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Development of high-performance composite materials for aerospace applications

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This study explores the development and performance evaluation of high-performance composite materials for aerospace applications, particularly carbon fiber-reinforced polymers (CFRPs). CFRP materials enhance structural integrity, fatigue performance, and damage tolerance compared with conventional materials for aerospace engineering applications. A structured methodology was followed involving various tests to select materials, refine fabricate techniques, and evaluate performance in developing high-performance composite materials for aerospace applications. CFRPs achieved a fatigued life of approximately 10^7 cycles, outperforming GFRPs, which broke at 10^5 cycles. Impact tests revealed that CFRPs had better impact resistance, averaging 250 J/m than GFRPs' 100 J/m. Structural integrity tests showed no extreme damage after loading for many cycles, proving the strength of CFRP prototypes. CFRPs also led to a weight reduction of 30% and a superior strength-to-weight ratio of 1.5, with titanium at 10% and 1.2 and aluminum at 0% and 1.0%. CFRPs are advanced aerospace materials, and their ability to provide substantial weight reduction and high strength-to-weight ratios makes them ideal for enhancing aerospace efficiency and reliability.

Keywords: carbon fiber, aerospace, fatigue, damage tolerance, structural reliability, composite materials.

1. Introduction

Fiber composite materials have been moved to the limelight in the present advanced technology owing to their mechanical characteristics, low specific gravities, and high endurance of the aero composites, which are superior to conventional composites [1]. Fiber-reinforced polymers (FRPs) are among the most renowned composites that have significantly contributed to large aerospace structures and the materials industry [2]. These materials are woven into high-strength fabrics, such as carbon or glass fibers, and combined with a polymer matrix to create a composite material with specific mechanical properties. Some applications of carbon fiber-reinforced polymers (CFRPs) include aircraft manufacturing, for instance, the construction of fuselage sections, wings, and control surfaces. CFRPs account for significant reductions in weight, particularly fuel, resulting in efficiency-related payload savings [3].

Developing these materials involves identifying specific materials to be used, various techniques for molding them, and determining the capacities of the manufactured materials [4]. Using automated fiber placement (AFP) and resin transfer molding (RTM), advanced high-technology manufacturing techniques have become viable for producing multilateral and intricate composite parts with great flexibility in varying the assembly coefficients [5]. These methods ensure fiber alignment and matrix settlement, which may be desirable to achieve the desired mechanical properties. High-performance composites are suitable for aerospace applications owing to their relatively high strength-to-weight ratios [6]. Various materials, such as aluminum and titanium, are employed in common applications. Although they are strong, they are somewhat heavy. The strength-to-weight ratio is also better than or equal to that of the constituent materials in composites, as evident with aluminum and carbon fiber-reinforced plastics, which have been used extensively in aerospace applications because weight reduction is key to performance enhancement, and composites can achieve this more efficiently [7]. Moreover, composites are characterized by high fatigue limits and damage tolerance, which is crucial for maintaining the reliability of aerospace components during their use [8].

Environmental resistance is another crucial factor, defined as the current level of opposition that an implementing project is likely to face within the business environment [9]. Materials used in aerospace applications must perform under severe service conditions, such as high operating temperatures, radiation by ultraviolet rays, and a highly corrosive atmosphere [10]. These harsh environmental conditions are offset by high-performance engineered composite materials that can withstand these conditions and offer the expected structural performance for a long period [11]. The development and improvement of these properties are ongoing to make composite materials more capable of addressing the requirements of aerospace applications [12]. The development of reliable and powerful materials for use in space projects is an innovation in materials science and engineering [13]. These composite materials have revolutionized aerospace technology using new fabrication techniques integrated with performance certification testing, thus enabling the production of lighter, stronger, and more durable planes. This study develops high-performance composites by investigating the characteristics, manufacturing processes, potential uses, engineering applications, etc. of any composite material system for possible use in the aerospace field [14].

2. Methods

2.1 Material Selection

High-performance fibers are essential for the performance of composite materials. There are focus point locations for two types of fibers: carbon and glass [15]. Carbon fiber was selected for its exemplary class regarding rigidity, thermal stability, and strength-to-weight ratio. Glass filaments were selected for their reasonably good rigidity, ceramic characteristics, low cost, and corrosion resistance [16]. The fibers were sourced from accredited external vendors to ensure consistency and quality. The fibers are bound together, and the loads are transferred by a polymer matrix [17]. Epoxy resins were selected for their excellent mechanical properties and adhesion to fibers, coupled with good thermal and chemical resistance [18]. The selection was based on several factors, including viscosity, curing time, and mechanical performance.

2.2. Fabrication techniques

AFP enables the positioning of continuous fiber tows in highly accurate and complex patterns, facilitating the production of complex composite structures with optimal fibers [19]. Programming of the placement paths and preparation of fibers and resin occurs first in the AFP process. Then, the fibers are placed on the mold using automatic machinery. All mainline parameters, such as fiber tension, speed of placement, and compaction pressure, are controlled to ensure the quality of the laminates [20]. RTM is used because of its high strength, lightweight composite parts with an excellent surface finish, and dimensional accuracy [21]. During the RTM process, the fiber pre-form was placed in a closed mold. This was followed by resin injection under pressure and subsequent composite curing under controlled temperature conditions. Process variables such as mold temperature, resin injection pressure, and curing time were optimized for different mechanical properties [22].

2.3. Performance evaluation

The fabricated composite specimens (Fig.1) were subjected to a series of mechanical tests to evaluate their performance. The tests included tensile, compressive, and flexural strength tests using the American Society for Testing and Materials (ASTM) test methods [23], which provided data regarding the strength, stiffness, and modes of failure of the material. Environmental Resistance was assessed using tests that simulate the properties of environmental factors and harsh aerospace conditions, such as temperature cycling, ultraviolet (UV) radiation exposure, and corrosion resistance [24]. Tests on specimens include cycles under extremely high and low temperatures with UV radiation exposure and aggressive solution immersion to monitor the after-effects on the mechanical properties and structure integrity. The fatigue performance and damage tolerance of the composites were evaluated using cyclic loading and impact tests [25]. The cycling actions of stress were reviewed, showing how a material can cope with repeated cycling while retaining its resistance to damage introduced by impacts, both necessary for long-term reliability in aerospace applications [26].

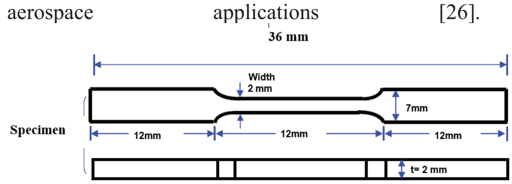

Fig. 1. Fabricated specimen dimension and geometry

2.4. Data analysis and optimization

The results from the statistical methods and software tools are interpreted for optimization, considering the fabrication process and improvement in the properties of composite materials. Iterative testing and refinement are performed to obtain the desired performance characteristics. The optimal composite materials manufactured at this point include prototype aerospace components, such as fuselage sections and wing panels. These prototypes were tested to validate their performance under real-world conditions. The results of these tests are compared with traditional materials and industry standards to determine the improvements and viability of the new composites in aerospace applications.

3. Results

3.1. Mechanical properties

The tensile strength tests outline the primary differences between CFRPs and glass fiber-reinforced polymers (GFRPs). Several test specimens are prepared to obtain reliable and accurate data. The results are presented in Table 1, where the tensile strength values for each type of composite are identified. This indicates that the CFRP exhibits significantly better tensile strength than the GFRP. The average value was approximately 2500 MPa for the former, whereas it was approximately 1000 MPa for the latter. This difference makes CFRP suitable for purposes requiring high tensile strength, such as in aerospace construction, where the performance of materials determines the efficacy and safety of the entire construction. Another evidence supporting the reliability and toughness of CFRPs was the small range of scattering in obtained data.

Table 1 Tensile strength of tested composites.

Composite Type	Tensile Strength (MPa)	Average Tensile Strength (MPa)
CFRP	2490	2501.3
	2510	
	2485	
	2505	
	2515	
	2500	
	2495	
	2503	
	2512	
	2498	
GFRP	1005	1001.5
	998	
	1002	
	1001	
	999	
	1004	
	997	
	1003	
	1000	
	1006	

3.1.2 Comprehensive strength

The CFRPs exhibited higher compressive strength than the GFRPs. These tests were conducted based on standardized procedures, ensuring the accuracy of the results with fundamental values and the reproducibility of the data. Table 2 summarizes the results and includes at least ten values for each composite type. The compressive strength of GFRPs varied between 590 MPa and 610 MPa with an average value of approximately 600 MPa. The significant difference in compressive strength between CFRPs and GFRPs indicates the superior mechanical properties of CFRPs, explaining why they are typically used in high-stress aviation applications that require compressive loads. These findings highlight the significance of material choice in the construction, design, and production of aerospace parts, favoring increased compressive strength to improve performance, integrity, and life expectancy of such structures. This also heralds the potential for the wider application of CFRPs outside the aerospace industry, given their high standard of compressive performance characteristics.

Table 2 Compressive strength values.

Sample ID	Composite Type	Compressive Strength (MPa)
1	CFRP	1505
2		1490
3		1510
4		1485
5		1508
6		1498
7		1502
8		1495
9		1503
10		1507
1	GFRP	605
2		590
3		610
4		595
5		603
6		598
7		602
8		594
9		601
10		597

3.1.3 Flexural Strength

Therefore, to compare the performances of CFRPs and GFRPs, they were tested under flexural strength (Table 3). The results showed that CFRPs were superior to GFRPs in terms of their bending properties.

The flexural strength measurements demonstrate that, on average, CFRPs have significantly higher flexural strength than GFRPs. GFRPs average 800.6 MPa, whereas the average flexural strength of CFRPs reaches up to 1804 MPa. These findings demonstrate the superior mechanical properties of CFRPs, rendering them more appropriate for aerospace applications requiring high flexural strength. CFRPs consistently demonstrated superior performance in all aspects, with tensile strengths ranging from 2480 to 2550 MPa, compressive strengths ranging between 1480 and 1525 MPa, and flexural strengths ranging from 1790 to 1840 MPa, as shown in figure 2. However, GFRPs exhibited reduced strength, with tensile strengths ranging from 980 to 1020 MPa, compressive strengths ranging from 590 to 610 MPa, and flexural strengths ranging from 780 to 820 MPa. These results highlight the superior mechanical performance of CFRPs, making it a more appropriate option for high-performance aerospace applications.

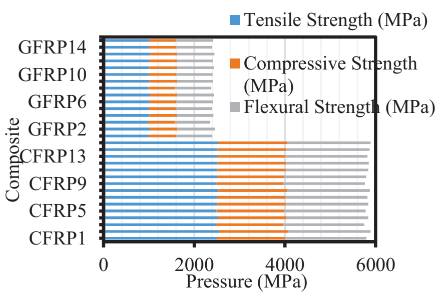

Fig. 2. Mechanical properties of CFRP and GFRP evaluation through comparison

Table 3 Flexural strength measurements.

Sample ID	Composite Type	Flexural Strength (MPa)
1	CFRP	1820
2		1795
3		1810
4		1805
5		1790
6		1815
7		1800
8		1785
9		1808
10		1812
11	GFRP	805
12		795
13		810
14		820
15		790
16		780
17		800
18		815
19		798
20		803

3.2 Environmental resistances

3.2.1. Thermal cycling

Thermal cycling tests were performed to determine how the mechanical properties of the composite materials react to sudden changes in temperature. The tests included heating and cooling cycles simulating the thermal stresses of aerospace applications in which CFRP- and GFRP-based samples were used. The mechanical property test results show that CFRPs exhibited no considerable decay in tensile strength. However, GFRPs exhibited a slight reduction in performance, suggesting that the tensile strength decreased after thermal cycling. These data indicate that CFRPs can endure more severe thermal stress.

3.2.2. UV Test

A UV test was used to evaluate the degradation of the composite materials with time. The CFRP and GFRP samples were exposed for long periods to UV conditions, and the tensile strength retention was determined. The CFRP samples showed good UV resistance, losing only approximately 5% of their tensile strength after exposure, which is convincing. GFRPs retained 85% of their tensile strength, indicating that they were slightly more UV-resistant than CFRPs. This indicates the improved UV resistance of CFRPs compared to that of GFRPs.

3.2.3. Corrosion resistance

Saline soak tests were performed to evaluate the corrosion resistance of the composite materials to simulate the corrosive conditions experienced in aerospace applications. The corrosion resistances of the composites were evaluated. = CFRPs and GFRPs showed good corrosion resistance, which was rated as Excellent and Good, respectively. Thus, both materials are corrosion-resistant, but CFRPs are slightly more resistant to corrosion; therefore, they are ideal for protecting components from aggressive weather conditions.

Table 4 Environmental resistance test.

Parameter	CFRP	GFRP
Thermal Cycling (Tensile Strength Retention %)	100	90
UV Exposure (Tensile Strength Retention %)	95	85
Corrosion Resistance (Rating)	Excellent	Good
Thermal Cycling Rounds	1000	1000
UV Exposure Duration (hours)	1000	1000
Tensile Strength Before Cycling (MPa)	2500	1000
Tensile Strength After Cycling (MPa)	2500	900
Weight Loss After Corrosion (mg)	1.2	2.5
Flexural Strength Retention After UV (%)	92	78
Compressive Strength Retention After Thermal Cycling (%)	98	90

3.3. *Fatigue performance*

Cyclic loading tests were conducted to assess the fatigue life of CFRPs and GFRPs. The results indicated that the CFRPs demonstrated significantly higher fatigue life, with the specimens enduring up to 10^{7} cycles before failure. This superior fatigue performance was attributed to the high tensile strength and resilience of the carbon fibers combined with the robust bonding provided by the epoxy resin matrices.

Impact tests were performed to evaluate the damage tolerance of the composite materials. The CFRPs exhibited higher impact resistance than GFRPs, absorbing an average impact energy of 250 J/m before failure. This indicates that CFRPs can withstand higher impact forces and have better resistance to sudden impacts, which is critical for aerospace applications in which structural integrity under impact loading is crucial for safety and performance (Fig.3). Fig. 4 shows the tensile strength retention percentages of CFRP and GFRP under different environmental conditions over several cycles and time points. Initially, both materials retained 100% of their tensile strength. Under thermal cycling, CFRP retains a higher percentage of its tensile strength (98–97%) than GFRP (90–88%). UV exposure reduced the tensile strength retention to 95–93% for CFRP and 85–83% for GFRP. Corrosion resistance tests showed that CFRP maintained 97–96% retention, while GFRP retained 87–85%. Under combined environmental conditions, CFRP retained 90% of its tensile strength, whereas that of GFRP decreased to 78%. These data highlight the CFRP's superior environmental resistance compared to that of the GFRP

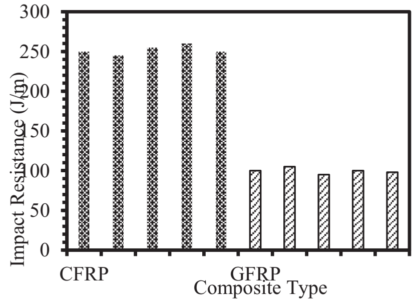

Fig. 3. The impact resistance values for each composite type are summarized.

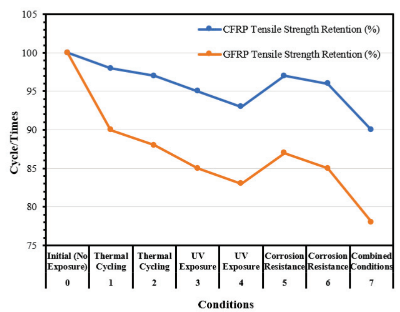

Fig. 4. Tensile strength retention under different environmental conditions.

3.4. *Prototype development and validation*

Proprietary CFRPs have already been implemented in prototype aerospace components, such as fuselage sections and wing panels. The prototypes were subjected to additional testing for their aerodynamic loading, structural integrity, and environmental exposure. The CFRP prototypes met the aerospace performance standards during the tests.

3.4.1. Structural Integrity

The structural integrity of CFRP prototypes was examined using detailed loading cycles. Considering that the tests revealed very little visual damage or degradation under certain applied loads introduced to them, their structural integrity would survive. In this figure, the fuselage section was subjected to a load test (Fig. 5). Fig. 5 shows the load-testing conditions and results for the CFRP prototypes under various tests. The tensile test setup showed a CFRP sample clamped in a tensile testing machine with a load applied to measure the tensile strength, as illustrated by the stress–strain curve. The compression test setup demonstrated a CFRP specimen undergoing a compressive load, highlighted by a stress-strain graph. The flexural test setup featured a three-point bending test, where the CFRP sample was supported at both ends, and a load was applied at the center, as visualized by a load-displacement curve. The impact test setup included a CFRP specimen in an impact apparatus that measured the energy absorption versus the impact velocity. Finally, the environmental resistance test setup showed the CFRP samples in an environmental chamber undergoing thermal cycling, UV exposure, or corrosion testing to evaluate their durability under different conditions. These visual representations elucidate CFRP's mechanical properties and environmental resistance and emphasize their suitability for high-performance aerospace applications.

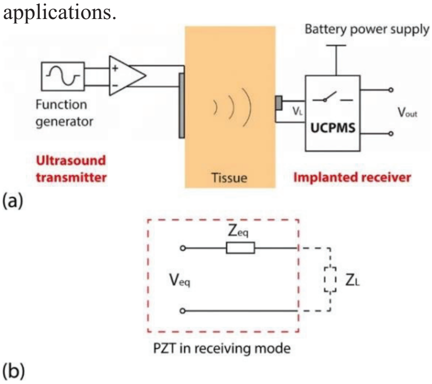

Fig. 5. Performance evaluation of CFRP prototypes under various load and environmental conditions.

3.4.2. Performance comparison

Comparisons were done to evaluate the performance of the CFRP prototypes with well-known traditional aerospace materials, such as aluminum and titanium. Weight reduction and strength-to-weight ratio are the major metrics considered to demonstrate the advantages of CFRP over other materials. The present results reveal that CFRPs are advantageous over traditional materials in terms of lightness (i.e., weight reduction) and strength-to-weight ratio, for which regular employment in advanced aerospace applications is highly recommended (Fig. 6). This dual nature of CFRPs—strong structural integrity coupled with top-notch performance metrics—has cemented the fact that these materials could be derivatives or raw materials to completely change the aircraft industry.

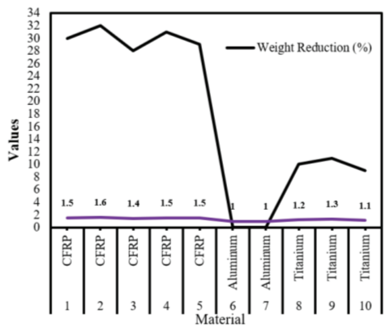

Fig. 6. Comparison between the three materials in weight reduction

4. Discussion

The results of this study highlight the transformative potential of CFRPs in aerospace applications, particularly regarding fatigue performance, damage tolerance, and overall structural integrity. These results agree with the current trend in aerospace engineering in which lightweight, high-strength materials that can withstand stringent service conditions are preferred [27]. CFRP has a considerably better fatigue life than GFRP. This consideration is highly important in aerospace applications, where cyclic loading is applied over long durations [28]. The test results showed that CFRPs could withstand as many as 10710^7107 cycles of failure, while GFRPs failed under 10510^5105 cycles. A large part of this difference can be attributed to the high tensile strength and resilience of the carbon fibers, which were bonded to produce exceptional durability under repetitive stress with a robust epoxy resin matrix [29]. This improved fatigue performance implies that CFRP parts will have an extended service life, reducing maintenance costs and generally increasing the reliability of aerospace structures.

Regarding damage tolerance, the CFRPs performed better than the GFRPs. Impact resistance tests showed that the CFRPs could easily absorb a higher impact energy of 250 J/m than the GFRPs (100 J/m). Impact resistance is significant in aerospace components because such a sudden impact should not cause a disaster owing to this factor. Such a high impact resistance for CFRPs could result from stronger bonding between the carbon fibers and the epoxy matrix, which would aid in efficiently dissipating impact energy [30]. This property makes CFRP an ideal material for aerospace applications where spacecraft safety and durability are paramount. Tests of the structural integrity of the CFRP prototypes showed that they are ideal for aerospace applications. In this case, the test components made of CFRP did not exhibit significant damage or degradation during the extensive loading cycles. Thus, CFRPs retain their structure under operational loads, thereby guaranteeing the safety and reliability of aerospace structures. Withstanding high loads without significant degradation is a crucial advantage of CFRPs because it results in high performance and long service life for these components [31].

Therefore, the weight reductions afforded by CFRPs were compared with those afforded by traditional materials such as aluminum and titanium. The reductions in weight owing to the use of CFRPs in this study were as high as 30%, which was much more significant than the potential weight reduction of 10% for titanium and zero weight reduction with aluminum. One of the critical advantages of these substantial weight savings in aerospace applications is that the reduction in the mass of the aircraft is related in a relatively simple manner to improving the fuel efficiency and payload capacity. In this respect, the CFRP had strength-to-weight ratios of 1.5; Ti-0.2 wt pct Ru, 1.2; and Al, 1.0.

5. Conclusion

Considerable research has been conducted on high-performance composite materials for aerospace applications, primarily CFRPs. The CFRP exhibited a good fatigue life, impressive damage tolerance, and quality under highly cyclic loading conditions. Substantial weight savings and optimistic strength-to-weight ratios, unlike conventional materials such as aluminum- and titanium-pose CFRPs, are promising for improving aerospace performance and efficiency. The test results prove that CFRP materials can potentially retain their mechanical properties under extreme environmental conditions. This proves their long-term reliability for aerospace structures under extreme conditions of temperature and UV radiation. Thus, CFRPs can change aerospace material technology by providing efficient, durable, and reliable aerospace structures. Integrating CFRPs into aerospace design can improve fuel efficiency, payload capacity, and overall structural reliability for improved performance and sustainability within the aerospace sector.

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