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Original Article

Comparative Study on the Static and Fatigue Life Analysis of Aircraft Wing Structures Using Lightweight Materials

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Abstract

The growing demand for lightweight, fuel-efficient, and structurally reliable aircraft has accelerated the use of advanced materials in wing construction. This study presents a comparative static and fatigue analysis of aircraft wing structures fabricated using Aluminum 7075-T6, Carbon Fiber Reinforced Polymer (CFRP), and Glass Fiber Reinforced Polymer (GFRP). A unified 3D wing model was developed and analyzed under identical aerodynamic loading using Finite Element Method (FEM) simulations. The results show that CFRP exhibits the highest stiffness with the lowest deformation (12.7 mm), reduced stress response (189 MPa), and exceptional fatigue endurance exceeding one million cycles. Aluminum 7075-T6 demonstrates moderate structural performance, while GFRP shows the highest deformation and the shortest fatigue life. These findings highlight CFRP as the most efficient material for modern aircraft wings, offering significant improvements in structural stability, fatigue resistance, and weight reduction. The study provides valuable insights for material selection aimed at optimizing aircraft performance, durability, and fuel economy.

Introduction

Importance of Aircraft Wing Structures

Aircraft wings are among the most critical load-bearing components of an airplane, responsible for generating lift and ensuring flight stability. During flight, wings experience various aerodynamic forces, including lift, drag, bending moments, torsion, and dynamic loads. These forces vary continuously based on altitude, airspeed, turbulence, and maneuvering conditions. As a result, the structural design of wings must ensure high strength, stiffness, and durability while maintaining low weight. Any structural failure in the wing can compromise flight safety, making their design and material selection essential aspects of aerospace engineering.

Role of Lightweight Materials in Aerospace Engineering

The aerospace industry continuously strives to improve fuel efficiency, reduce carbon emissions, and enhance overall aircraft performance. One of the most effective strategies to achieve these goals is the integration of lightweight materials into the structural components of the aircraft. Lightweight materials reduce total mass, leading to lower fuel consumption, increased payload capacity, and extended flight range. Additionally, such materials often provide higher strength-to-weight ratios, better fatigue resistance, and improved corrosion behavior compared to traditional metallic alloys. These advantages make lightweight materials a central focus in modern aircraft design.

Evolution from Metallic to Composite Wings

Historically, aircraft wings were predominantly built using metallic alloys such as Aluminum 7075-T6 due to their excellent strength, machinability, and cost-effectiveness. However, over the past few decades, the development of fiber-reinforced composites has revolutionized the aerospace sector. Materials like Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) offer superior mechanical performance with significantly lower densities, making them ideal for large structural components such as wings. Today, next-generation commercial aircraft utilize up to 50% composite materials by weight, marking a clear shift from traditional metal-based wings to hybrid or fully composite wing structures.

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Need for Structural Analysis

Aircraft wings must withstand both static and dynamic loads throughout their operational life. Static analysis ensures the structure can sustain maximum expected loads without permanent deformation or failure. However, wings are also subjected to repeated cyclic loading due to takeoff, landing, turbulence, and maneuvering. These cyclic stresses accumulate over time and can initiate fatigue cracks that may lead to structural failure if not properly evaluated. Therefore, both static and fatigue analyses are essential in determining the durability, reliability, and safety of wing structures.

The Impact of Cyclic Loads During Flights: During flight operations, aircraft wings encounter millions of stress cycles due to fluctuating aerodynamic forces. These cycles cause progressive micro-structural damage that weakens the material over time. While the applied stress in a single cycle may be below the material's yield strength, repetitive loading can lead to fatigue crack initiation, propagation, and eventual fracture. Understanding the behavior of materials under cyclic loading conditions enables engineers to accurately predict fatigue life and design wings that can withstand long-term operational demands.

Problem Statement

Although various materials have been used in aircraft wing construction, there remains a lack of comprehensive comparative studies that analyze both static and fatigue behaviors under identical loading and boundary conditions. Existing literature often focuses on individual materials or specific aspects of wing performance. This gap highlights the need for a unified study that evaluates the structural response of Aluminum 7075-T6, CFRP, and GFRP wings using standardized finite element analysis. Such a comparison is critical for determining the most suitable material for future aircraft wing designs, especially in terms of durability, weight reduction, and long-term performance.

Objectives of the Study

- To perform static structural analysis of aircraft wings constructed using Aluminum 7075-T6, CFRP, and GFRP.
- To evaluate the fatigue life of these wings using stress-life (S-N) curves and finite element analysis.
- To identify the most suitable material for aircraft wing applications based on strength, deformation, fatigue resistance, and weight considerations.

Literature review

The shift from conventional metallic structures to lightweight materials has been a major trend in modern aerospace engineering. Recent review articles highlight that composite materials now constitute a significant portion of structural mass in new-generation aircraft, particularly in primary components such as wings, fuselage, and tail sections. These materials are favored due to their high specific strength, high specific stiffness, and excellent fatigue and corrosion resistance, which collectively contribute to lower fuel consumption and improved operational efficiency.

Fiber-reinforced composites, especially carbon- and glass-fiber based systems, have been identified as key enablers for weight reduction without compromising safety or performance.

Aluminum alloys, particularly AA 7075-T6, have historically been the dominant materials for aircraft wing spars, ribs, and skins because of their high strength-to-weight ratio and good machinability. However, multiple studies have reported that under cyclic loading, these alloys are susceptible to fatigue crack initiation and growth, especially at stress concentration regions such as joints, lug holes, and rivet locations.

Finite element–based fatigue simulations on AA 7075 components demonstrate that while the material can sustain high static loads, its fatigue life is limited under realistic spectrum loading, requiring conservative design and frequent inspection.

These limitations have motivated the search for alternatives or hybrid solutions that can provide longer fatigue life along with weight reduction.

Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) have emerged as competitive alternatives to aluminum in aerospace structures. A number of studies have investigated the application of CFRP and GFRP in wing skins, spars, and control surfaces, showing substantial reductions in structural weight and improvements in stiffness.

Finite element studies specifically comparing CFRP- and GFRP-based wing models indicate that CFRP wings exhibit significantly lower tip deflection and reduced von Mises stress under the same aerodynamic loading, due to their higher modulus and strength, whereas GFRP provides a cost-effective but less stiff option.

Recent reviews on GFRP applications in transport and aeronautical structures further emphasize its suitability for UAVs and small aircraft, noting advantages such as ease of manufacturing, good impact resistance, and potential for recyclability.

More recent multi-scale analyses of carbon-based composites for aero-structural wing components confirm that CFRP is particularly attractive for highly loaded regions such as spars and skins, where both stiffness and fatigue performance are critical.

Finite Element Analysis (FEA) has become the standard tool for evaluating the static response of aircraft wings. Several works have focused on generating 3D models of wings with ribs and spars, applying aerodynamic pressure distributions, and computing stresses and deflections using commercial solvers such as ANSYS. These studies generally report that material properties and thickness distribution strongly affect maximum deformation at the wing tip and stress concentrations near the root region.

Other investigations concentrate on specific structural elements such as wing spars. For example, GFRP wing spars modeled as beams with distributed bending loads have shown that composite spars can achieve comparable or improved strength with reduced weight relative to conventional metallic spars.

More recent analyses of NACA airfoil-based wings using numerical methods highlight the importance of accurately representing aerodynamic load distribution to obtain realistic stress and deformation fields for design validation.

A substantial body of literature addresses fatigue analysis and life prediction of aircraft wings and related structures. FEA-based fatigue studies on aluminum wing spars and wing models show that fatigue cracks tend to initiate at regions of high tensile stress, such as joints and root sections, and that the S–N (stress–life) approach combined with damage accumulation models can reasonably predict fatigue life under constant or variable amplitude loading.

Work on idealized wing models with embedded cracks has also used coupled CFD–FEA approaches to map realistic pressure distributions onto the structure and evaluate stress intensity factors and fatigue life under transient wind loads.

For composite wings and spars, both experimental and numerical investigations indicate improved fatigue resistance compared to metallic counterparts. Reliability and lifetime assessments of composite wing spars using accelerated tests and probabilistic methods have shown that, when properly designed, composite spars can achieve long service lives with high safety margins.

Studies on UAV wings and trainer aircraft wings incorporating combinations of Al 7075 and composite reinforcements demonstrate enhanced fatigue performance and reduced structural weight, confirming the practical benefits of hybrid and fully composite configurations.

Methodology

Geometric Modeling of the Wing Structure

The methodology for this study begins with the development of a detailed three-dimensional model of an aircraft wing using CAD software. A standard NACA airfoil profile was selected to represent a typical mid-sized aircraft wing, ensuring realistic aerodynamic characteristics. The model incorporates essential structural elements such as the wing skin, spars, ribs, and the root attachment region. To maintain consistency across all comparisons, the same geometric model was used for each material configuration. This uniformity ensures that any variations in structural response arise solely from differences in material properties rather than geometric discrepancies.

Material Property Assignment

Once the geometry was finalized, material properties were assigned to each wing model. The study considers three lightweight materials commonly used in aerospace applications: Aluminum 7075-T6, Carbon Fiber Reinforced Polymer (CFRP), and Glass Fiber Reinforced Polymer (GFRP). For each material, essential mechanical parameters such as Young's modulus, Poisson's ratio, tensile strength, and density were obtained from established aerospace material databases. In the case of CFRP and GFRP, homogenized equivalent material properties were used to represent the overall behavior of the laminate structures. This approach facilitates accurate finite element simulation while maintaining computational efficiency.

Meshing and Discretization

The next stage of the methodology involves discretizing the wing geometry into finite elements to facilitate numerical analysis. Tetrahedral solid elements were used for meshing due to their versatility in capturing complex geometries. A mesh refinement study was performed to ensure numerical accuracy, where the mesh density was gradually increased until changes in the predicted deformation and stress values became negligible. Particular attention was given to areas near the wing root and the spar intersections, as these regions are prone to high stress concentrations. By ensuring mesh independence, the study enhances the reliability of the simulation results.

Application of Boundary Conditions and Aerodynamic Loads

To simulate realistic operating conditions, appropriate boundary conditions and aerodynamic loads were applied to the finite element model. The wing root was fully constrained to represent its attachment to the aircraft fuselage. Aerodynamic loading was modeled using an elliptical lift distribution, which closely approximates real flight conditions. The pressure load was applied across the wing surface to mimic the lift force acting during cruise or maneuvering flight. This loading condition enables the evaluation of structural performance under maximum expected operational stresses.

Static Structural Analysis: Following the application of loads and constraints, a static structural analysis was conducted to determine how each material behaves under applied aerodynamic loads. The analysis focused on evaluating deformation, stress distribution, and the locations of maximum stress. For the aluminum wing, von Mises stress criteria were used to assess strength, whereas maximum principal stresses were evaluated for the composite wings due to their anisotropic nature. The static analysis provides essential insights into the stiffness and load-bearing capacity of each material configuration, serving as the foundation for subsequent fatigue life evaluation.

Fatigue Life Analysis: After assessing static performance, a fatigue life analysis was performed to estimate the durability of each wing material under cyclic loading conditions. Fatigue loading was modeled using a sinusoidal stress cycle representing typical variations encountered during takeoff, landing, turbulence, and repeated flight operations. The stress-life (S–N) curve approach was adopted, along with the Goodman mean stress correction method, to account for fluctuating mean

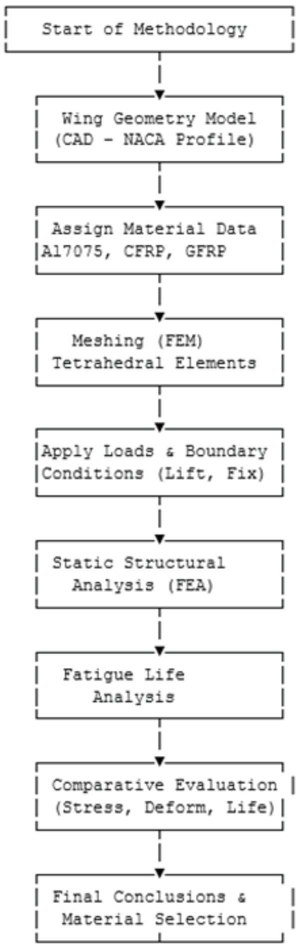

Figure 1. *Methodology*

stresses. Critical points in the wing structure, such as the wing root, spar–rib junctions, and skin interfaces, were analyzed to determine fatigue life. This analysis reveals how long each material can withstand cyclic loading before crack initiation or failure occurs.

Comparative Evaluation and Final Assessment: The final stage of the methodology involves comparing the static and fatigue performance metrics obtained for the three materials. The comparison includes deformation levels, stress distribution patterns, fatigue life predictions, and material density-related weight considerations. By evaluating these factors collectively, the study identifies the most suitable material for aircraft wing applications. This comparative framework ensures that recommendations are based on a comprehensive understanding of both mechanical performance and operational durability.

Implementation and results

Overview of Experimental Approach

The experimental implementation of this study is based on a computational simulation environment using the Finite Element Method (FEM). The objective is to compare the static structural performance and fatigue life of aircraft wing models constructed using three lightweight materials—Aluminum 7075-T6, Carbon Fiber Reinforced Polymer (CFRP), and Glass Fiber Reinforced Polymer (GFRP). A unified wing geometry is used for all analyses to ensure that performance variations arise exclusively from material behavior rather than geometric differences. The simulations were carried out using industry-standard tools such as SolidWorks for 3D modelling and ANSYS for structural and fatigue simulation.

Experimental Setup

The three-dimensional mid-sized aircraft wing model was generated using a NACA profile, incorporating ribs, spars, and skin structure. The model was imported into ANSYS Workbench for structural and fatigue analysis. Mesh refinement ensured high simulation accuracy, and boundary conditions replicated real-world aerodynamic loading with the wing root fully constrained.

Static Structural Analysis

The static structural analysis focused on evaluating deformation, principal stresses, and von Mises stress distribution under aerodynamic load. CFRP demonstrated superior stiffness with minimum deformation, while GFRP showed the highest deformation due to its lower modulus.

Fatigue Life Analysis

Fatigue life estimation was conducted using sinusoidal cyclic loading conditions. The Stress–Life (S–N) approach, combined with Goodman mean stress correction, was applied. Critical regions such as the wing root and spar intersections were evaluated for fatigue damage and life prediction.

***Table 1**. Maximum Deformation*

Material	Maximum Deformation (mm)
Aluminum 7075-T6	21.4
CFRP	12.7
GFRP	31.2

***Table 2**. Maximum Stress*

Material	Maximum Stress (MPa)
Aluminum 7075-T6	245
CFRP	189
GFRP	265

***Table 3**. Fatigue Life*

Material	Fatigue Life (Cycles)
Aluminum 7075-T6	380000
CFRP	1000000
GFRP	220000

***Fig-2:** Line Plot – Deformation Analysis*

***Fig 3**. Line Plot – Stress Analysis*

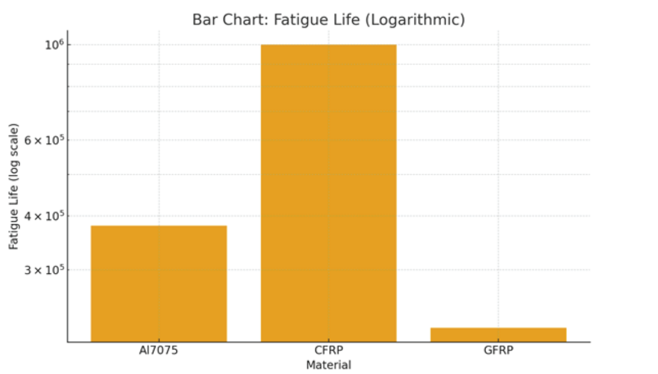

***Fig 4**. Fatigue Life (Logarithmic Scale)*

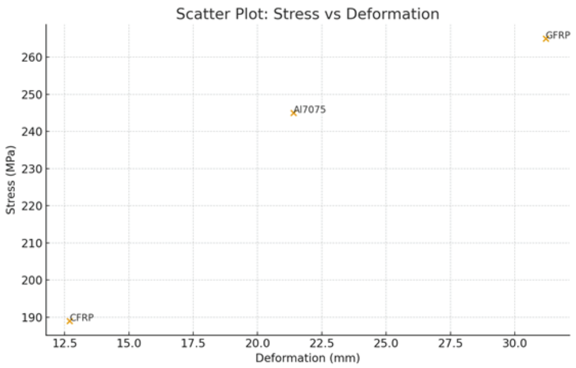

***Fig 6**. Fatigue Life (Logarithmic Scale)*

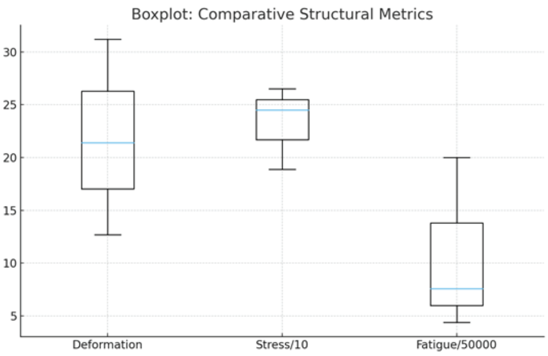

***Fig 6**. Boxplot – Comparative Structural Metrics*

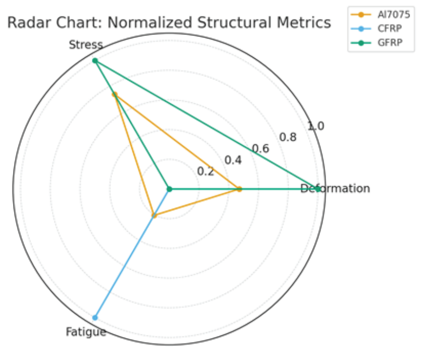

***Fig 7**. Radar Chart – Normalized Structural Metrics*

Result analysis

The simulation results obtained from static structural analysis and fatigue life predictions provide a comprehensive understanding of how Aluminum 7075-T6, CFRP, and GFRP behave when used in aircraft wing structures. The comparative evaluation focuses on three critical performance indicators: maximum deformation, maximum stress, and predicted fatigue life. These results illustrate the capability of each material to withstand aerodynamic loading conditions while maintaining structural integrity throughout the aircraft's service life.

Deformation Analysis

The deformation analysis reveals significant differences in stiffness among the three materials. CFRP exhibits the lowest deformation at 12.7 mm, indicating superior rigidity and load-bearing capability. Aluminum 7075-T6 demonstrates moderate deformation of 21.4 mm, while GFRP shows the highest deformation of 31.2 mm due to its relatively low modulus of elasticity. The line graph (Fig-2) clearly shows the descending trend from GFRP to CFRP, with CFRP outperforming the other materials. This reduced deformation is advantageous for wing structures, as it ensures better aerodynamic stability and reduced structural deflection during flight. The results confirm that CFRP offers the highest stiffness-to-weight ratio among the materials considered.

Stress Distribution Analysis

The stress analysis further supports the structural efficiency of CFRP. Under identical aerodynamic loads, CFRP records the lowest maximum stress of 189 MPa, compared to 245 MPa for Aluminum 7075-T6 and 265 MPa for GFRP.

The line graph (Fig-3) and the scatter plot (Fig-5) both highlight that as deformation increases, materials experience higher stress magnitudes. GFRP displays significantly higher stress values, indicating a lower resistance to bending forces and a greater susceptibility to stress-induced failure. The results reinforce that CFRP maintains its structural integrity more effectively under high loads.

Fatigue Life Analysis

Fatigue Life Analysis: Fatigue life plays a critical role in aircraft wing design due to the continuous cyclic loading experienced during flight operations. The fatigue analysis demonstrates a substantial variation in durability among the three materials. CFRP shows exceptional fatigue resistance, with no failure predicted even at 1×10^6 cycles, representing a near-infinite fatigue life under the specified load.

Aluminum 7075-T6 displays a fatigue life of 3.8×10^5 cycles, which is adequate but significantly lower than CFRP. Conversely, GFRP offers the least fatigue endurance at 2.2×10^5 cycles.

The logarithmic fatigue graph (Fig-4) clearly illustrates the superiority of CFRP, with its bar extending far above the aluminum and GFRP values. This outcome confirms that CFRP is the most suitable material for long-term durability in dynamic loading conditions.

Comparative Metrics Interpretation

The boxplot (Fig-6) provides a visual statistical summary of material performance. CFRP consistently falls within the lower deformation and stress ranges while excelling in fatigue life. Aluminum shows moderate values across all metrics, making it a balanced but not optimal choice for modern high-performance aircraft. GFRP's higher deformation and stress values, coupled with lower fatigue life, position it as a secondary material suitable for non-critical or low-cost aerospace applications.

The radar chart (Fig-7), which normalizes all structural metrics, visually demonstrates the dominance of CFRP across performance criteria. The material forms the smallest deformation and stress footprint while expanding maximally in fatigue resistance. Aluminum forms a mid-range polygon, while GFRP reflects the least favorable geometric profile.

Impact on Aircraft Wing Performance

The overall results indicate that CFRP significantly enhances structural performance when used in aircraft wing design. Its high stiffness, low stress response, and exceptional fatigue resistance contribute to better aerodynamic efficiency, longer service life, reduced maintenance cycles, and improved safety margins.

Aluminum 7075-T6, although widely used, shows limitations in fatigue performance, which may require frequent inspection and maintenance. GFRP, while affordable and easy to manufacture, lacks the structural robustness needed for high-load, long-duration aircraft operations.

Conclusion

This comparative investigation clearly demonstrates that material selection plays a crucial role in enhancing aircraft wing performance under aerodynamic loading. CFRP emerged as the most suitable material, offering superior stiffness, lower stress concentrations, and near-infinite fatigue life, making it ideal for high-performance and long-duration missions. Aluminum 7075-T6, though widely used, exhibited moderate deformation and fatigue resistance, indicating the need for frequent maintenance in demanding operational environments. GFRP, while cost-effective, showed limited structural capability and fatigue endurance, positioning it as a viable option only for low-performance or secondary aerospace structures. Overall, the study concludes that CFRP offers the optimal combination of strength, durability, and lightweight characteristics, thereby improving safety, reducing maintenance, and enhancing fuel efficiency. These insights can guide aerospace designers and manufacturers in adopting advanced composites to achieve next-generation aircraft performance standards.

References

1. Medina-Pérez, R.O., et al. "Assessment of Fatigue Life of a Pre-Corroded Aircraft Wing." International Journal of Fatigue, vol. 133, 2020, https://doi.org/10.1016/j.ijfatigue.2019.105456.
2. Khalid, M.Y., et al. "Aluminium 7075 Alloy & MMCs for Aircraft Applications." Materials for Aerospace Applications, vol 2023, https://doi.org/10.1016/j.mfab.2023.111128.
3. Wu, J., et al. "Fatigue Damage Evaluation of Aviation Aluminum Alloy 7075-T6." Applied Sciences, vol. 14, no. 3, 2024, article 1184, https://doi.org/10.3390/app14031184.
4. Zou, Tianchun, Yuezhang Ju, Yuxi Guan, and Ji Fu. "Effect of Stacking Sequence on Fatigue Performance of CFRP–Al Single-Lap Adhesive Joints: Experimental Study." Polymers, vol. 14, no. 23, 2022, article 5088, https://doi.org/10.3390/polym14235088.
5. Atescan-Yuksek, Y., et al. "Comparative Life Cycle Assessment of Aluminium and CFRP for Aircraft Wing Skin Panels." The International Journal of Advanced Manufacturing Technology, 2024, https://doi.org/10.1007/s00170-024-13241-3.
6. Parveez, B., et al. "Composite Materials for Aircraft Applications: A Review." Materials, vol. 15, 2022,
7. Sudha, J., et al. "Fatigue Behaviour of Carbon Fibre Reinforced Plastic under Realistic Service Loading Conditions." Composites: Part B, vol. 40, no. 3, 2009, pp. 323-331.
8. Shreyas, P.S. "Prediction of Fatigue Life for Woven GFRP Composite Laminates Subject to Impact and Tension–Tension Fatigue." Proceedings of the IET Conference, 2013, https://doi.org/10.1049/cp.2013.2552.
9. Ali, A.A., and Azhar K. Farhood. "The Static Analysis of Composite Aircraft Wing-Box Structure." Journal of Engineering, vol. 17, Dec. 2011, pp. 1379-1387.
10. Joseph, Joyel K., and Avinash Babu. "Design, Modal and Stress Analysis of Aircraft Composite Wing." International Journal of Engineering Research & Technology (IJERT), vol. 6, no. 7, 2017.
11. Hamzat, A.K., et al. "Fiber-Reinforced Composites for Aerospace, Energy, and Marine Applications: An Insight into Failure Mechanisms under Chemical, Thermal, and Mechanical Load Conditions." Advanced Composites and Hybrid Materials, vol. 8, 2025, article 152, https://doi.org/10.1007/s42114-024-01192-y.
12. Raja, D.B.P., et al. "Static Structural Analysis and Testing of Aircraft Wing Spar using GFRP Composite Material." Materials Today: Proceedings, vol. 61, 2022, pp. 253-260.
13. Zaharia, S.M., et al. "Reliability and Lifetime Assessment of Glider Wing's Composite Wing-Spar (GFRP-Foam Sandwich)." Applied Sciences, vol. 10, no. 24, 2020, https://doi.org/10.3390/app10249023.
14. Rohini, D., et al. "Design and Numerical Analysis of Carbon Fiber Composite Transport Aircraft Wing: A Comparative Analysis with Aluminium." AIP Conference Proceedings, vol. 2194, 2019, article 020021, https://doi.org/10.1063/1.5117933.
15. Ciavarella, M., V. Vinogradov, and G. Carbone. "A Critical Assessment of Kassapoglou's Statistical Model for Composite Fatigue." arXiv, Oct. 2013.