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Mechanical Behaviour and Structural Evaluation of Carbon Fiber–Pineapple Leaf Fiber Reinforced Hybrid Bio-Composites for Aircraft Applications

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Abstract

The growing emphasis on sustainable and lightweight materials has accelerated the exploration of bio-composites as alternatives to conventional aerospace materials. In this study, hybrid composites reinforced with carbon fiber and pineapple leaf fiber (PALF) were fabricated and evaluated to determine their mechanical performance and suitability for aerospace applications. PALF, being a renewable and biodegradable fiber, offers low density and good tensile properties, while carbon fiber contributes superior strength, stiffness, and thermal stability. Hybrid composites were developed using epoxy resin with varying fiber ratios of 70:30, 60:40, and 50:50 (carbon fiber to PALF) to exploit the complementary advantages of both reinforcements. Experimental results indicate that increasing PALF content enhances impact resistance and environmental sustainability, whereas higher carbon fiber content improves tensile strength and stiffness. Among the tested configurations, the 60:40 ratio exhibited an optimal balance between strength, flexibility, and durability, making it suitable for non-structural aerospace components such as interior panels and seating structures. Overall, the findings highlight the potential of PALF-based hybrid composites in reducing structural weight, improving fuel efficiency, and promoting environmentally responsible material usage in aerospace and related industries.

Keywords

Bio-composites, Pineapple Leaf Fiber (PALF), Carbon Fiber Hybrid Composites, Aerospace Materials, Mechanical Characterization.

1. Introduction

As environmental concerns and sustainability goals have grown, bio-composites, which consist of natural fibers and offer benefits like biodegradability, cost-effectiveness, and reduced environmental impact, have emerged as a promising alternative to conventional synthetic materials [1]. The aviation industry is rapidly looking for

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emerging materials to improve overall performance, lessweight, and improve fuel efficiency. This study explores the fabrication and characterization of a hybrid bio-composite generated from pineapple leaf fiber (PALF) and carbon fiber. PALF is a renewable, lightweight, and high-strength natural fiber, making it an attractive candidate for composite reinforcement. Carbon fiber, widely used in aerospace applications, provides superior strength, stiffness, and thermal stability. By combining these fibers, the study aims to achieve a balance between strength, weight reduction, and environmental sustainability [2-5].

Making bio-composites with different fiber ratios (70:30, 60:40, and 50:50) and examining their mechanical characteristics are the main goals of the study. ASTM D638-14 standards are used to evaluate key performance metrics, such as tensile strength, Young's modulus, impact resistance, and thermal stability [6-8]. To improve fuel efficiency without sacrificing performance, the study also looks at the viability of employing PALF-carbon fiber composites in non-structural aviation parts, including cabin panels and seat constructions. This research advances sustainable materials in aeronautical engineering by examining hybrid bio-composites. The results offer insightful information about the potential of PALF-based composites as environmentally acceptable substitutes, supporting the aviation industry's efforts to lower carbon emissions and advance greener technology [9-12].

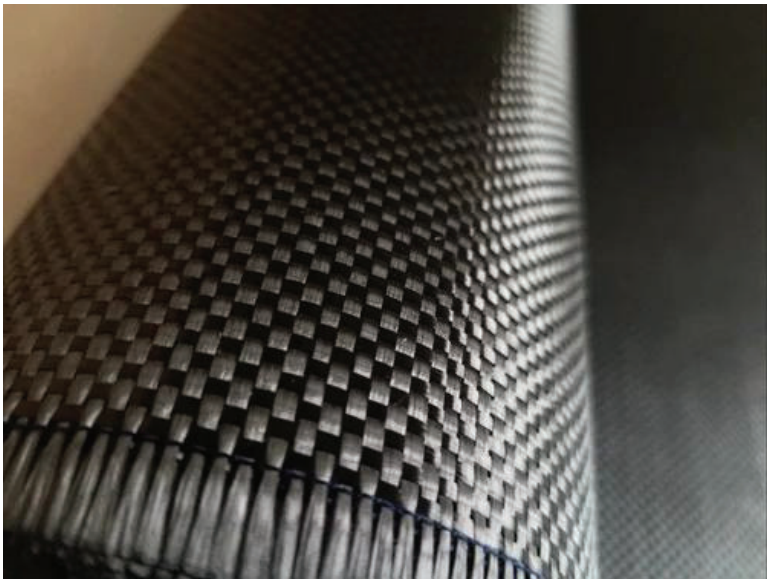

Fig 1: Carbon Fiber extracted

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2. Literature Survey:

Because of their strength, sustainability, and light weight, hybrid bio-composites are trending more and more popular in the aero industry. These materials combine synthetic reinforcements with natural fibers to provide a balance between environmental benefits and mechanical efficiency [13-14]. When paired with carbon fiber, pineapple leaf fiber (PALF) shows great promise for aeronautical applications by improving stiffness and tensile characteristics [15].

According to research, hybrid composites preserve their lightweight structure while increasing tensile strength, Young's modulus, and impact resistance [6], [12]. According to research by Fiore et al. and Koronis et al., the ideal strength and flexibility are achieved with a 60:40PALFcarbon fiber ratio [14], [16].Effective fiber-matrix bonding is crucial for performance. Surface treatments like alkali and silane modifications enhance adhesion and mechanical properties [9], [22]. Studies confirm that fiber roughness and hydrophobic treatments further improve durability and load-bearing capacity [20], [21].Bio-composites also offer sustainability advantages, reducing carbon footprint and promoting recyclability. They hold potential for aerospace interiors and non-structural applications [13], [23]. Strategies for scaling bio-composite production for aviation have been explored to enhance feasibility [24].

3. Objectives of the Study

- Fabrication and Development of PALF-Carbon Fiber Hybrid Composites
- Mechanical Characterization and Performance Evaluation
- Assessment of Feasibility for Aerospace Applications

4. Methodology:

This research focuses on the fabrication and characterization of the bio-composite materials using pineapple leaf fiber (PALF) and carbon fiber in different proportions. The methodology includes material selection, composite fabrication, and mechanical testing to evaluate the performance of these hybrid composites.

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4.1 Selection of Materials

The Selection of materials is performed based on the available resources and the materials are listed below with the justification behind choosing them.

- **Natural Fiber:** Pineapple Leaf Fiber (PALF), it is an eco-friendly and renewable material.
- **Synthetic Fiber:** Carbon fiber, chosen for the reason of its high strength-to-weight ratio and stiffness.
- **Resin:** Epoxy resin is used as a matrix material for fiber bonding and composite formation.

4.2. Fabrication of Bio-Composites

The composites were fabricated with varying proportions of PALF and carbon fiber (70:30, 60:40, and 50:50) using the following steps:

Table 1: Detailed dimensions of the specimen as per the ASTM D638-14.

Parameter	Value (mm)
Overall Length	165
Gauge Length	50
Length of Narrow Section	57
Length of Narrow Grips	115
Overall Width	19
Gauge Width	13
Thickness	3.2

4.2.1 Preparation of Fibers

- PALF was extracted from pineapple leaves, cleaned, and treated with an alkali solution to enhance fiber-matrix adhesion.
- Carbon fiber was cut into desired lengths to match the composite molding requirements.

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4.2.2 Composite Fabrication Process

- The fibers were arranged in layers according to the selected proportions.
- Epoxy resin was prepared and infused into the fiber layers using the Hand layup technique to ensure proper impregnation and air bubble removal.
- The composite was cured at controlled temperature and pressureto enhance mechanical properties.
- After curing, the composite samples were trimmed and prepared for mechanical testing as per ASTMD638-14standards. (Dimensions for trimming is mentioned in Table no.1)

Fig 2: Preparation of Specimen as per the standard of ASTM D638-14

4.3. Mechanical Testing and Characterization

Tests conducted in compliance with ASTM D638-14 guidelines evaluated the mechanical properties of the bio-composites that were created. The following tests were performed:

- The Tensile Test is to determine elongation at break, Young's modulus, and tensile strength of the composite material.
- The main reasonfor the Flexural Strength Test is to evaluate the composite's resistance to bending forces.
- The Impact Resistance Test is to assess the resilience and energy-absorbing potential of the composite.
- The density measurement test is to assess how well a material balances weight and strength.

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4.4. Data Analysis and Validation

- The experimental results were analyzed to compare the performance of different fiber ratios.
- The optimal composite composition was identified based on the balance between strength, flexibility, and sustainability.
- The viability of employing PALF-carbon fiber composites in aerospace applications was established by validating the results with the body of existing research.

Fig 3: Different Composition Specimen for Testing as per the standard of ASTM D638-14

5. Results and Discussion:

Mechanical characteristics such as tensile strength, Young's modulus, elongation at break, maximum force, and density were evaluated for the composite specimens with different ratios of carbon fiber and pineapple leaf fiber (PALF). The specimens were tested at the Geological & Metallurgical Laboratories (GLM), Bangalore, after being prepared in accordance with ASTM D638-14 standards.

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5.1. Mechanical Properties with Varying in Fiber Compositions.

- **Tensile Test:**

With the increase in the percentage of carbon fiber, the tensile strength is also increased up to 60%, after that the slightly reduction of strength.

The tested Results are Mentioned Below:

- 50:50 PALF-Carbon Fiber Composite: 43.1 MPa
- 40:60 PALF-Carbon Fiber Composite: 79.5 MPa
- 30:70 PALF-Carbon Fiber Composite: 76.8 MPa

Due to its greater load-bearing capacity, this trend indicates that increasing the carbon fiber content up to 60% greatly improves the tensile strength

- **Young's Modulus Test:**

The results of Young's Modulus are mentioned below with an increase in the carbon fiber.

- 50:50 Composite: 5734.6 MPa
- 40:60 Composite: 8003.6 MPa
- 30:70 Composite: 8697.7 MPa

Since carbon fiber is stiffer than PALF, it is to be predicted that the composite will become stiffer as the percentage of carbon fiber increases.

- **Elongation at Break**

- 50:50 Composite: 3.4%
- 40:60 Composite: 4.4%
- 30:70 Composite: 2.0%

The highest elongation at break was observed in the 60% carbon fiber specimen, indicating better flexibility and ductility. However, at 70% carbon fiber, the material became more brittle, leading to reduced elongation.

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- **Maximum Force and Density**

- Maximum force: Increased from 2965.25 N (50:50) to 3862 N (60:40) and slightly decreased to 3061 N (70:30).
- Density: Increased with carbon fiber content from 1.35 g/cm³ (50:50) to 1.45 g/cm³ (70:30), reflecting the higher density of carbon fiber compared to PALF

Table2: Nature of Sample 50:50, Carbon Fiber & Pineapple Fiber

Parameters	Observations	Test Method
Width x Thickness, mm	14.28 x 4.82	ASTM-D638-14
Maximum Force, N	2965.25	
Tensile Strength, MPa	43.1	
% Elongation (on 50mm GL)	3.4	
Young's Modulus, MPa	5734.6	

Table3: Nature of Sample 60:40, Carbon Fiber & Pineapple Fiber

Table4: Nature of Sample 70:30, Carbon Fiber & Pineapple Fiber

Parameters	Observations	Test Method
Width x Thickness, mm	12.15 x 3.28	ASTM-D638-14
Maximum Force, N	3061.00	
Tensile Strength, MPa	76.8	
% Elongation (on 50mm GL)	2.0	
Young's Modulus, MPa	8697.7	

Width x Thickness, mm	13.20 x 3.68	ASTM-D638-14
Maximum Force, N	3862.00	
Tensile Strength, MPa	79.5	
% Elongation (on 50mm GL)	4.4	
Young's Modulus, MPa	8003.6	

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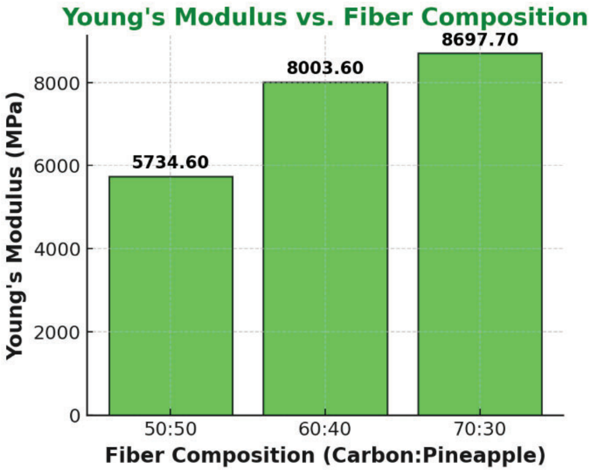
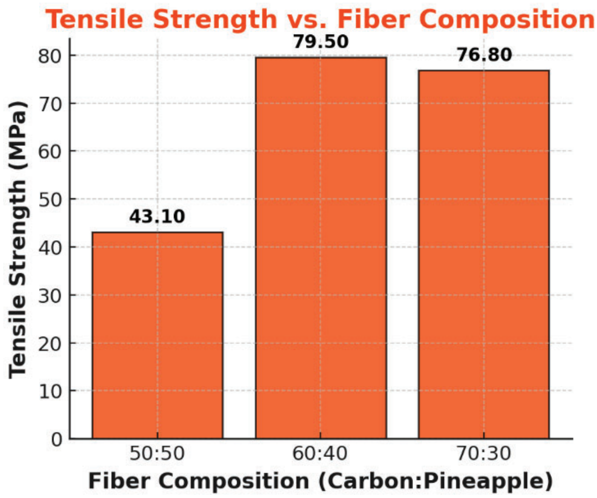
5.2. Discussion on Composite Performance

The results indicate that the optimum mechanical performance is achieved at a 60:40 carbon fiber-PALF proportion, the peak value will be achievedat the point of breakage during the tensile test, Young's Modulus Test, and in the elongation test. The 70:30 composite exhibited higher stiffness but reduced ductility, making it more brittle.The slight drop in tensile strength beyond 60% carbon fiber suggests that excessive carbon fiber content might lead to poor adhesion within the epoxy matrix, affecting the composite's strength. Additionally, the increase in density with carbon fiber content may influence the application suitability of these composite structures inthe aero industry, where weight reduction is crucial.





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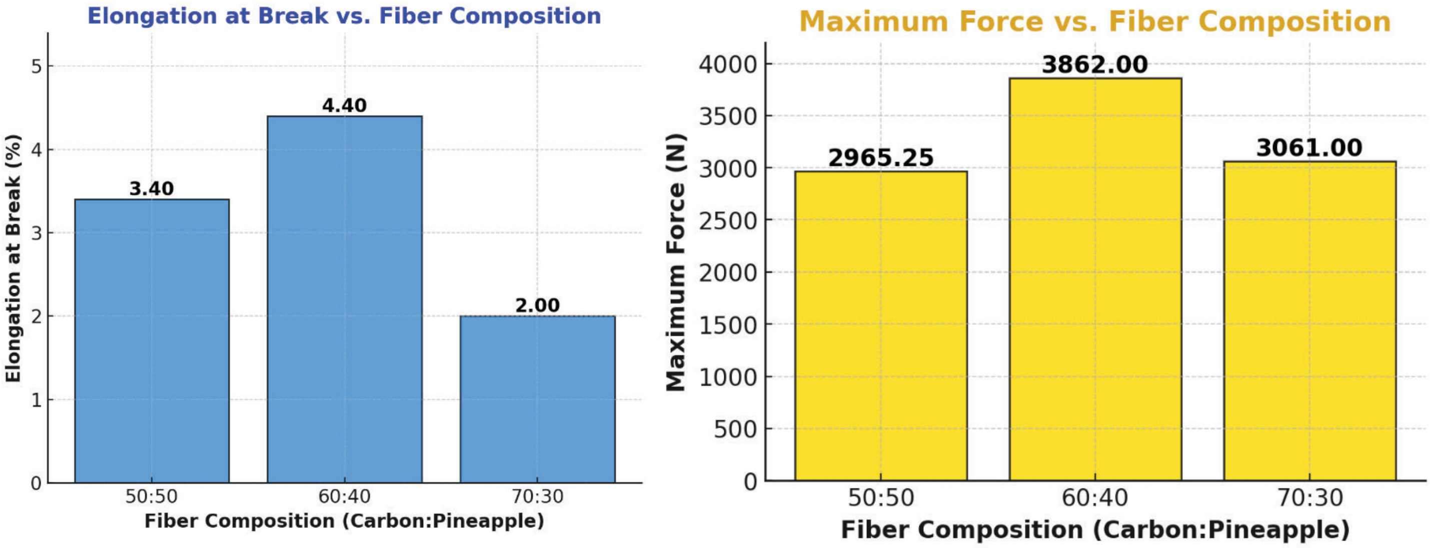

Fig.4 **Composite Performance**

6. Conclusion

The study demonstrates the fabrication and evaluation of hybrid bio-composites reinforced with carbon fiber and pineapple leaf fiber (PALF). Mechanical properties such as tensile strength, Young's modulus, and impact resistance were found to vary with fiber composition. The 60% carbon fiber–40% PALF composite achieved an optimal balance of strength, flexibility, and sustainability, making it suitable for non-structural aerospace applications like interior panels and cabin components. Increased PALF content enhanced sustainability while maintaining adequate performance. Although PALF offers an eco-friendly alternative to synthetic materials, processing challenges remain. Future research should focus on advanced manufacturing techniques and hybridization strategies to extend its application to structural aerospace components.

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