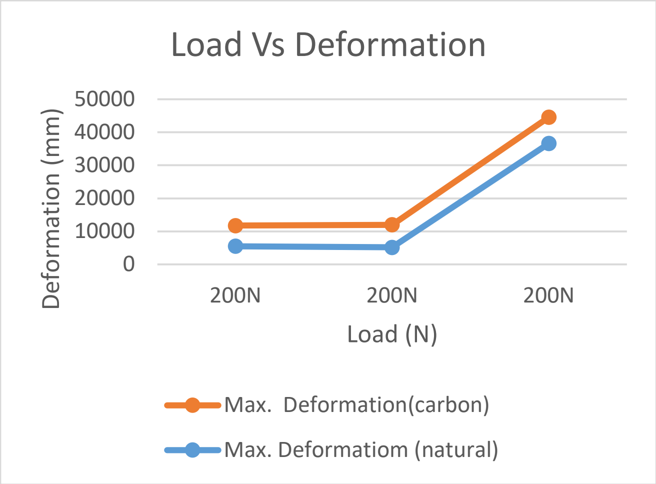


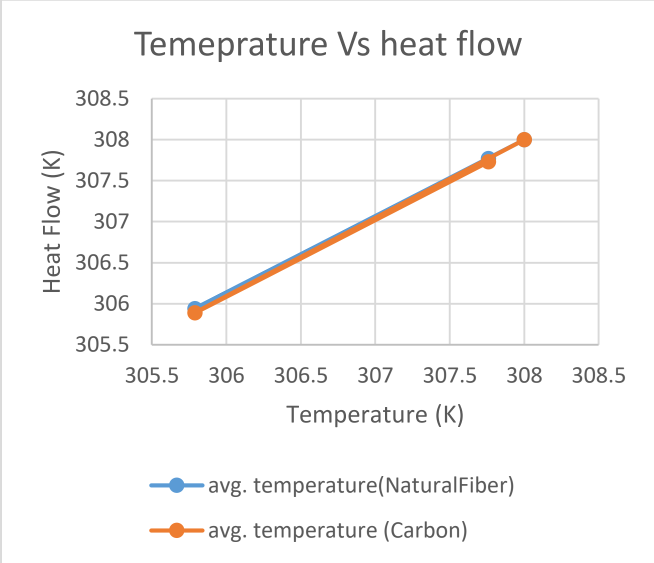
Figure 4 Steady State-Thermal Analysis of Stringer

5.4. Temperature and Convection

Thermal analysis investigates six scenarios where the stringer temperature inside the wing is consistently set at 308K. Convection rates of 0.05 and 0.06 W/mm²·K are applied at both ends. This study focuses on how temperature is distributed, making sure that thermal performance meets the demands of operational conditions. Steady-state thermal analysis is performed with a 308K (35°C) temperature on the stringer face along the x-axis and convection at both ends (0.05W/mm²·K and 0.06W/mm²·K). Graph 1 illustrates how natural fiber composites, like coconut coir and sisal, stack up against carbon fiber composites when subjected to different loads. At the lower end of the scale (200N), both types of materials show stable deformation, although carbon fiber does experience a bit more deformation. As the load ramps up, carbon fiber composites tend to deform more dramatically, while the natural fiber composites manage to maintain a steadier rise. This suggests that natural fiber composites provide better structural stability under moderate loads, effectively resisting deformation. Plus, their affordability, eco-friendliness, and biodegradability make them a compelling alternative to carbon fiber for less critical uses, such as in automotive interiors and secondary aerospace structures. However, when it comes to high-stress situations, hybrid composites might strike a better balance between strength and sustainability. Graph 2. shows how temperature relates to heat flow in natural fiber composites, like coconut coir and sisal, compared to carbon fiber composites. Interestingly, both types of materials display almost the same thermal behavior, as seen in the overlapping curves. As the temperature rises, the heat flow steadily increases, indicating that natural fiber composites can hold and transfer heat just as effectively as carbon fiber composites. This finding implies that natural fiber composites have similar thermal stability, making them a great choice for applications that need moderate thermal resistance. Their ability to perform on par with carbon fiber in terms of heat flow behavior highlights their potential as a sustainable and cost-effective option in industries like automotive and aerospace, where reducing weight and being eco-friendly are key priorities. The simulation results showed in table 3., that composites made from coconut coir and sisal fiber, reinforced with epoxy resin, displayed impressive thermal and mechanical properties when compared to traditional carbon fiber composites. In Cases 1 to 3, the natural fiber composites kept an average temperature around 305.9 K, with a steady minimum temperature of 295.15 K, which indicates While the deformation values varied—Case 3 hit a maximum deformation of 36,628 mm—the average deformation in Cases 1 and 2 (2,883.4 mm and 2,708.4 mm, respectively) was significantly lower than what we saw in some carbon fiber cases. On the other hand, carbon fiber composites (Cases 4 to 6) had slightly higher average temperatures, hovering around 307.75 K, and showed greater deformation across the board, with average values ranging from 3,304.9 mm to 4,192.1 mm and maximum deformations reaching up to 7,937.2 mm. These results imply that coconut coir and sisal fibers, when paired with epoxy resin, can serve as a promising, eco-friendly alternative to carbon fiber composites, especially in situations where moderate mechanical strength and thermal stability are adequate. Graph 1 shows Load vs. Deformation Comparison of Carbon and Natural Materials GRAPH 2 shows Comparison of Heat Flow Between Natural Fibre and Carbon Materials However, natural fiber composites may struggle under extreme loads or in high-performance structural applications, like primary aerospace components or high-speed automotive parts. Their relatively lower tensile strength and higher moisture absorption could impact long-term durability in tough environments. Thus, coconut coir and sisal fiber composites are ideally suited for non-critical components where sustainability, cost-effectiveness, and biodegradability take precedence over maximum mechanical performance.



Graph 1 Load vs. Deformation Comparison of Carbon and Natural Materials



GRAPH 2 Comparison of Heat Flow Between Natural Fibre and Carbon Materials

Table 3 Deformation and Temperature Values of Composite Materials

Composite Materials	No. of cases	Temperature		Deformation	
		Average(K)	Minimum(K)	Average (mm)	Maximum(mm)
Coco Fiber And Sisal Fiber with Epoxy Resin	Case 1	305.79	295.15	2883.4	5454.6
	Case 2	305.94	295.15	2708.4	5123.7
	Case 3	305.89	295.15	19333	36628
Carbon Fiber with Epoxy Resin	Case 4	307.76	295.2	3304.9	6256.1
	Case 5	307.77	295.15	3625.4	6862.8
	Case 6	307.73	295.21	4192.1	7937.2

Conclusion

The integration of carbon along with natural fiber composites presents a compelling approach to the development of sustainable, high-performance materials for diverse industrial applications. Carbon fibers offer superior mechanical strength plus thermal stability. Natural fibers, such as sisal and coconut coir, contribute advantages in sustainability, weight reduction, plus cost-effectiveness. Composites mixing materials effectively balance ecological benefits with structural integrity, especially if improved via fiber treatments and the advanced resin systems. As certain industries move toward fully eco-friendly solutions, these hybrid systems show real potential for applications in vehicular, aerospace, and construction sectors, duly aligning performance demands with ecological responsibility.

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