

Design and Analysis on Aerodynamics, Structural Integrity, and Vibrational Behavior of Boeing 747 Wing Structure Using CATIA and ANSYS

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Abstract

This research details the comprehensive design and multi-disciplinary analysis of a Boeing-like aircraft wing, constructed with realistic geometry using CATIA to replicate commercial standards and tapering effects. Aerodynamic characteristics were assessed via CFD simulations to evaluate lift, drag, and stall thresholds across varying angles of attack, establishing optimal operating conditions. Finite Element Analysis (FEA) in ANSYS compared structural performance of Carbon, Aluminum, Glass E, Glass S, and Kevlar under identical constraints, focusing on deformation, stress, and strain metrics. Kevlar and Carbon fiber demonstrated superior stiffness and lightweight properties. Modal analysis revealed higher natural frequencies, especially in Kevlar, resulting in improved resonance resistance and dynamic stability. The integration of CATIA and ANSYS provided a robust framework for optimizing the Boeing 747 wing's aerodynamic efficiency, structural fidelity, and vibration control.

Keywords: Aircraft wing, CATIA, ANSYS, Aerodynamics, Vibration analysis

Introduction

Aircraft wings are essential structural elements designed to produce lift, allowing heavier-than-air vehicles to fly by utilizing carefully crafted air foil cross-sections that create favourable pressure differentials as air moves over their surfaces. Projecting outward from the fuselage, wings not only provide the main lifting force but also play crucial roles in stabilizing, controlling, and manoeuvring the aircraft throughout flight.

Modern wings frequently integrate systems such as fuel tanks, landing gear, and movable control surfaces—including flaps and ailerons—to enhance operational capability and safety. Robust enough to withstand substantial aerodynamic and structural stresses from take-off through landing, contemporary wing designs may feature additions like winglets, which reduce vortex drag and boost fuel economy.

Design parameters such as sweep angle, aspect ratio, and thickness-to-chord ratio are individually optimized for performance, with wings constructed in diverse configurations—straight, swept, or delta shapes—depending on the aircraft's intended speed and mission profile. Every aspect of wing geometry is specifically engineered to balance optimal aerodynamic efficiency with structural strength, making the wings the principal surfaces governing the aircraft's overall performance envelope.

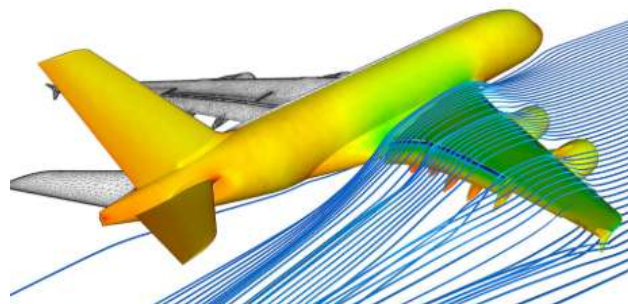


Fig 1: Aerodynamics on wing.

Aircraft wing design has evolved dramatically, driven by advances in materials, aerodynamics, and engineering. Early wings were made from wood and fabric, with simple rectangular shapes suited to low-

speed flight. As speed demands grew, tapered and elliptical planforms were introduced to minimize drag and boost efficiency. The transition to metal construction enhanced strength, durability, and precision in manufacturing.

The jet era brought the widespread use of swept and delta wings, which help delay compressibility effects at high speeds. Long-distance aircraft benefited from high-aspect-ratio wings, improving fuel efficiency and range. Cutting-edge innovations include variable-sweep wings, blended wing bodies, and morphing technologies for adaptive control. Winglets, slats, and advanced flaps have further reduced drag and improved low-speed handling.

Civilian, military, and UAV designs each feature wings tailored to their operational roles, reflecting constant efforts to balance efficiency, safety, and performance in aviation's ongoing progress.

The Boeing 747 Wing

The Boeing 747, often called the "Queen of the Skies," is renowned for its advanced wing design, featuring a span exceeding 68 meters, a high aspect ratio, and moderate sweep to balance efficient cruise performance with effective take-off and landing capabilities. Its wing incorporates sophisticated high-lift devices, such as leading-edge slats and multi-slotted flaps, which optimize lift at low speeds, while variants utilize winglets or raked wingtips to reduce vortex drag and enhance fuel efficiency. The internal wing structure employs high-strength aluminum alloys and composites to improve durability, reduce weight, and extend fatigue life, with reinforced spars, ribs, and stringers engineered to withstand substantial aerodynamic loads and provide space for fuel storage.

During flight, the 747's wingtips are engineered to flex upward, displaying the wing's vital structural flexibility for load absorption. This iconic design harmoniously combines aerodynamics, strength, and operational

capability, enabling the aircraft's legendary long-haul performance.

The goal of this project is to systematically analyze the aerodynamic properties, structural resilience, deformation behavior, stress distribution, strain response, and vibration characteristics of aircraft wings. Special emphasis is placed on evaluating and contrasting materials—including Carbon fiber, Aluminum, E-glass, S-glass, and Kevlar—to advance efficiency and reliability in aerospace engineering. Key objectives encompass assessing aerodynamic performance through lift, drag, and pressure distribution for various materials; conducting structural analyses to track stress, strain, and deformation under loading; performing vibration analyses to pinpoint natural frequencies and mode shapes for dynamic stability; and ultimately, selecting optimal materials based on criteria like strength-to-weight ratio and durability, thereby enhancing overall wing design and performance.

Literature review

Numerous studies have addressed the multidisciplinary challenges associated with the aerodynamic, structural, and vibrational performance of aircraft wings. Agrawal et al. (2021) [1] performed an in-depth modal analysis of rectangular-section aircraft wings using finite element modeling, focusing on how structural deformation affects vibration behavior under realistic loading conditions. Their results, which link aerodynamic pressures with structural deformation, provide a fundamental basis for predicting fatigue life and enhancing vibration resistance. Banerjee et al. [2] further advanced this by incorporating CFD-derived aerodynamic data into prestressed modal analyses, revealing a strong correlation between deformation, stress, and natural frequencies, which emphasizes the crucial role of aeroelastic coupling in wing design. Dessena et al. (2022) [3] complemented these findings by conducting ground vibration tests on flexible, high-

aspect-ratio wings, supplying experimental data that validate numerical vibration models. Together, these studies underscore the importance of integrating simulation and experimental data for precise modeling of wing dynamics. Further progress includes the work by Han Jinglong & Cui Peng (2011) [4] who applied fully coupled CFD-CSD methods to simulate transonic flutter behaviors across various Mach numbers. Li, Jaiman & Khoo (2020) [5] and Li & Jaiman (2022) [6] introduced innovative fluid-structure interaction models that incorporate vortex shedding and dynamic deformation to demonstrate the effects of unsteady aerodynamic loading on vibration and drag. Chai et al. (2021) [7] investigated aeroelastic stability and suggested control methods to shift natural frequencies, thereby improving dynamic safety margins. Patil (2004) [8] and Perera & Guo (2009) [9] explored the impact of nonlinear geometric deformation and material tailoring on wing vibration and stress, while Afonso et al. (2017) [10] provided a comprehensive review of nonlinear aeroelastic effects in large-span wings, advocating integrated aerodynamic-structural modeling. Collectively, these contributions offer essential insights into vibration prediction, material selection, and structural optimization in advanced aircraft wing design.

Methodology

The methodology of this study is structured into three main phases, starting with the aerodynamic analysis of the aircraft wing using Computational Fluid Dynamics (CFD). A detailed 3D wing model is created in CATIA and then imported into ANSYS Fluent, where a high-resolution mesh—especially refined near the leading and trailing edges—is generated to precisely capture flow characteristics. Realistic flight conditions are simulated by applying boundary conditions such as velocity inlet, pressure outlet, and no-slip walls. Simulations are run over various angles of attack to assess lift and drag behaviour, with pressure contours, streamline visualizations, and velocity profiles used to identify flow

separation regions and stall angles. Lift (C_l) and drag (C_d) coefficients are extracted and validated through comparison with standard NACA data.

The second phase involves structural analysis via Finite Element Analysis (FEA) in ANSYS Mechanical, where aerodynamic loads obtained from CFD are mapped onto the wing model, meshed with high-quality tetrahedral and hexahedral elements. Various materials—Carbon Fiber, Aluminium, Glass E, Glass S, and Kevlar—are evaluated under identical wing-root constraints. Stress, strain, and deformation are assessed using Von Mises stress criteria to identify potential failure points and fatigue-prone areas.

The final phase comprises vibration analysis using modal and harmonic response simulations. Modal analysis determines natural frequencies and mode shapes, while harmonic analysis applies sinusoidal loads that mimic flight-induced vibrations. The amplitude responses are examined to evaluate resonance risk, and stress-strain results are compared with static analyses to ensure structural safety under dynamic loading conditions.

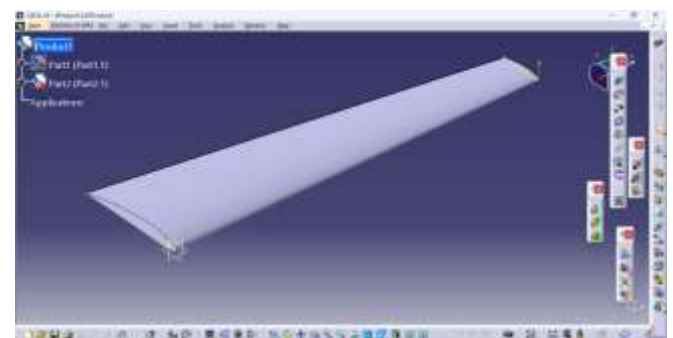


Fig 2: 3D model of wing..

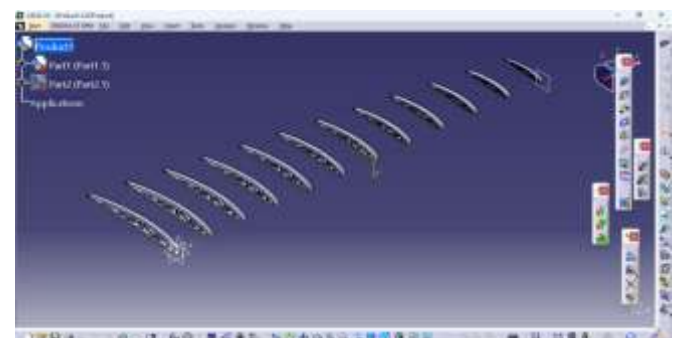


Fig 3: truss alignment in wing.

The 3D wing model designed for the Boeing 747 accurately represents the structural and aerodynamic features typical of large commercial airliners. It spans 75 meters in total wingspan, capturing the vast scale and complexity of the real wing. The chord length starts at 20 meters at the root and tapers down to 4.5 meters at the tip, creating a tapered planform essential for reducing induced drag and optimizing lift distribution across the span. This tapered shape also enhances roll control while minimizing structural weight. Key aerodynamic and structural features such as leading-edge sweep, wing twist (washout), and internal components like spars, ribs, and fuel tanks are integrated into the CAD design to improve efficiency and strength. The wing geometry is developed by defining air foil cross-sections along the span and lofting them to form a smooth aerodynamic surface. Control surfaces including ailerons, flaps, spoilers, and slats are incorporated to support flight control and lift augmentation. Utilizing CATIA software, known for its precision in aerospace design, allows for detailed parametric modelling, facilitating easy adjustments and compatibility with simulation tools. The model is engineered to bear high loads near the root and to reflect the varying pressure and velocity distributions from root to tip. This comprehensive modelling approach sets the stage for subsequent CFD aerodynamic simulations, structural finite element analyses, and vibration studies, ensuring the wing meets the demanding performance, safety, and efficiency requirements of the Boeing 747 long-haul aircraft.

CFD simulation

The Computational Fluid Dynamics (CFD) analysis commenced with preparing the wing geometry in CATIA, followed by exporting the model in IGES format to ensure compatibility with ANSYS software. The geometry was then imported into ANSYS 2022 WORKBENCH, where the Fluid Flow (FLUENT)

solver was selected for simulation. To achieve accurate aerodynamic results, a structured mesh was created around the air foil region, utilizing edge meshing and applying a bias factor to refine the boundary layer area. The solid body was suppressed during meshing, resulting in a grid comprising roughly 359,721 nodes and 352,000 elements. Key boundary conditions, including inlet, outlet, air foil wall, ground, and free surface, were defined to replicate realistic flight scenarios. A 3D pressure-based solver was employed, ignoring gravity as the focus was on pressure-induced aerodynamic forces. The k-epsilon ($k-\epsilon$) turbulence model was chosen for its reliability in external flow simulations. Airflow was set at a constant velocity of 138.8 m/s at the inlet, while the outlet was maintained at 0 Pa to simulate the pressure difference across the air foil.

After setting up the solver, reference conditions were established to calculate aerodynamic coefficients of lift and drag. The simulation ran under steady-state conditions for up to 500 iterations, with convergence criteria set to 10^{-5} for pressure, momentum, and velocity to ensure precise outcomes. Upon convergence, post-processing visualized the flow characteristics, revealing higher velocity on the upper air foil surface consistent with the Bernoulli principle and turbulence trailing the air foil. Pressure distribution showed a peak at the front stagnation point and a sharp drop along the upper surface, generating substantial lift. These simulation insights validated the aerodynamic performance of the wing and provided realistic pressure loads and force data essential for subsequent structural and vibration analyses.

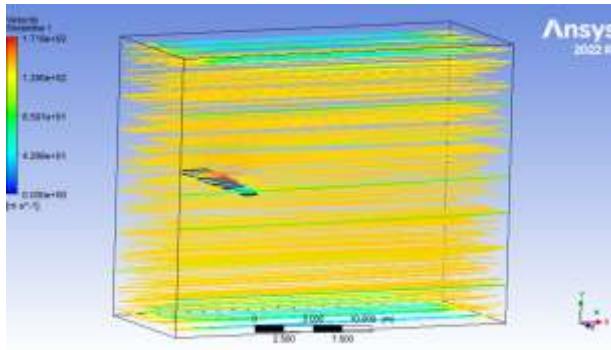


Fig 4: velocity distribution around wing

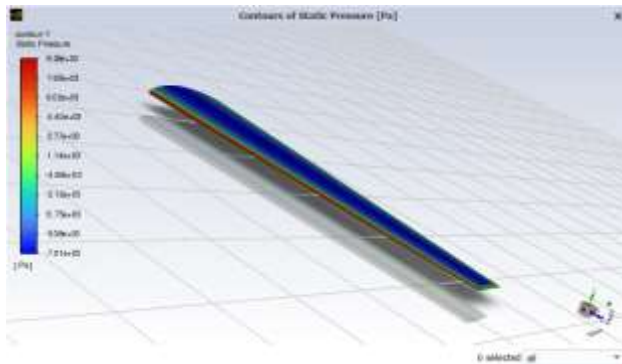


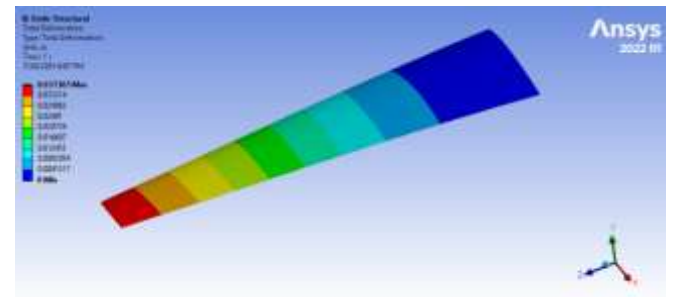
Fig 5: pressure distribution around wing.

Structural analysis

In structural analysis, applying loading conditions precisely is vital for acquiring realistic simulation outcomes. ANSYS Workbench provides multiple load application methods, including point loads, pressure loads, hydrostatic loads, joint loads, and bolt penetration loads, which can be assigned to model edges, faces, or entire bodies depending on the geometry and load case. For aircraft wing analysis, accurately applying directional aerodynamic pressure loads is crucial to replicate real flight behaviour. Boundary conditions were set by fixing the wing root to simulate its attachment to the fuselage, while aerodynamic pressures from CFD outputs were mapped onto the wing's external surfaces. The solver was then activated to compute the structural response.

Post-processing within ANSYS is integral for result interpretation, allowing visualization of total and directional deformation, stress, and strain distributions. These outputs can be graphically displayed and exported for documentation. The wing geometry was developed in CATIA, exported in IGES format, and analysed on a

64-bit system with 4GB RAM using ANSYS 2022, suitable for both static structural and modal analyses. The mesh consisted of tetrahedral elements totalling 20,276 elements and 5,261 nodes. Materials including Carbon Fiber, Aluminium, Glass E, Glass S, and Kevlar, each defined by distinct mechanical properties like Young's modulus, Poisson's ratio, and density, were tested to understand deformation responses under load. Simulation results regarding deformation and stress offered valuable insights into material performance, facilitating optimal wing design focused on strength, stability, and weight efficiency.



The image illustrates the total deformation of the wing after applying a dynamic pressure load to its surface, where red indicates regions of maximum deformation and blue represents areas with minimum deformation. The greatest deformation occurs at the wingtip due to the lack of support, making it prone to bending. Conversely, the minimum deformation is observed at the hub area, as clearly visible in the image. Overall, the maximum deformation reaches 0.037 meters, which is a significant amount of deformation to consider.

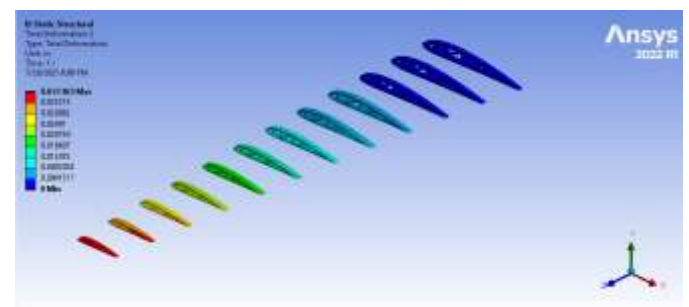


Fig 7: Deformation on the truss structure with Kevlar material.

The image above depicts the total deformation of the wing after a dynamic pressure load was applied. The red areas indicate the regions of maximum deformation, while blue shows the minimum deformation zones. The greatest deformation occurs at the wingtip because it lacks support, making it highly susceptible to bending. The smallest deformation is observed at the hub of the propeller, as clearly visible in the image. Overall, the maximum deformation reaches 0.037 meters, which is a significant amount of deformation to consider for structural integrity.

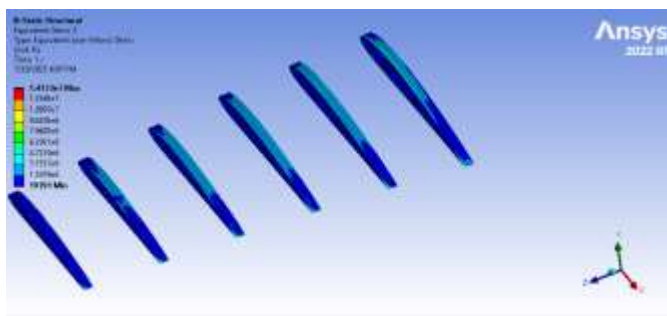


Fig 8: stress on truss with Kevlar material..

The figure above illustrates stress distribution on the truss when subjected to dynamic pressure loading. In the image, blue represents areas of minimum stress, while red indicates regions of maximum stress. Most of the truss experiences low stress levels, with higher stresses concentrated at the connection points between the truss and the wing. Although the entire structure remains safely within design limits, the highest stresses are primarily found at sharp corners of the truss where stress concentrations occur.

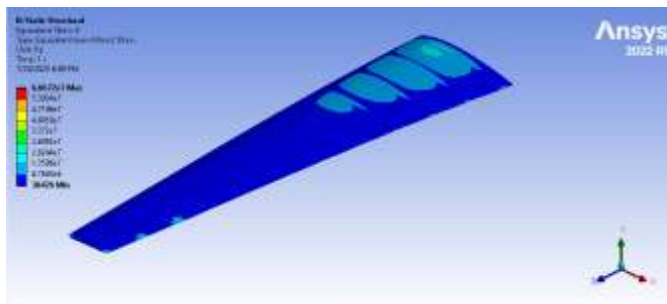


Fig 9: stresses Shell with Kevlar material.

The figure above illustrates the stress distribution on the wing under dynamic pressure loading, where blue represents areas of minimum stress and red indicates

regions of maximum stress. Overall, the wing experiences mostly low stress levels, with higher stresses concentrated at the connection between the truss and the wing. The entire structure remains within safe design limits, although the greatest stresses are primarily located at the wing root.

Vibration analysis

Vibration analysis plays a vital role in aircraft wing design by ensuring structural integrity, safety, and optimal performance under dynamic flight conditions. Wings are subjected to various vibration sources, including gusts, engine vibrations, and aerodynamic instabilities, which can cause resonance, fatigue, or failure if not properly accounted for during design. Modal analysis performed in ANSYS software reveals the natural frequencies and corresponding mode shapes of the wing, providing insight into its responses to vibration modes such as bending and torsion. By fixing the wing at the fuselage end and leaving the opposite end free, realistic boundary conditions simulate in-flight behavior accurately. Material properties, such as stiffness and density, significantly affect vibrational characteristics; for example, lightweight Kevlar results in lower natural frequencies, whereas stiffer materials like Glass S increase frequencies, thereby improving dynamic stability. Consistent meshing and material modeling in structural and modal analyses help identify critical vibration modes, enabling design modifications that prevent resonance and ensure aeroelastic stability.

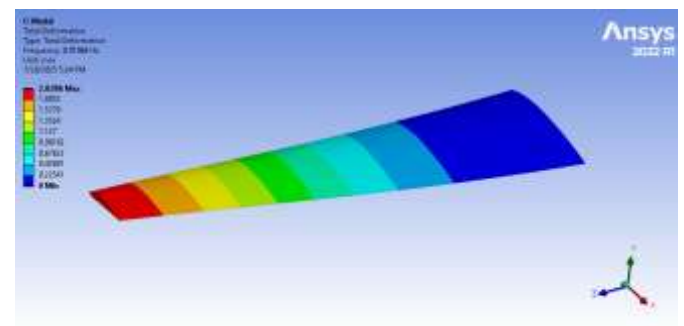
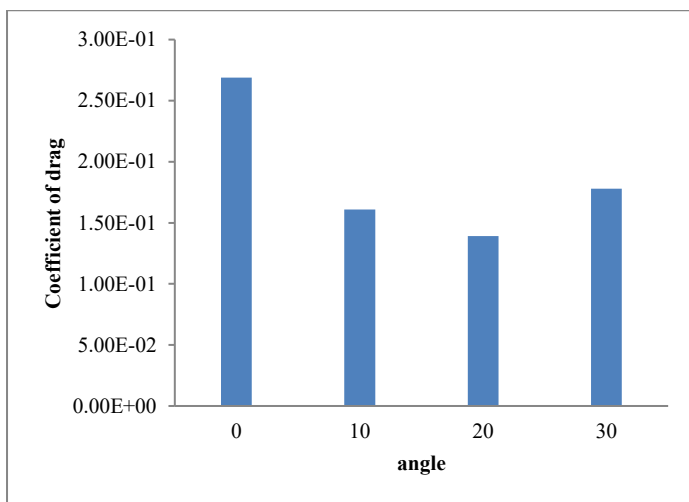


Fig 10:1st mode shape of flight wing with Kevlar material.

Results and discussion

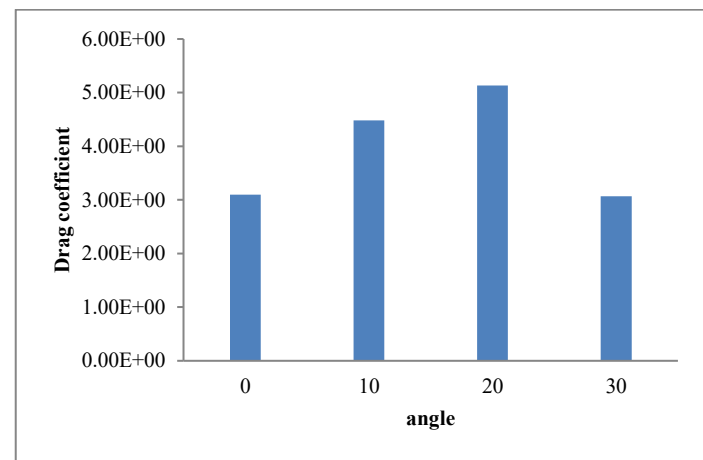
The results and discussion chapter starts with evaluating the aerodynamic performance of the 3D wing model at different angles of attack, showing how lift and drag coefficients vary under various flight conditions. Lift increases with the angle of attack up to a critical point, after which stall causes a significant drop, while drag rises non-linearly due to boundary layer separation and vortex formation. These results are essential for determining the optimal operating angle and maximizing the lift-to-drag ratio, thereby enhancing aerodynamic efficiency. Structural analysis examines the behavior of several materials under aerodynamic loading, focusing on deformation, stress, and strain to identify the best strength-to-weight combinations. Stiffer materials like Kevlar and Glass S exhibit lower stress and deformation levels, confirming their effectiveness for aerospace use. Vibration and modal analysis identify natural frequencies and mode shapes, helping to prevent resonance during flight. Materials with higher natural frequencies offer improved resistance to vibration-induced failures, promoting stable flight. Together, these comprehensive findings guide effective design strategies for safe, efficient, and structurally robust aircraft wings.



Graph 1: drag coefficient for 3D model wing with different angle of attack.

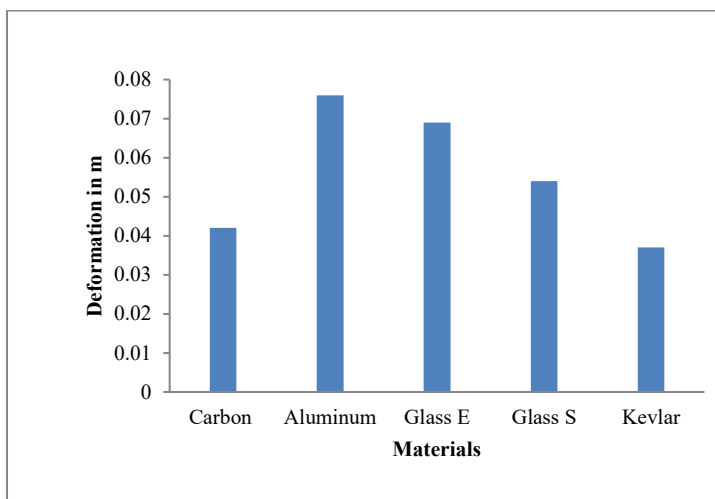
The table shows how the drag coefficient (CD) varies with angle of attack for a 3D aircraft wing, reflecting

changes in aerodynamic resistance. At 0°, CD is highest at 0.269 due to initial form and friction drag. As the angle increases to 10° and 20°, CD drops to 0.161 and 0.139, indicating improved flow attachment and aerodynamic efficiency. However, at 30°, CD rises again to 0.178, signaling flow separation and the onset of stall. This non-linear trend highlights the influence of flow behavior and pressure distribution on drag, emphasizing the need to maintain the wing within optimal angles for efficient and stable flight.



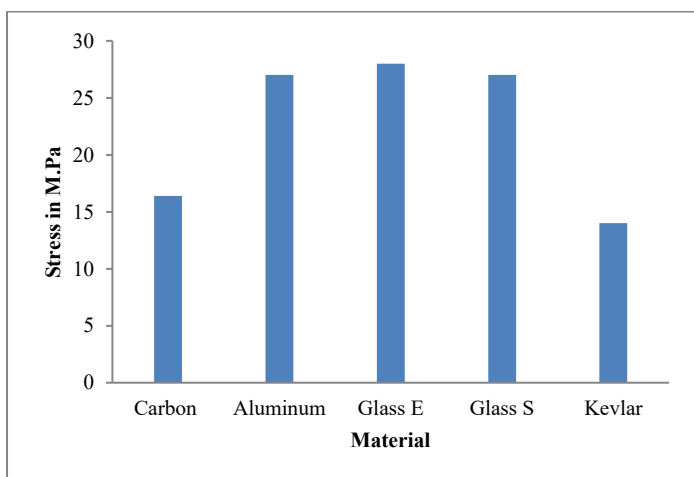
Graph 2: Lit coefficient for 3D model wing with different angle of attack.

The lift coefficient (CL) data indicates strong aerodynamic performance of the 3D wing model, with lift increasing steadily from 0° to 20° angle of attack due to enhanced pressure differences across the airfoil. The maximum lift is achieved at 20°, after which the CL drops significantly at 30°, signaling the onset of stall caused by airflow separation. This trend highlights the critical role of angle of attack in lift generation and emphasizes the need to operate within optimal limits—typically below stall—to ensure flight stability and efficiency.



Graph 3: Deformation with different materials.

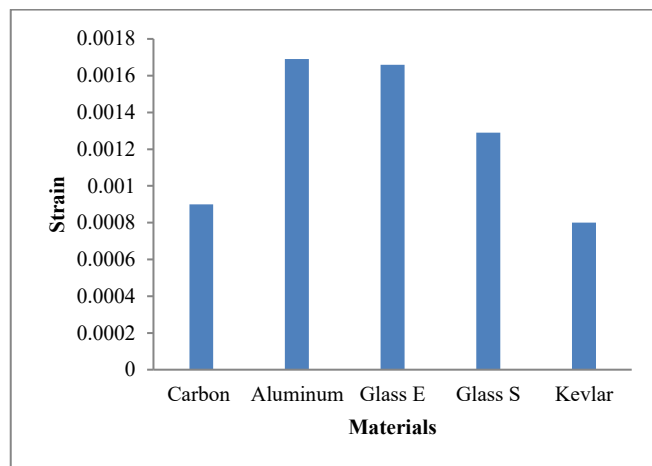
The deformation results reveal that Kevlar exhibits the least deformation (0.037 m), making it the stiffest and most effective material for maintaining wing shape under load. Carbon fiber follows with slightly higher deformation (0.042 m), still offering excellent strength and low weight. Aluminum shows the highest deformation (0.076 m), indicating lower stiffness, while Glass E (0.069 m) and Glass S (0.054 m) perform moderately. These findings confirm that Kevlar and Carbon are ideal for aerospace wing structures where minimal deflection and high structural integrity are essential.



Graph 4: Stress for different materials.

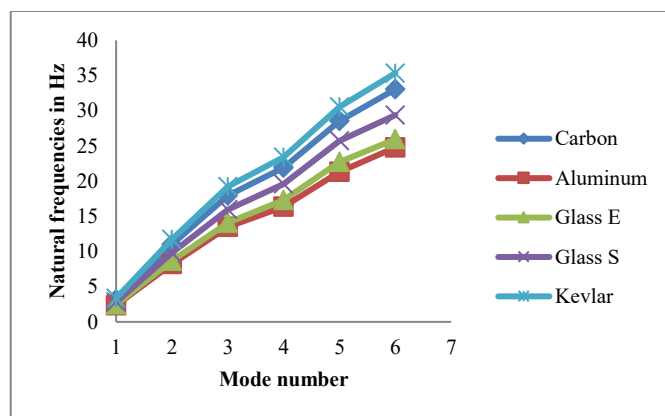
The stress analysis shows that Kevlar and Carbon fiber are the most efficient materials for aircraft wings, with lower stress values of 14 MPa and 16.4 MPa respectively, indicating better load distribution and reduced risk of failure. In contrast, Aluminum, Glass E,

and Glass S exhibit higher stresses (27–28 MPa), suggesting they endure more internal force and may be more prone to fatigue. This confirms Kevlar and Carbon as superior choices for lightweight, durable wing structures under continuous aerodynamic loading.



Graph 5: Strain with different materials.

The strain values indicate that Kevlar and Carbon fiber deform the least under applied stress, with strains of 0.0008 and 0.0009 respectively, highlighting their high stiffness and shape retention—ideal for aircraft wings. In contrast, Aluminum, Glass E, and Glass S show higher strains, indicating greater flexibility but reduced suitability for components requiring minimal deformation. This comparison confirms Kevlar and Carbon as the most effective materials for maintaining structural integrity and aerodynamic stability in aerospace applications.



Graph 6: Table: Natural frequencies.

The natural frequency data shows that Kevlar offers the highest stiffness and best vibration resistance, making it ideal for aircraft wing applications. Carbon fiber follows

closely with strong dynamic performance and a good strength-to-weight ratio. Glass S performs moderately well, while Glass E and Aluminum show lower frequencies, indicating less resistance to vibration. Overall, Kevlar and Carbon are the most suitable materials for minimizing resonance and enhancing wing stability.

Conclusion

This study successfully developed a 3D aircraft wing model in CATIA featuring realistic tapered geometry, and conducted comprehensive aerodynamic, structural, and vibration analyses using ANSYS. The aerodynamic evaluation identified an optimal angle of attack at 20°, yielding a peak lift coefficient of 5.13 and a minimum drag coefficient of 0.139. Structurally, Kevlar demonstrated superior performance with the lowest deformation (0.037 m), stress (14 MPa), and strain (0.0008), highlighting its excellent stiffness-to-weight ratio. Vibration analysis showed Kevlar to have the highest natural frequency at 3.37 Hz, indicating enhanced resistance to dynamic instability. Carbon fiber also exhibited strong performance across all tests. These findings emphasize Kevlar and Carbon fiber as prime candidates for lightweight, high-strength wing construction, while showcasing the effective integration of CATIA and ANSYS for validating aerospace aerodynamic and structural designs.

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