Design and Comparative Structural Analysis of a UAV Wing Using Composite Materials

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ABSTRACT- *This paper presents the modelling and comparative structural analysis of a fixed-wing unmanned aerial vehicle (UAV) wing using a classical NACA 4412 airfoil. A three-dimensional wing geometry is developed and analysed under equivalent aerodynamic loading using finite element analysis. The structural response of different composite materials, including CFRP–Epoxy, CFRP–PEEK, Kevlar/Epoxy, and selected GFRP systems, is evaluated in terms of von Mises stress and total deformation. The results are compared using graphical and regression-based statistical methods to identify trends in material behaviour under identical loading conditions. The objective of this research is to gain insight into the effect of material stiffness and density on the wing structure of a UAV.*

The research work is focused on the structural performance of a fixed-wing UAV designed with the NACA 4412 airfoil, and the impact of various composite materials on stress and displacement.

Keywords - UAV wing, NACA 4412, finite element analysis, composite materials, equivalent aerodynamic loading, regressionanaly

INTRODUCTION

Unmanned aerial vehicles (UAVs) are essential tools for various tasks like surveillance, remote sensing, environmental monitoring, topographical mapping, and scientific research. These tasks need airframes that offer high aerodynamic efficiency and strong structure while staying lightweight. This helps maximize endurance, payload capacity, and overall efficiency. Among the different parts of an airframe, the wing plays a key role as the lifting surface. It also faces significant aerodynamic, inertial, and maneuver loads. For this reason, designing wings that are both light and structurally efficient is crucial in UAV development. Modern UAVs often use carbon fiber reinforced polymers (CFRP), glass fiber reinforced polymers (GFRP), and aramid fiber reinforced polymers (AFRP). These materials are favored for their excellent strength-to-weight ratio, high stiffness, resistance to corrosion, and durability against fatigue. Additionally, the unique properties of composite materials allow for customized designs. Engineers can orient fibers specifically based on the loading conditions and stiffness needs, making them ideal for aerospace. Among the various airfoil shapes for fixed-wing UAVs, the NACA 4412 airfoil has been thoroughly studied and validated for low-speed flight. Its moderate camber and thickness offer effective lift, a gradual stall, and sufficient internal space for structural components like spars and ribs. Thus, understanding the structural performance of UAV wings made from different composite materials under aerodynamic loads is vital during the initial design stage. This understanding assists in selecting suitable materials and developing efficient, sustainable wing designs for UAVs.

A. Carbon Fiber Reinforced Polymer (CFRP)

Carbon Fiber Reinforced Polymer (CFRP) is widely used in designing high-performance UAV wing structures. Its excellent specific strength and stiffness are crucial for reducing the weight of the structure while maintaining its aerodynamic shape. In this research, CFRP is considered one of the main materials for the NACA 4412 wing, particularly for load-bearing parts like wing skins and spars. Carbon fibers have a high elastic modulus, which gives them strong resistance to spanwise bending and torsion from aerodynamic lift forces and maneuvering. The high stiffness of carbon fibers works well for the NACA 4412 airfoil section. This airfoil features a cambered surface that generates a higher lift coefficient at low angles of attack, which increases the bending moment along the wing span. Additionally, the low density of CFRP helps reduce the wing's weight, improving the UAV's endurance and payload capacity. The anisotropic nature of CFRP allows for the fibers to be oriented in line with the main stresses of the wing structure. However, the brittle failure mode of CFRP and its higher cost compared to other materials are factors to consider during the initial design phase. The NACA 4412 airfoil was chosen for buckling analysis because its higher camber results in a more accurate aerodynamic loading distribution and structural response for UAV wings. The NACA 4412 has realistic lift characteristics, making it suitable for structural analysis under aerodynamic loads.

B. Glass Fiber Reinforced Polymer (GFRP)

Glass Fiber Reinforced Polymer (GFRP) is commonly used in UAV wings as an economical substitute for CFRP, which has relatively good strength, longevity, and resistance to impact. In this research, GFRP is considered as a substitute material for the NACA 4412 wing design with the same geometric and loading requirements.

GFRP has lower rigidity than CFRP, which translates to higher elastic deflection when subjected to aerodynamic loading. In the case of the NACA 4412 airfoil, this can result in higher wing deflection and better resistance to damage. GFRP is more applicable to secondary structural components like ribs, control surfaces, and wing skins of low-cost UAVs.

Another advantage of GFRP is its electrical insulation characteristic, which is advantageous for UAV wings containing antennas and avionic systems.

LITERATURE OVERVIEW

Optimization of structure and material is a very significant area for the improvement of unmanned aerial vehicles (UAVs) performance and reliability, particularly considering the stringent weight constraints and loading conditions. In this context, Aswin Kumar et al. (2021) performed an in-depth analysis on the structural optimization of a multi-rotor UAV structure using computational structural analysis techniques. The authors employed finite element analysis (FEA) to examine the stress response, deformation, and factor of safety of the structure subjected to loading conditions. The authors demonstrated that topology and size optimization techniques could result in a significant weight reduction of the structure without compromising its strength and stiffness properties. The findings of the authors revealed that computational structural analysis is an effective approach for optimizing the strength-weight ratio of UAV structures, thereby increasing the payload capacity and efficiency of flight.

The application of composite materials in the design of UAV wings has been widely researched due to the superior mechanical properties of composite materials. A research paper titled “Structural Analysis of UAV Wings Designed Using Composite Materials” was published in the International Journal for Research in Applied Science & Engineering Technology (IJRASET). The research paper compared the use of composite materials with the conventional use of metallic materials in the design of UAV wings. The research paper applied finite element analysis to investigate the stress, strain, and deformation characteristics of composite materials subjected to aerodynamic loads. The results of the research paper validated that composite materials possess the ability to reduce weight by a substantial amount with high stiffness and strength. The research paper also validated that composite materials possess better fatigue life and damping coefficients than metallic materials.

A good theoretical knowledge of material properties is necessary for the effective analysis of results of structural analysis. Callister and Rethwisch, in their book "Materials Science and Engineering: An Introduction," have provided a theoretical background for the understanding of mechanical properties of materials such as elasticity, plasticity, fracture, and fatigue. The book describes stress-strain relationships, anisotropic properties of composites, and failure theories of structural materials. These topics assume importance in the context of UAV structures, which are prone to cyclic loading, bending, and torsion. The book is an important reference for material selection and for matching simulation results with actual material properties, thus enhancing the theoretical background of computational structural analysis.

Further details on the design of a UAV wing were obtained through the analysis and design of a VTOL UAV wing using finite element analysis, which was published in the STTKD journal. The paper sought to assess the design of a wing intended for vertical take-off and landing missions, which entail complicated loading conditions. The authors applied FEA to determine stress concentration, deformation, and safety factors resulting from aerodynamic and thrust loads. The paper demonstrated that FEA is applicable in determining stress concentration factors and the safety of the structure prior to the development of the prototype. The paper emphasized the significance of computational analysis in reducing development time and costs while ensuring the reliability of the structure in the design of a UAV win

METHODOLOGY

A. Wing Geometry Modelling

The geometric modelling of the UAV wing was done using the traditional NACA 4412 airfoil section, which has been widely adopted in low-speed fixed-wing UAV designs because of its desirable lift properties and simplicity of design. The two-dimensional airfoil points were created and loaded into the CAD system to develop the initial airfoil shape. A three-dimensional wing shape was then created by specifying essential design variables like root chord length, tip chord length, total wingspan, and angle of sweep, thus simulating a practical tapered wing design. Wingspan = 450mm , Root chord = 180mm , Tip Chord = 120mm , Taper Ratio = 0.667.

The airfoil shape was then extruded and lofted to create a smooth three-dimensional wing surface. The wing was assumed to be a cantilever wing, with the assumption that the root section is fixed to the fuselage and the tip section is free. This assumption is a practical simulation of the actual wing boundary condition experienced during UAV flight. The resulting geometry was then validated for continuity and accuracy before being imported into the finite element analysis environment.

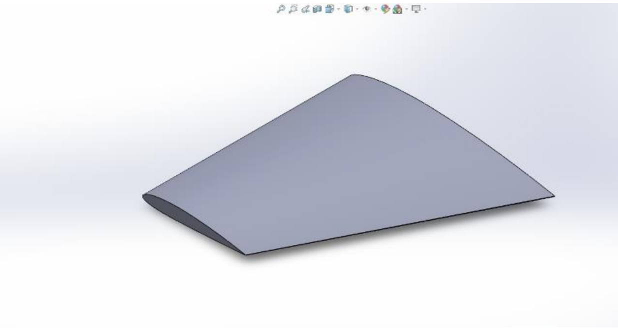


Fig 1: Wing Design

B. Material Selection

In order to assess the effect of material properties on the structural behaviour of the UAV wing, a number of composite material systems that are widely used in aerospace engineering have been chosen for comparison. These are Carbon Fiber Reinforced Polymer (CFRP) with an epoxy matrix, CFRP with a PEEK thermoplastic matrix, Kevlar/Epoxy, and various forms of Glass Fiber Reinforced Polymer (GFRP).

Fig 2: Wing Structure

In order to maintain a level of consistency and facilitate a fair comparison under the same loading and boundary conditions, all the materials were idealized as linear elastic isotropic materials. While it is true that composite materials are anisotropic in nature, this simplification enables a direct comparison of the structural behaviour of the materials based on their elastic properties. The material properties of Young’s modulus, Poisson’s ratio, density, and tensile strength were chosen from standard literature and material handbooks.

C. Boundary Conditions and Loading

Realistic boundary conditions and loading configurations were also established. The wing root area was fully fixed, preventing all translational and rotational degrees of freedom to model a cantilevered wing mounting on the fuselage. This boundary condition is important to ensure that the wing response is dominated by bending and shear deformations along the wing span.

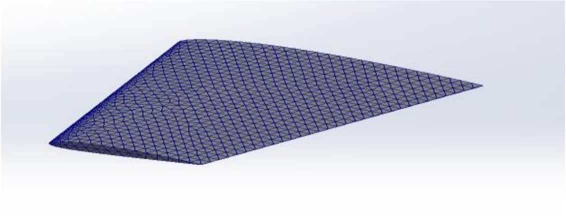


Fig 3: Fine mesh

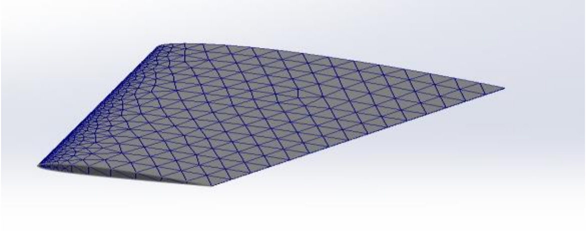


Fig 4: Default mesh

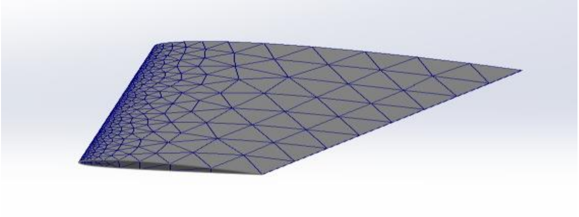


Fig 5: Coarse mesh

Mesh convergence analysis confirmed that the numerical results are independent of mesh size, ensuring solution accuracy. Buckling analysis was performed on a larger span wing to evaluate structural instability, where increased slenderness enhances susceptibility to buckling. The use of different airfoil geometries and scales was based on analysis requirements, balancing computational efficiency and realistic structural behavior.

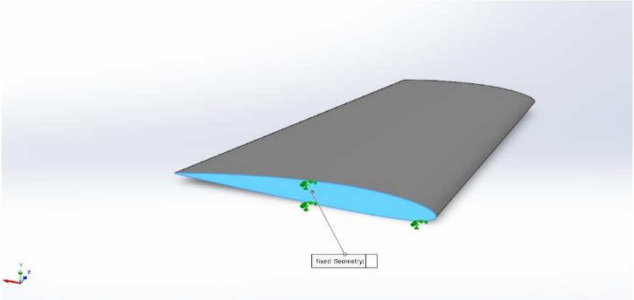


Fig 6: Fixed support

Aerodynamic loading was modelled by applying an equivalent uniformly distributed pressure load acting normal to the wing surface. This simplified loading model is adequate to model the overall effect of lift forces generated during steady-level flight, without requiring complex fluid-structure interaction or computational fluid dynamics (CFD) simulations. The application of the same pressure value for all material models enabled a direct comparison of the structural responses, independent of material properties.

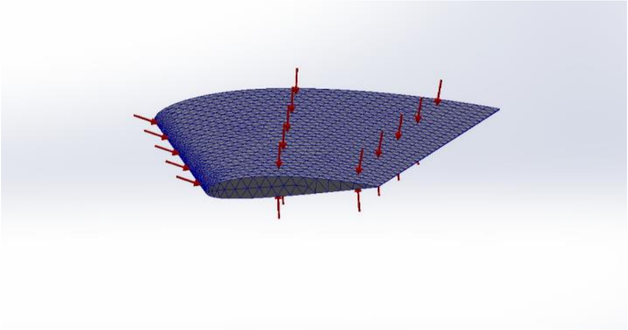


Fig 7: Meshing

Calculation of Equivalent Aerodynamic Pressure:

The equivalent aerodynamic pressure applied on the UAV wing is calculated using the dynamic pressure equation:

$q = (1/2)\ \rho\ V^2$

where:

ρ = air density = 1.225 kg/m^3 (standard sea-level condition)

V = UAV flight velocity

For a typical small UAV, a cruise velocity of 55 m/s is considered.

Substitution of Values

$q = (1/2) \times 1.225 \times (55)^2$

$q = 0.6125 \times 3025$

$q = 1851\ \mathrm{N/m^2}$

Final Applied Pressure

The calculated dynamic pressure is approximately 1850 N/m^2, which is rounded off to 2000 N/m^2 for application in the structural analysis.

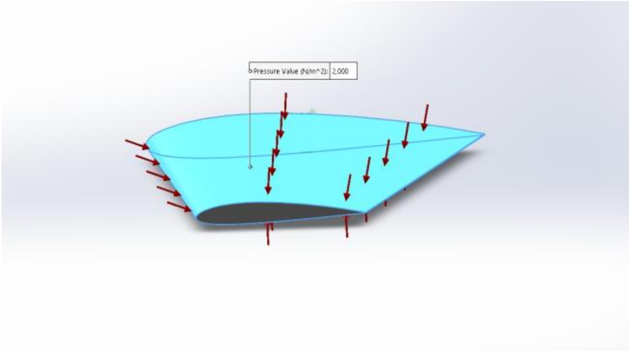


Fig 8: Equivalent Pressure

D. Finite Element Analysis

Finite Element Analysis (FEA) was carried out using SolidWorks Simulation, a popular structural analysis software. The three-dimensional wing model was meshed with solid finite elements to accurately capture the wing geometry. A mesh refinement study was carried out to ensure mesh convergence, where the mesh size was progressively decreased until the differences in stress and displacement values became inconsequential.

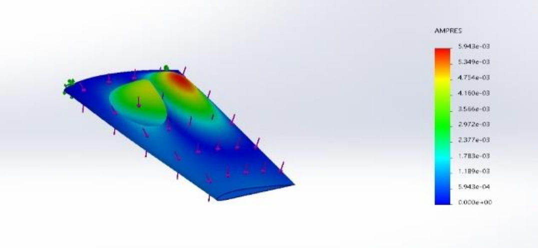


Fig 9: Buckling analysis

For each material combination, a static structural analysis was carried out with the same boundary conditions and loading. The two key outputs obtained from the analysis included the maximum von Mises stress, which captures the stress condition of the wing, and the maximum resultant displacement (URES), which captures the stiffness and bending response of the wing. These outputs are extremely valuable in understanding the structural integrity and displacement response of the UAV wing for each material combination.

E. Modal Analysis

The wing of a fixed-wing UAV is checked to see how it handles movement and if it is strong enough when it is vibrating. We use a kind of test called modal analysis on the wing to find out its natural frequencies and mode shapes. These things are really important to know so we can figure out if the wing will vibrate much when it is flying because of the air moving around it or the engine shaking. We look at materials like CFRP, GFRP and other traditional materials to see how they are different in terms of stiffness, weight and how they move. The results help us decide which material is better, at handling vibration having natural frequencies and being more stable. Modal analysis of the fixed-wing UAV wing really helps us make the wing design better so it works well is safe and lasts a time when it is being used.

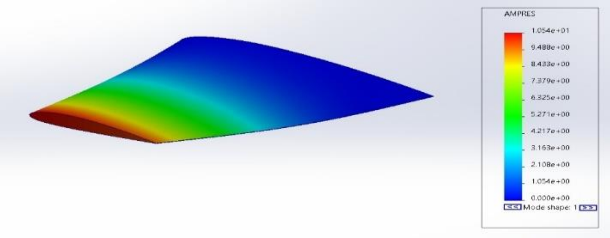


Fig 10: Mode 1

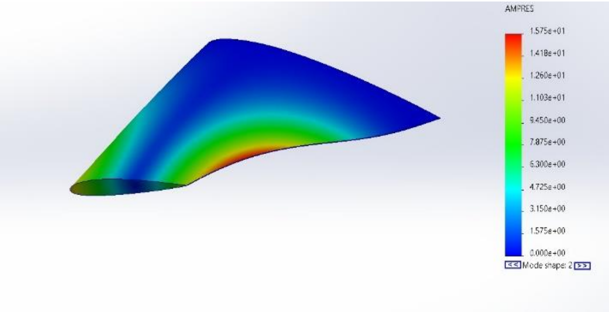


Fig 11: Mode 2

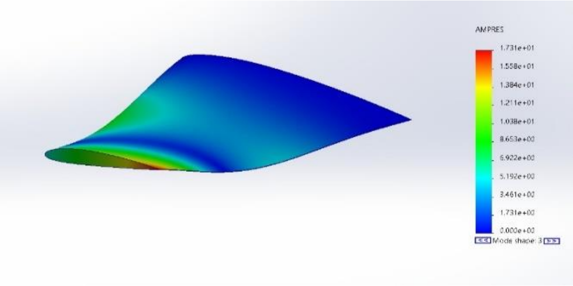
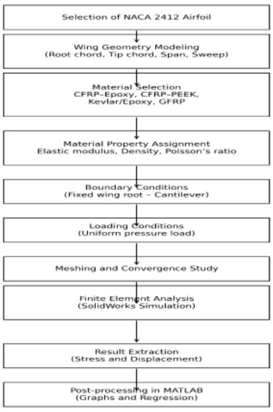


Fig 12: Mode 3

Table 1:

Material	Mode 1 - Bending	Mode 2 - Torsion	Mode 3 – 2nd bending	Mode 4 - Chord	Mode 5 – 2nd Torsion
CFRP PEEK	1389	4258.6	5761.3	8002.8	8778.1
Kevlar	1286.2	3910.6	5321.9	7376.4	8070.5
Vinyl ester	857.3	2683.4	3577.7	4893.2	5515.6
Polyester Resin	770.4	2430.6	3222.2	4504.4	4990.0
Epoxy Resin	1008.7	3169.6	4213.8	5885.9	6511.5

The UAVs wing has kinds of vibrations that happen at different natural frequencies. The first mode is the bending mode, where the wing bends the most from one end to the other. The second mode is the twisting mode, where the UAVs wing twists around its axis. The third mode is another bending mode. It happens at a higher frequency, which shows that the UAVs wing is very stiff. The fourth mode is the bending mode that happens along the chord direction, where the wing bends from front, to back. The fifth mode is another twisting mode. It is more complicated and happens at a higher order,which shows that the UAVs wing can twist in many different ways.



RESULTS AND DISCUSSION

The response of the wing structure of the UAV was analyzed for the same loading and boundary conditions for various material systems to determine the effect of material properties on displacement and stress responses. The analysis was carried out mainly for maximum displacement and von Mises stress, as these values are essential indicators of stiffness and strength, respectively. The outcome of the study shows that the stiffness of the material, as indicated by the elastic modulus, is the major factor that determines the deformation of the wing, while the stress response is affected by the combined effect of stiffness, density, and material-related loading characteristics. Regression analysis was used to determine the response behavior and ensure the consistency of the structural response of various material.

Maximum Displacement

The results of the maximum displacement clearly indicate that the higher the elastic modulus, the lower the deformation for the same loading conditions. This observation is in line with the conventional principles of structural mechanics, which state that higher stiffness leads to greater resistance to bending and lower deflection. The CFRP-based composite material had the lowest displacement among the materials considered for analysis, owing to its highest elastic modulus and highest stiffness-to-weight ratio. Kevlar and GFRP systems, on the other hand, had relatively higher displacement due to their relatively lower stiffness.

Regression analysis between the elastic modulus and the maximum displacement clearly indicated an inverse relationship between the two variables, which confirms that the deformation of the wing reduces systematically with an increase in stiffness. The aim of this regression analysis is to determine the characteristics of deformation and also to make sure that the behavior of the structure is consistent for different materials. The strong correlation has confirmed the validity of the finite element model and also ensured that the results are a true representation of the mechanical behavior of the wing structure.

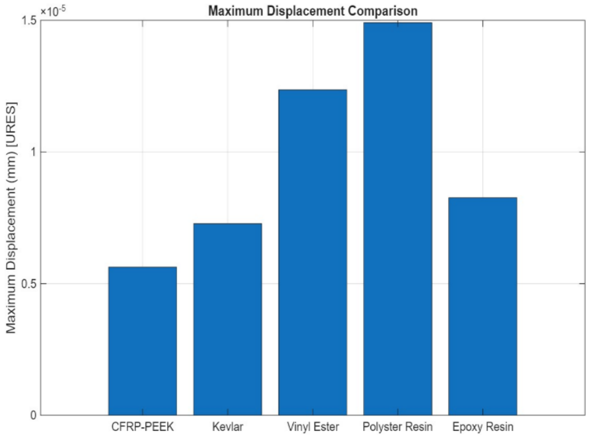


Fig 13: Graph representing the maximum displacement of wing with different materials

The graph compares the maximum displacement values of the UAV wing structure made of different material systems under the same loading and boundary conditions. The y-axis indicates the maximum displacement in millimeters, and the x-axis identifies the materials, which include Epoxy, CFRP-PEEK, Kevlar, Vinyl Ester, Polyester Resin, and Epoxy Resin.

From the graph, it is clear that CFRP-PEEK has a small displacement, which shows the advantage of carbon fiber reinforcement with a high-performance polymer matrix. Kevlar has a moderate displacement, which shows a balance between flexibility and stiffness.

In contrast, *Vinyl Ester* and *Polyester Resin* exhibit significantly higher displacement values, with Polyester Resin showing the maximum deformation. Such a phenomenon can be ascribed to their relatively lower elastic modulus, which causes them to be less stiff and more prone to bending under the applied load. Epoxy Resin has an intermediate displacement response, which is better than that of Vinyl Ester and Polyester Resin but not as good as that of Epoxy or CFRP composites.

From the graph, it is evident that there is an inverse relationship between stiffness and maximum displacement. The materials with higher elastic modulus and superior reinforcement properties exhibit lower displacement, thus justifying the effect of stiffness in regulating the displacement of the wing.

Table 2:

Material	**Factor of Safety**	**Specific Stiffness**	**Specific Strength**
Kevlar	8.9419e+05	3.5714e+07	4.2857e+06
CFRP-PEEK	1.6897e+05	4.1935e+07	7.7419e+05
Epoxy Resin	3.6249e+05	2.25e+07	1.5e+06
Polyester Resin	59018	1.3158e+07	2.6316e+05
Vinyl ester	9282.2	1.6216e+07	40541

The table shows that all materials have good structural performance in terms of safety and efficiency. However, extremely high Factor of Safety (FoS) indicates that all materials have been overdesigned, which is not good in terms of weight. The balanced Factor of Safety is also evident in composite materials, which have high specific strengths and specific stiffness

Specific Strength and Specific Stiffness are significant parameters that reflect the efficiency of materials used in aerospace applications. The high specific Strength and Specific Stiffness of CFRP-PEEK confirm that it is suitable for lightweight UAV wing structures. However, unlike other composite materials, Kevlar shows high specific Strength but low specific Stiffness, which indicates high deformability. Therefore, composite materials have high specific Strength and specific Stiffness than neat resin materials.

Von Mises Stress

The result of the von Mises stress analysis is useful in understanding the distribution of the internal stresses in the wing structure. Unlike the displacement, the von Mises stress is not directly proportional to the elastic modulus. Rather, the stress is a function of the material stiffness, density, and resistance to the internal forces. Materials that are stiffer, such as CFRP, have higher concentrations of stress, while materials that are less stiff, such as GFRP and Kevlar, have higher deformation areas.

However, the von Mises stress values for all the material systems remained within the permissible limits, thus ensuring that the wing structure meets the strength requirements under the applied loading conditions. The consistency in the stress distributions for all the material systems further validates the accuracy of the finite element analysis and hence the comparative structural analysis.

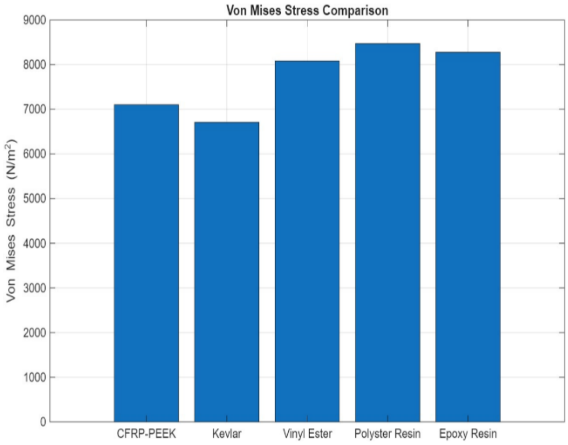


Fig 14: Graph representing the von mises stress of different material

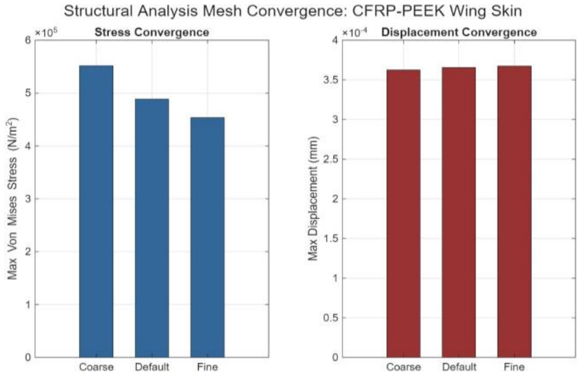


Fig 15: Comparison of stress convergence and Displacement convergence

The image presents a mesh convergence study for a CFRP-PEEK wing skin, illustrating how the results vary with different mesh densities—coarse, default, and fine. In the stress convergence plot, the maximum von Mises stress decreases from approximately 5.5×10^5 N/m^2 for the coarse mesh to about 4.5×10^5 N/m^2 for the fine mesh, indicating that the coarse mesh tends to overestimate stress and that the solution stabilizes as the mesh is refined. In contrast, the displacement convergence plot shows a slight increase in maximum displacement from around 3.62×10^{-4} mm to 3.67×10^{-4} mm as the mesh becomes finer, with only minimal variation between the default and fine meshes. This behavior suggests that the displacement results are already close to convergence. Overall, the small changes observed between successive refinements confirm that the analysis has achieved mesh independence, and the fine mesh provides the most accurate and reliable solution.

CONCLUSION

This study looks at the design and analysis of a UAV wing. It is based on airfoil geometry and used finite element methods. The researchers compared materials to see how they handled stress, deformation and efficiency.

It was found that fiber-reinforced composites are much better than resin materials when it comes to strength and stiffness.

The UAV wing was analyzed to see how it would behave under conditions. The natural frequencies of the UAV wing are high enough that resonance is not a problem when the UAV is being used normally. A mesh convergence was also carried out.

A buckling analysis on an UAV wing and found that it can be unstable if it is too long and thin. This means that the wing can deform, away from the part that is attached to the UAV.

So this study shows that the materials used the design of the UAV wing and the methods used to test it are all very important. They all play a role, in making a UAV wing that's lightweight and strong. The study highlights the importance of UAV wing designs.

FUTURE SCOPE

Future work can focus on incorporating more realistic structural and loading conditions to further enhance the accuracy of the analysis. This includes performing fatigue analysis under cyclic loading to estimate the service life of the wing, and dynamic loading studies to simulate real flight conditions such as gust loads.

The current model assumes an equivalent homogeneous material; future studies can implement detailed composite laminate modeling to capture anisotropic behavior more accurately.

Solid modeling was used for simplicity, while shell modeling can provide more accurate thin-structure behavior and can be explored in future work.

Additionally, the structural analysis can be extended to a full wing model including ribs and spars to better represent real aircraft structures. Localized reinforcement strategies at critical regions such as the wing root can also be explored to improve structural performance.

Advanced studies such as nonlinear and aeroelastic analysis can further improve the understanding of UAV wing behavior under realistic operating conditions.

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