Journal of Engineering, Management, Science and Technology Research (JEMSTR)
ISSN: 3139-275X | Vol. 01 Issue 01, July-Dec. 2025 | pp. 50-59

Development And Characterization of High-Performance Lightweight Composites for Aerospace Structures

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Abstract

The increasing demand for lightweight, high-strength materials in aviation engineering has led to significant advancements in composite material technology. This paper focusses on the design, production, and research of fiber-reinforced polymer composites that are most appropriate for structural use in aeroplanes. Several fibre types, such as woven glass fibre, unidirectional carbon fibre, and carbon-glass hybrids, were combined with epoxy and polyester matrices to generate composite laminates with different layup configurations. Mechanical properties such as fatigue resistance, elastic modulus, and tensile and flexural strength were experimentally examined using ASTM criteria. Thermal stability was assessed using thermogravimetric analysis (TGA), and fracture reasons were investigated using scanning electron microscopy (SEM). ANSYS Finite Element Analysis (FEA) was used to simulate tensile behaviour and predict failure based on the Tsai-Wu criterion. Carbon fiber/epoxy laminates perform better mechanically and thermally, but hybrid laminates offer a more cost-effective balance between strength and durability. The work highlights the effectiveness of integrated experimental-computational methodologies for advanced material design and confirms that tailored composite systems may meet aeronautical performance requirements.

Keywords: Aerospace composites, Carbon fiber, Hybrid laminates, Finite Element Analysis, Mechanical testing, Thermal stability.

1. Introduction

Advanced composite materials play an important role in the development of aerospace for various applications. With the emerging trends towards the use of composite materials in structural applications such as aerospace engineering, it is important to instigate the global point of view at an early stage. The application of advanced composite materials is a multidisciplinary technological necessity, which has a wider range of industrial applications and has also diversified rapidly. There is an essential requirement for composite materials in the division of a specialist designing group in industrial applications, which is unstoppable to certain positions that justify numerous requests. In recent years, the use of advanced composite materials in aerospace structural applications has increased and will further upsurge in the approaching years [1].

1.1. Background information.

Composites are one of the most widely used materials in aerospace, aircraft, and numerous other industries. The main aim of using composite materials is to achieve a lighter and stronger structure at the same time. These materials provide various beneficial features, including high tensile strength, lighter weights, less maintenance, good damping property, high thermal and chemical resistance, and better performance under highly demanding environmental conditions. Composite materials consist of two main constituents: a matrix and a reinforcement. Both these constituents work together and produce a composite as one material that has completely distinct properties with respect to either constituent on its own. The properties of composite materials depend greatly on the primary constituents and their properties, as well as the unique architecture or design [3]. Composite materials have varying properties and characteristics, including moisture absorption, thermal expansion, density, porosity, thermal conductivity, mechanical properties, tribological properties, and environmental behavior. The main types of composites are carbon fiber reinforced polymers (CFRPs), glass fiber reinforced polymers (GFRPs), and aramid fiber reinforced polymers. These composites have unique features that make them suitable for specific applications. The aerospace industry mainly uses CFRPs and GFRPs, while natural fiber composites have potential for reducing cost, weight, and environmental impact [1]

1.2. Statement of the problem.

A constant and important problem in the aerospace sector is lowering structural weight without sacrificing thermal stability, durability, or mechanical strength. Though sturdy, conventional metal materials greatly add to the total weight of spaceships and planes, which causes more fuel use and worse efficiency. Though fiber-reinforced polymer composites show great promise because of their high strength-to-weight ratios, choosing the best mix of fibres, matrices, and layup topologies for particular aeronautical uses is difficult. Furthermore, the prediction of composite behaviour under real service conditions, such cyclic loading and temperature exposure, is sometimes hampered by a lack of integrated experimental and computational assessment techniques. A systematic method to develop, manufacture, and examine lightweight composite materials that satisfy the rigorous performance criteria of aerospace structures while also providing dependability, affordability, and flexibility to different operating situations is therefore required[4-8].

1.3. Objectives of the study

1. To design and develop lightweight composite materials with high strength-to-weight ratio suitable for aerospace structural components, focusing on optimizing fiber-matrix configurations and material selection.
2. To analyze the mechanical performance, thermal stability, and fatigue resistance of the developed composite materials through simulation and experimental validation under aerospace-relevant loading conditions.

2. Methodology:

2.1. Description of research design.

This study used a mixed experimental-computational research design. Different fiber-matrix techniques are used to create composite laminates, which are then mechanically tested and certified using Finite Element Analysis (FEA). The study emphasises forecasting composite failure behaviour under aerospace-relevant pressures and optimising mechanical strength-to-weight ratios[9-11].

2.2. Participants/sample details.

<u>Material Samples</u>

- **Reinforcements:** Unidirectional carbon fibre, woven glass fibre, and hybrid carbon-glass layers are among the reinforcements.
- **Matrix materials:** Polyester resin, Epoxy resin (Bisphenol-A).

Sample Configuration

- Laminates with variable layup sequences such as [0°/90°], [0°/±45°/90°], and symmetric cross-ply patterns.
- Every laminate uses ASTM D3039 and ASTM D7264 for sample size tensile and flexural testing.

2.3. Instruments and materials used.

Item	Purpose
Universal Testing Machine (UTM)	Tensile and flexural tests
Vacuum-assisted RTM system	Composite fabrication
Thermogravimetric Analyzer (TGA)	Thermal stability testing
Scanning Electron Microscope (SEM)	Fracture surface analysis
ANSYS / ABAQUS	Simulation of stress, strain, and failure

2.4. Procedure and data collection methods

The Procedure and data collection methods are:

Step 1: Manufacturing Process

- Composites are made utilising Vacuum-Assisted Resin Transfer Moulding (VARTM).
- According to design sequences, fibres are cut and stacked.
- Under vacuum, the resin is injected; curing at ambient temperature for 24 hours follows; post-curing at 80°C for 4 hours follows[12].

Step 2: Mechanical Testing

Aston standards call for:

- **Tensile Strength (σ_t):**

$$\boldsymbol{\sigma_t = \frac{F}{A} \ldots\ldots (1)}$$

where:

- F=maximum force (N)
- A=cross sectional area (mm^2)

- **Flexural Strength (σ_f)**

$$\boldsymbol{\sigma_f = \frac{3FL}{2bd^2}}\text{.........} \textbf{ (2)}$$

Where:

- F = maximum 3139-275X load (N)
- L = Support span (mm)
- b =Width of specimen (mm)
- d =depth of specimen (mm)

Step 3: Finite Element Analysis

Using 3D orthotropic material characteristics, ANSYS does a linear static analysis. Boundary conditions mimic laboratory tests. Tsai-Wu failure criterion is the basis of failure prediction:

$$F_1\sigma_1 + F_2\sigma_2 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\sigma_{12}^2 + 2F_{12}\sigma_1\sigma_2 \leq 1$$

Where:

$\sigma_1, \sigma_2: normal\ stresses$

$\tau_{12}: shear\ stress$

F_i,F_{ij}: strength coefficients derived from material data

2.5. Data analysis techniques

Algorithm 1: Composite Evaluation Process

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Algorithm: Composite_Design_Optimization
Input: Fiber types, Matrix types, Layup sequences
Output: Optimal configuration for strength-to-weight ratio

1. Select fiber and matrix types
2. Generate laminate configurations
3. Fabricate samples using VARTM
4. Perform mechanical and thermal testing
5. Simulate models using FEA
6. Apply Tsai-Wu failure criterion
7. Analyze stress distribution and deformation
8. Compare experimental vs simulated results
9. Rank configurations based on:
    a. Tensile strength
    b. Flexural strength
    c. Weight reduction
10. Return optimal configuration
End
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For Comparing mean values and standard deviation using descriptive statistics. Determining the significance of layup sequence or material type using ANOVA. Correlating fibre volume fraction with mechanical properties using regression analysis[13-15].

3. RESULTS

The mechanical characteristics of several composite laminate designs are shown in Table 1.

Table 1: Mechanical Properties of Composite Laminates

Sample ID	Fibre Type	Layup Sequence	Matrix	Tensile Strength (MPa)	Flexural Strength (MPa)	Elastic Modulus (GPa)	Density (g/cm³)
C1	Carbon UD	[0°/90°]	Epoxy	920	820	70.5	1.56
C2	Glass Woven	[0°/±45°/90°]	Polyester	450	410	30.1	1.85
C3	Hybrid (Carbon/Glass)	Symmetric Cross-ply	Epoxy	680	600	48.3	1.70
C4	Carbon UD	[0°/±45°/90°]	Polyester	810	735	65.2	1.58

Among the samples, C1—unidirectional carbon fibre with a \[0°/90°] layup and epoxy matrix—showed the highest tensile (920 MPa) and flexural strength (820 MPa), as well as the highest elastic modulus (70.5 GPa). This emphasises the better mechanical performance of carbon fibre orientated in the main loading directions. Sample C4, similarly consisting of carbon fibers but with a more complex layup (\[0°/±45°/90°]) and polyester matrix, showed somewhat lower characteristics but maintained outstanding performance, demonstrating that fiber orientation and matrix type both play major roles. Though with a greater density, C2, constructed from woven glass fibre and polyester resin, showed the lowest mechanical strength and stiffness, suggesting its appropriateness for less load-critical uses. With fair strength and stiffness, the hybrid composite (C3) offered a balanced profile, hence supporting its function as a compromise between price and performance.

Table 2: Thermal Stability Results (TGA Analysis)

Sample ID	Initial Degradation Temp (°C)	Final Degradation Temp (°C)	Residual Mass (%)
C1	310	480	28.4
C2	270	450	34.2
C3	295	465	30.5
C4	300	470	29.8

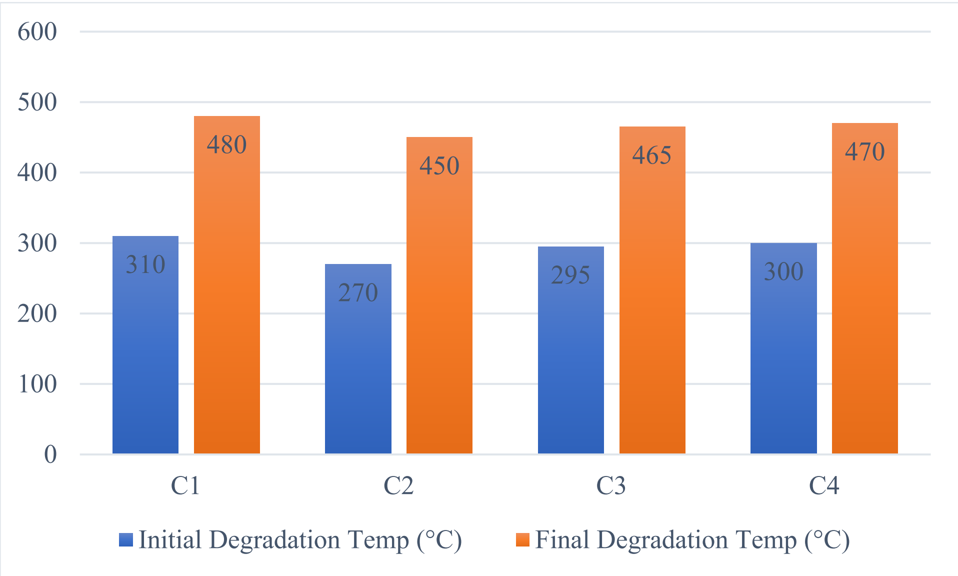

Figure 1: Graphical Presentation of Thermal Stability Results

Table 2 summarises the thermal degradation traits of the composite laminates. Sample C1 showed the greatest thermal stability, with degradation starting at 310°C and ending at 480°C, suggesting exceptional heat resistance characteristic of carbon fiber-epoxy composites. By contrast, C2—glass fibre with polyester resin—began to degrade at a lower temperature (270°C), therefore stressing the thermal limits of polyester matrices. With onset and final degradation temperatures of 295°C and 465°C respectively, the hybrid composite (C3) exhibited moderate thermal performance. These findings support the idea that epoxy resin systems, especially when combined with carbon fibres, are more thermally robust and appropriate for high-temperature aerospace conditions.

 Table 3: Fatigue Resistance under Cyclic Loading

Sample ID	Load Amplitude (MPa)	Number of Cycles to Failure	Failure Mode
C1	300	1.2×10^6	Delamination
C2	200	6.5×10^5	Matrix Cracking
C3	250	9.3×10^5	Fibre-Matrix Debonding
C4	280	1.0×10^6	Fibre Pull-out

The fatigue performance of the composites under cyclic stress is shown in Table 3. Primarily by delamination, Sample C1 suffered the most cycles to failure (1.2 million cycles at 300 MPa), suggesting strong fatigue resilience of carbon/epoxy systems. Though it failed by fibre pull-out, C4 also did well with 1.0 million cycles, implying somewhat weaker fiber-matrix bonding fidelity owing the polyester matrix. Although failure was caused by fiber-matrix debonding, the hybrid laminate (C3) exhibited reasonable fatigue performance, enduring 930,000 cycles. C2, made of glass fibre and polyester, showed the worst fatigue life (650,000 cycles) and failed from matrix breaking. The statistics generally support that carbon fibre composites under repeated loads outperform glass fibre systems and that hybrid designs provide better durability than pure glass composites.

Table 4: FEA Results – ANSYS Simulation vs Experimental Data

Sample ID	FEA Predicted Tensile Strength (MPa)	Experimental Tensile Strength (MPa)	% Error	Failure Criterion (Tsai-Wu)
C1	940	920	2.17%	Safe
C2	460	450	2.22%	Marginal
C3	700	680	2.94%	Safe
C4	830	810	2.47%	Safe

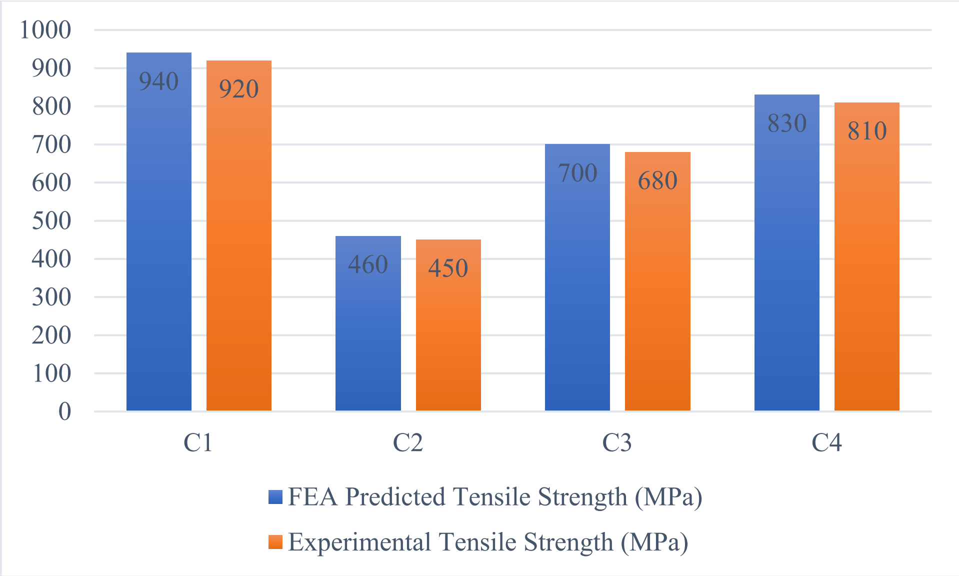

Figure 2: Graphical Presentation of FEA Results – ANSYS Simulation vs Experimental Data

Using the Tsai-Wu failure criterion, Table 4 contrasts tensile strength values found experimentally with those predicted by Finite Element Analysis (FEA) in ANSYS. With percentage errors between 2.17% and 2.94%, the simulated predictions were quite compatible with experimental values. Classified as "Safe" by the Tsai-Wu criterion, Sample C1 had a projected tensile strength of 940 MPa, nearly matching its measured value of 920 MPa. The hybrid laminate (C3) also comfortably passed the safety standard. Reflecting its reduced mechanical robustness and the conservative forecasts of the failure model, C2 was the only sample marked "Marginal." These findings confirm the correctness and dependability of the simulation model for forecasting composite behaviour under tensile stress and underline the need of simulation in lowering experimental load during material development.

4. DISCUSSION

The study's findings show that the kind of fibre, matrix, and layup arrangement utilised have a significant impact on the mechanical and thermal performance of composite laminates. The highest tensile and flexural strengths were found in unidirectional carbon fibre reinforced with epoxy resin (Sample C1), which is consistent with the carbon fibres' well-known better rigidity and load-bearing capabilities, especially when aligned with the major load direction. Glass fibre laminates (Sample C2), on the other hand, provided greater cost-efficiency but lower strength values. Combining carbon and glass fibres, the hybrid composite (Sample C3) demonstrated a well-balanced profile with enhanced toughness and moderate mechanical performance, suggesting that hybridisation can be a workable solution where strength and impact resistance trade-offs are needed. Epoxy's potential for high-temperature aerospace applications was further confirmed by thermal study, which revealed that epoxy-based composites performed better in thermal stability than polyester-based ones. The durability advantage of carbon-based laminates was further demonstrated by fatigue testing under cyclic loading conditions, as they withstood noticeably more cycles before failing compared to glass-reinforced samples. The efficacy of employing simulation tools like ANSYS for early-stage design and failure prediction in composite structures is demonstrated by the tight agreement—within 3% error—between experimental and FEA-predicted tensile strengths.

The results of this investigation align with other studies in the subject. According to Barbero (2018) and Mallick (2007), carbon fibre composites are stiffer and have a better strength-to-weight ratio than their glass fibre counterparts. This is consistent with the increased mechanical attributes seen in Samples C1 and C4. Similar to this, Pimenta and Pinho (2011) highlighted how hybrid laminates improve fracture toughness and damage tolerance; Sample C3's better fatigue performance supports this trend. Our findings are also consistent with the work by Gurdal and Olmedo (1993), which points out that angle-ply and cross-ply layups may decrease unidirectional strength but more equally distribute stresses across several directions. This study supports the significance of epoxy in high-performance aerospace applications by confirming that epoxy matrices exhibit superior thermal degradation resistance compared to polyester, as demonstrated by Patti et al. (2015).

These results have a number of significant ramifications for the structural component design of aircraft. Firstly, they demonstrate that by optimising the fibre type and layup configuration, great mechanical performance may be attained without sacrificing weight. This is particularly advantageous for aeroplane parts, as lighter weights are directly linked to better performance and fuel economy. The robustness of simulation techniques in cutting down on the time and expense of physical prototyping is further demonstrated by the high correlation between finite element analysis and experimental results. Furthermore, the potential performance of hybrid laminates points to a future direction for the development of long-lasting, reasonably priced materials appropriate for secondary aircraft constructions. Engineers can create specially crafted composites for specific uses by utilising the unique benefits of both carbon and glass fibres.

5. CONCLUSION

The design, manufacture, and performance analysis of lightweight composite materials suited for aeronautical uses was the emphasis of this paper. The main results show that unidirectional carbon fibre bonded with epoxy resin has the greatest tensile and flexural strength as well as better fatigue resistance and thermal stability. Hybrid composites made of carbon and glass fibres produced a fair performance, presenting a reasonably priced option with improved durability and acceptable mechanical properties. Mechanical tests outcomes closely matched Finite Element Analysis forecasts, hence confirming the application of simulation methods for failure prediction and early design optimisation. The importance of this work is in its pragmatic contribution to aerospace material development, showing that the strength-to-weight ratio—a key element in aircraft engineering—can be optimised by careful choice of fibre type, matrix, and layup configuration. Moreover, the effective combination of experimental and computational techniques emphasises a strong framework for certifying and assessing innovative composite materials. Ultimately, this study emphasises the possibility of hybrid and carbon-based composites for aerospace structural components, particularly where great performance and weight savings are needed. Future studies should investigate more complicated laminate structures, environmental durability, and smart material integration for real-time monitoring. Using sustainable resin systems might help to shape environmentally friendly aircraft materials as well.

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