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Design and Analysis of UAV Propeller for Composite Materials

Dhinnesh S[1], *Guru Prasath K S*[2], *Venkatesh N*[3]
[1,2]*UG Student, PSG College of Technology, Coimbatore, India*
[3]*Assistant Professor, Department of Aerospace Engineering, SNS College of Technology, Coimbatore, India.*
Emails: *dhinnesh2003@gmail.com*[1], *prasathguru1008@gmail.com* [2], *venkataero2@gmail.com*[3]

Abstract

Unmanned Aerial Vehicles (UAVs) have witnessed significant advancements and growth in recent years, where the efficiency and performance of propellers play a vital role. This study focuses on the design and analysis of UAV propellers utilizing ANSYS software. The propeller's structural behavior and aerodynamic effects are investigated through advanced engineering approaches. This study involves using ANSYS software to conduct a comprehensive analysis of UAV propellers, focusing on a comparative study of three distinct materials: Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP), and aluminum alloy. A comparative study is conducted by analyzing various results such as maxim stress, maximum deformation and also the fluid flows. By considering the advantages and limitations of CFRP, GFRP, and aluminum alloy, this research contributes to the advancement of unmanned aerial technology, driving innovation and efficiency in UAV design and performance optimization.

Keywords: *ANSYS; Aluminum alloy; Composite materials; Propeller.*

1. Introduction

The propulsive system of multi-rotor UAVs heavily relies on the performance of their propellers, particularly in electric propulsion systems where endurance can be a limiting factor. As such, ongoing research in propeller technology aims to enhance the overall performance and longevity of multi-rotor UAVs. This study focuses on comparing GFRP, CFRP and Aluminum alloy for the application of UAV propeller manufacturing. The analyses are carried out on ANSYS to find out maximum stress, maximum deformation and also pressure and velocity distribution. Comparative studies have been conducted to evaluate the performance of composite propeller shafts against traditional steel shafts. These studies have consistently shown that carbon epoxy and e-glass epoxy composites exhibit superior mechanical properties and lower weight compared to steel, making them the preferred choice for propeller shaft applications. Carbon/Epoxy and Glass/Epoxy composite materials have gained prominence in propeller design due to their excellent strength-to-weight ratio and corrosion resistance properties. These composites offer a viable alternative to the field. There should not be an extensive review of the traditional steel shafts, enabling significant weight reduction without compromising structural integrity. The adoption of composite materials has led to a substantial reduction in the weight of propellers. The lower density of composites compared to steel translates to lighter shafts, contributing to improved fuel efficiency and overall vehicle performance. Ramesh et al. (2021) compared the propeller made with CFRP and GFRP materials with Aluminum using ANSYS with the help of various parameters such as equivalent stress, normal stress and maximum deformation. It was found that Epoxy E-Glass-UD is preferred over the other materials as it was observed with deformation of 3.8 μm and low stress of 55556 Pa. [1] Sridhar et al. (2010) conducted an investigation into the frictional resistance and propulsion performance of propellers using Computational Fluid Dynamics (CFD) techniques. The study focused on geometric modeling and mesh generation using CATIA-V5 for four-bladed propellers operating at a thrust force of 346 kN at 30 revolutions per second (rps). By leveraging CFD techniques, Sridhar et al. aimed to provide insights into the frictional resistance and propulsion characteristics of propellers, facilitating advancements in propeller design and optimization.

The computational results obtained from the CFD simulations were compared with existing experimental data. This comparison aimed to validate the accuracy and reliability of the CFD model in predicting propeller performance under open water conditions.[2] Alka Sawale et al. aim to streamline the design of a propeller for a current UAV, with the objective of achieving a maximum thrust of 1000 N while rotating at 8000 rpm at higher speeds. The diameter of the propeller is constrained to 1000 mm, and the maximum available power is limited to 40 kW. To ensure lightweight construction, the propeller will be fabricated using carbon fiber composite materials. Propellers serve as a vital component in. By optimizing the design and material composition of the propeller, the research aims to enhance the performance and efficiency of the UAV, ultimately contributing to advancements in unmanned aerial technology. Rangaswamy et al. (2004) introduced a drive shaft constructed from E-Glass Epoxy and HS Carbon Epoxy multilayered composites. The researchers utilized genetic algorithms (GA) for optimization and ANSYS software for analysis to achieve an optimal stacking sequence and enhance torque transmission capacity. Additionally, they aimed to improve vibration characteristics during bending. By employing composite materials, the team achieved significant weight reduction ranging from 48% to 86% compared to conventional steel drive shafts. These findings highlight the potential of genetic algorithms in efficiently optimizing complex designs, thereby offering practical solutions for real-world engineering applications. [3] Abdul et al. (2015) has performed design and analysis of composite material marine shaft using ANSYS workbench. They observed that Glass Fiber Reinforced Plastic (GFRP) material can give a better performance with respect to static and dynamic analysis when compared with other materials such as CFRP and Aluminum [4]

2. Method

2.1.CFRP

CFRP exhibits exceptional flexibility, allowing it to conform to complex shapes and withstand bending without fracturing. Its high tensile strength enables it to withstand significant loads without deformation or failure, making it suitable for applications requiring structural integrity. Additionally, CFRP boasts low weight, contributing to overall weight reduction in structures and components. Its high resistance to corrosion, chemicals, and environmental factors ensures long-term durability and reliability. Despite its numerous advantages, CFRP is associated with high production costs due to the complexity of manufacturing processes and the expense of raw materials. However, its exceptional properties and characteristics make it an indispensable material in industries where performance, durability, and weight savings are paramount. [5]

Table 1 Mechanical Properties of CFRP

PROPERTY	VALUES (v)
Young's modulus	1.3×10^5 MPa
Poisson's ratio	0.3
Mass density	1600 Kg/m^3
Shear modulus	5×10^{10} Pa
Bulk modulus	1.083×10^{11} Pa

2.2.GFRP

In the realm of propeller construction, Glass Fiber Reinforced Plastic (GFRP) emerges as a compelling material choice, offering a blend of advantageous properties ideal for propeller design. GFRP, a composite material composed of fine glass fibers embedded in a polymer matrix, showcases remarkable strength-to-weight ratio, making it an optimal candidate for propellers where both durability and lightness are paramount. GFRP's inherent corrosion resistance makes it particularly well-suited for marine applications, ensuring prolonged service life even in harsh saltwater environments. Additionally, its excellent tensile strength enables propellers to withstand the considerable stresses experienced during operation, while its flexibility allows for efficient energy transfer, contributing to enhanced performance. In polymer matrix composites, a wide range of varieties are available, including unidirectional fiber, bidirectional fiber, prepreg production, and wet condition products, among others. These variations encompass different configurations of glass and carbon fibers, each offering unique properties and characteristics. These diverse materials are utilized in the construction of propellers and subjected to analysis using ANSYS Workbench to identify the most suitable material capable of effectively withstanding high loading conditions [6]. Through rigorous analysis, the material with the optimal combination of properties is selected to ensure optimal performance across all loading conditions (Table 1).

Table 2 Mechanical Properties of GFRP

PROPERTY	VALUES (v)
Young's modulus	1.25×10^5 MPa
Poisson's ratio	0.32
Mass density	7590 Kg/m^3
Shear modulus	4.73×10^{10} Pa
Bulk modulus	1.15×10^{11} Pa

3. Modeling and CFD Analysis

3.1.Model

The modeling of the propeller (Figure 1) is done using Creo parametric 6.0 and then imported into the ANSYS using STEP file format. The diameter of the propeller is 127 mm and the pitch is 127 mm.

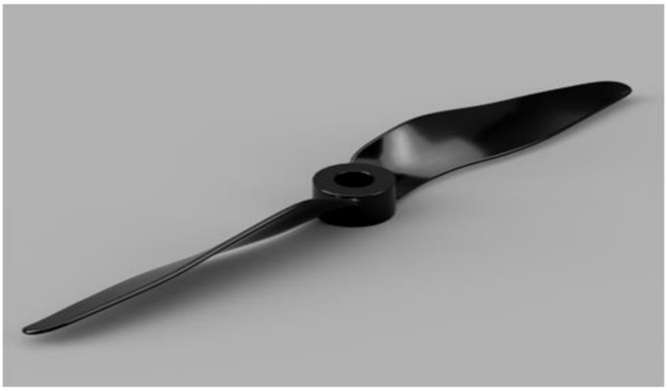

Figure 1 3D Model of the Propeller

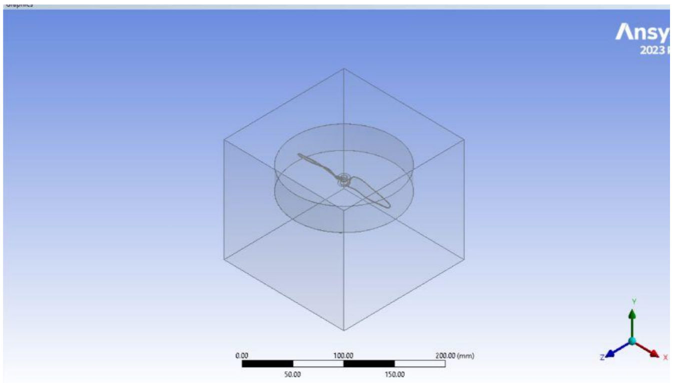

Figure 2 Enclosure Built Around the Propeller

3.2.Discussion

Computational fluid dynamics, or CFD, is a numerical simulation technique that engineers use to solve problems with fluid flow and fluid-solid interaction [7]. It solves issues related to a variety of applications, including heat transfer, engine analysis, aerodynamics, and aerospace, by using the concepts of fluid mechanics. Researchers and engineers use CFD to examine the interaction between fluids (liquids or gasses) and solid surfaces using intuitive simulation tools. In order to run CFD, an enclosure was built around the propeller model once it was loaded into ANSYS' fluid flow module. The propeller enclosure is depicted in Fig. 2. The inlet velocity is set at 15 m/s, and the propeller rotation is set to 7000 rpm for simulation purposes. Table 3 displays the parameters of the simulation. The flow simulation is done using the K-epsilon turbulent model with iterations of 100. Fig.3 shows the thrust force calculation obtained from the software i.e., 0.387 N. And the pressure contours and velocity contours are obtained which is shown in Fig 4 and Fig 5. The velocity streaming around the propeller is depicted in Fig 6.

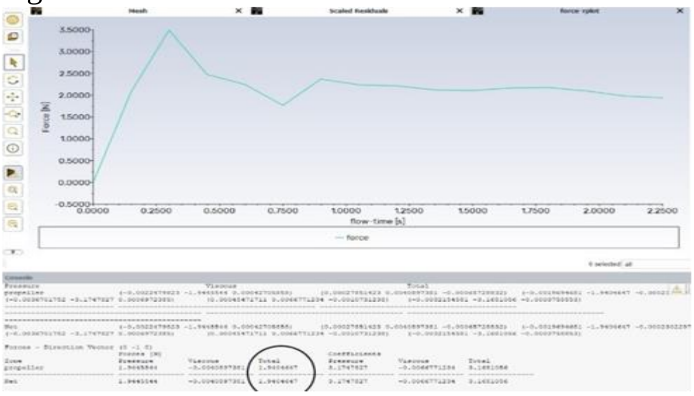

Figure 3 Thrust Calculation

In ANSYS Fluent, pressure contour, velocity contour, and velocity streamline images serve as crucial visualizations for understanding fluid flow behavior. Pressure contours illustrate pressure distribution across the domain, with warmer colors denoting higher pressure and cooler colors indicating lower pressure. Velocity contours show fluid velocity distribution, highlighting flow patterns and velocity gradients. Velocity streamlines visualize fluid particle trajectories, revealing flow structures, recirculation zones, and areas of convergence or divergence. Together, these images provide valuable insights into flow characteristics, aiding in the analysis of system efficiency, stability, and performance (Table 3).

Table 3 Parameters Set for Simulation

PROPERTY	VALUES (v)
Propeller rotation	7000 rpm
Maximum Meshing Size	5 mm
Gravity	9.81 m/s^2
Time	Transient
Time step size	0.15
No of Iterations per step	100
No of time steps	15
Operating density	1.225 kg/m^3
Inlet velocity	15 m/s

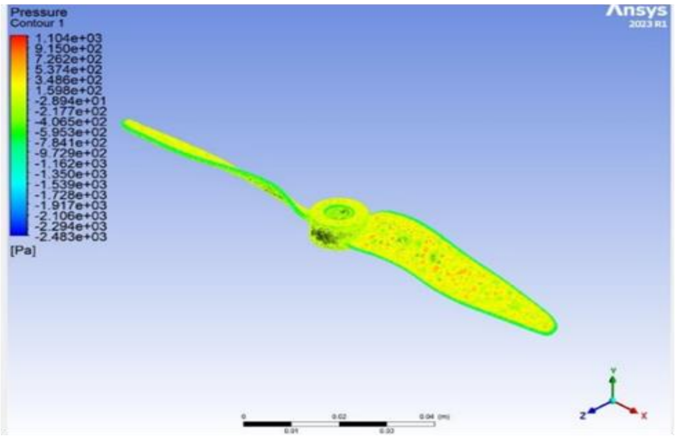

Figure 4 Pressure Contour

4. Transient Structural Analysis

Primarily three materials are selected which can be used in the manufacturing of the propeller. In those three materials Aluminum alloys is selected as the reference material and it's compared with the other two materials CFRP and GFRP. In the materials library of the ANSYS workbench, Epoxy E-Glass UD is selected for the GFRP and Epoxy Carbon UD (230 GPa)

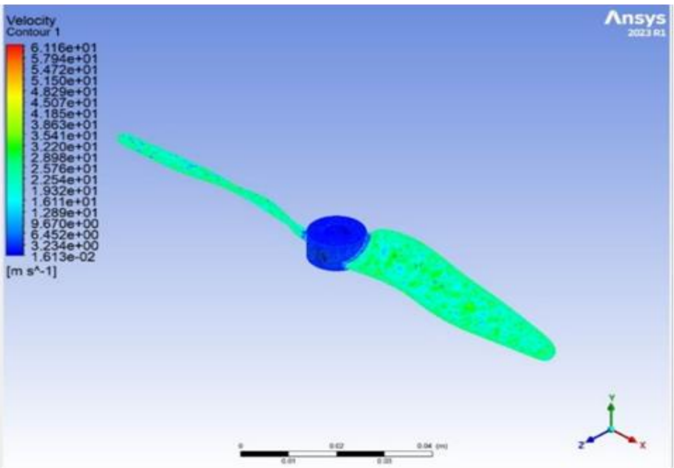

Figure 5 Velocity Contour

In the transient structural module of the ANSYS workbench, the analysis is carried out where the hub of the propeller is fixed. The Following parameters are found as output for all the three materials assumed for the analysis of the propeller.

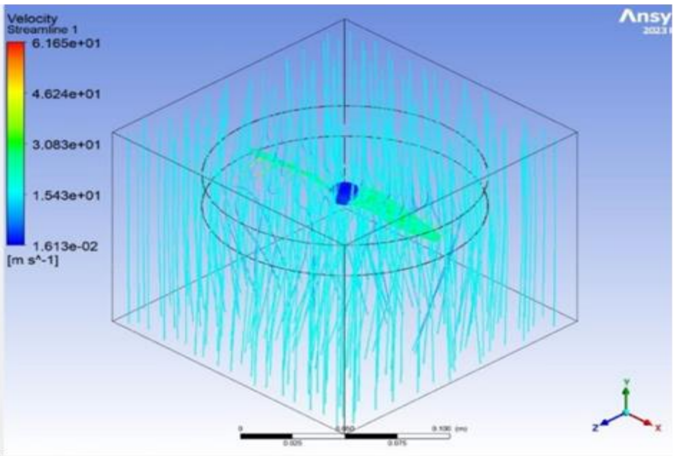

Figure 6 Velocity Streamline in the Enclosure

The obtained result of maximum deformation and the von misses stress and strain are shown in figure 7,8,9.

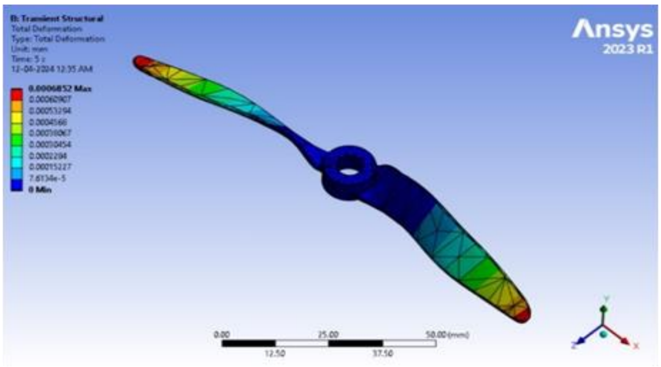

Figure 7 Maximum Deformation of Aluminum Alloy

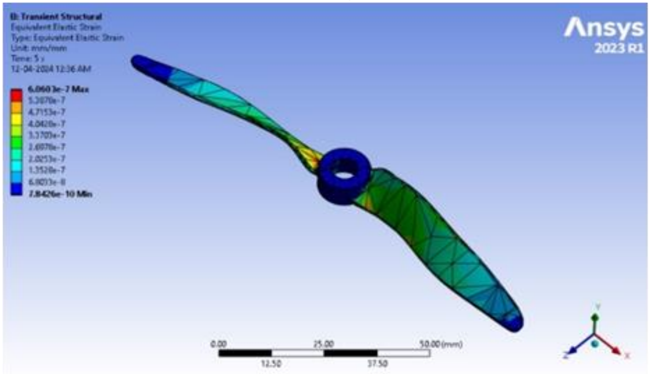

Figure 8 Von Mises Stress of Aluminum Alloy

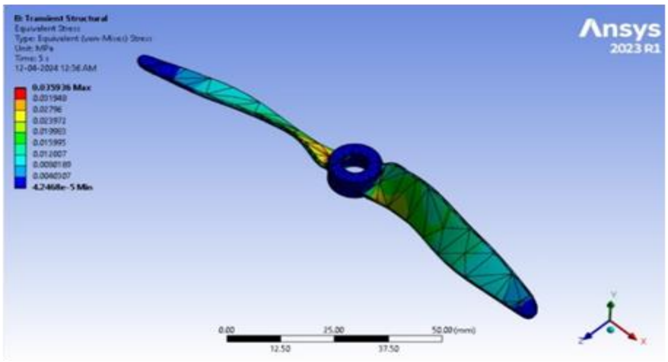

Figure 9 Von Mises Strain of Aluminum Alloy

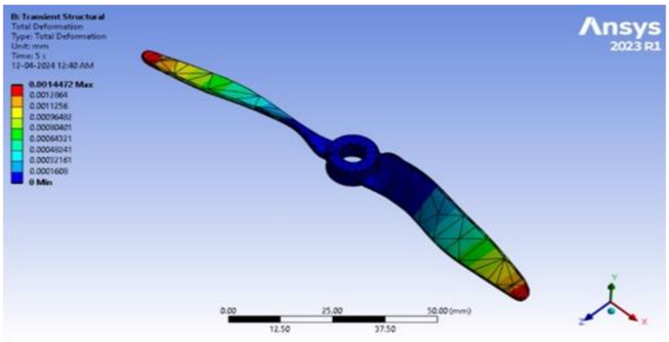

Figure 10 Maximum Deformation of Epoxy E-Glass UD

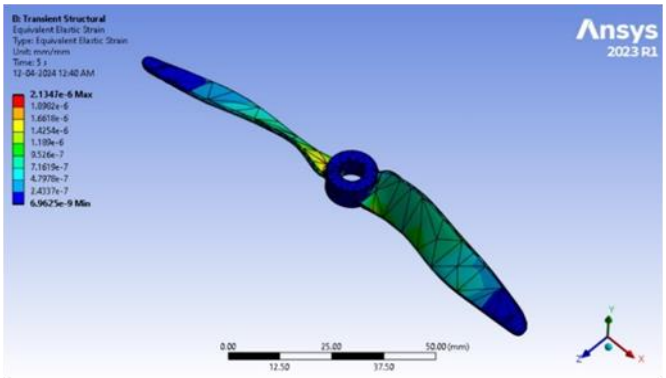

Figure 11 Von Mises Stress of Epoxy E-Glass UD

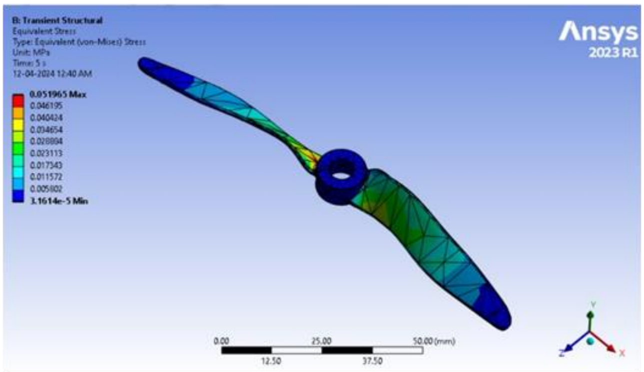

Figure 12 Von Mises Strain of Epoxy E-Glass UD

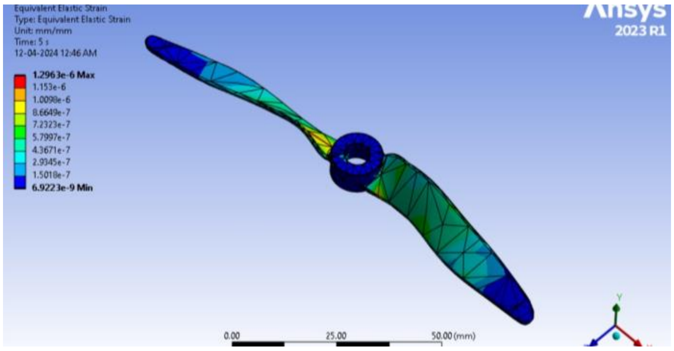

Figure 13 Maximum Deformation of Epoxy Carbon UD (230 GPa) Prepeg

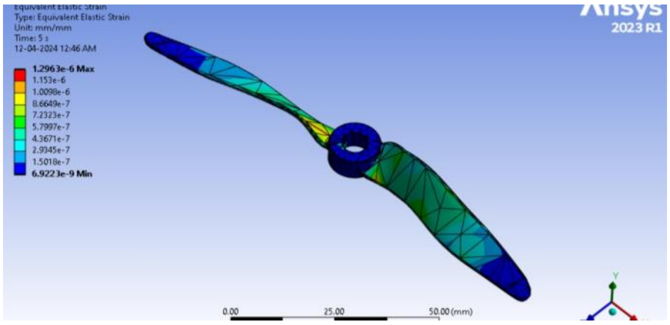

Figure 14 Von Mises Stress of Epoxy Carbon UD (230 GPa) Prepeg

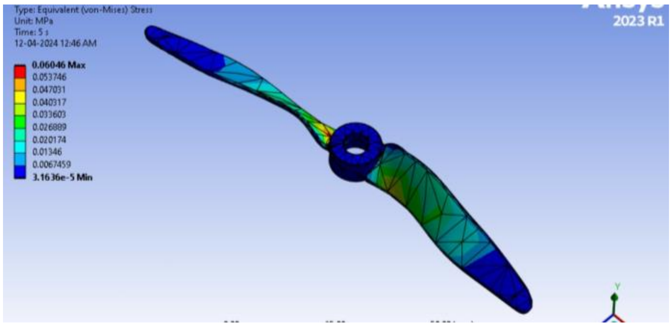

Figure 15 Von Mises Strain of Epoxy Carbon UD (230 GPa) Prepeg

5. Results & Discussions

Aluminum: Aluminum has the lowest Von Mises stress (0.0359 MPa) of the three materials. This means that it is less likely to deform or break under stress. Aluminum is also a relatively lightweight material, which is important for UAV propellers as it helps to improve flight efficiency. (Refer Fig 7,8,9)

CFRP (Carbon Fiber Reinforced Polymer): CFRP has a higher Von Mises stress (0.060 MPa) than aluminum, but a lower Von Mises strain which is 1.296×10^{-6} mm. This means that it is stiffer than aluminum and can deform less under stress. CFRP is also a very strong material, which is important for UAV propellers that need to withstand the high forces generated by the motor. However, CFRP is also more expensive than aluminum. (Refer Fig 10,11,12)

GFRP (Glass Fiber Reinforced Polymer): GFRP has a higher Von Mises stress (0.0519 MPa) than aluminum and a higher Von Mises strain (2.13×10^{-6} mm) than both aluminum and CFRP. This means that it is less stiff and less strong than the other two materials. However, GFRP is also the least expensive of the three materials. (Refer Fig 13,14,15). The simulation results are obtained from the Ansys workbench and fluid flow. Then the results are compared for all three different materials. Table 4 shows the comparison of the various outputs found with the three materials used. So, from the above comparison it can be concluded that the best material for a UAV propeller will depend on the specific application. If weight is the most important factor, then aluminum is the best choice. If strength and stiffness are more important, then CFRP is the better option. GFRP is a good option for budget-minded applications where weight is not a critical factor and deformation is a critical factor. GFRP, while less stiff and stronger than CFRP, offers a cost-effective alternative with lower weight. UAV propellers need to withstand the high forces generated by the motor by also with low material cost.

Conclusion

In conclusion, the comparative study of Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) composites for UAV propeller design and analysis using ANSYS software has provided valuable insights into their respective performance characteristics. Aluminum exhibits the lowest Von Mises stress, making it less likely to deform under stress and a lightweight option for improved flight efficiency. CFRP demonstrates higher stiffness and strength compared to aluminum, making it suitable for withstanding high forces generated by the motor, despite being more expensive.

Table 4 Comparison of Results

Materials	Von misses stress (MPa)	Von Mises strain (mm)	Max Deformation (mm)
Aluminum	0.0359	$6.06\text{x } 10^{-7}$	0.00068
CFRP	0.060	$1.296\text{x } 10^{-6}$	0.000655
GFRP	0.0519	$2.13\text{x } 10^{-6}$	0.00144

GFRP, while less stiff and stronger than CFRP, offers a cost-effective alternative with lower weight. The choice of material ultimately depends on specific application requirements, with aluminum being optimal for weight-sensitive applications, CFRP excelling in strength and stiffness, and GFRP providing a cost-effective solution. Further considerations include fatigue resistance and impact resistance, where CFRP performs well. Overall, this study contributes to the understanding of material selection for UAV propeller design, aiding in the optimization of performance and efficiency in aerospace applications. Thus, the comparative analysis for various suitable materials used for the production of propeller is done using ANSYS

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