

SIMULATION OF FATIGUE AND DEFORMATION OF CARBON FIBER DRONE PROPELLERS USING THE FINITE ELEMENT METHOD (FEM)

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Abstract. This study analyses finite elements in the structural calculation of a drone propeller in carbon fiber with loads that represent live use. The output of this study evaluates the effect of load variations on deformation, stress distribution, and safety factors as key indicators of structural performance. A three-dimensional propeller model is developed based on the actual geometric configuration and analysed using the Finite Element Method (FEM). Several loadings are considered: a base load with a total mass of 3.6 kg, and two additional loading conditions with increasing masses of 0.5 kg and 0.75 kg. The applied loads are converted into equivalent forces distributed along the propeller blades to simulate realistic operating conditions. Simulations show that increasing the applied load causes a proportional increase in the maximum deformation and a significant reduction in the minimum safety factor. The maximum deformation increases from 14.933 mm at the base load to 18.044 mm at the highest load. The blade tip is consistently identified as a critical region, where the highest deformation and stress concentration occur due to bending-dominated behaviour. The safety factor ranges from 0.51341 to 0.42489 as the load increases, indicating a decrease in structural safety. Fatigue loading is mentioned, this study addresses fatigue qualitatively based on stress concentration and safety factor trends, as explicit S–N curve data, load cycle definitions, and mean stress corrections are not included. The results emphasize the importance of structural optimization and accurate material modelling to improve the reliability and durability of carbon fiber drone propellers under various load conditions.

Keywords: Drone; Propeller; Deformation; Finite Element Method (FEM)

1 Introduction

Drone technology has advanced significantly in recent years. Originally designed for military purposes, drones have found growing applications in various civilian fields, such as mapping, agriculture, surveillance, and even goods delivery[1]. The most notable development is the use of drones for rapid delivery services. In the United States, drone-based delivery has become a significant trend[2]. Large companies are leveraging drones to simplify logistics, shorten delivery times, and lower operational costs compared to traditional

transportation methods[3]. A prominent example is the partnership between Walgreens and Wing, a drone service provider, to implement drone delivery in the Dallas–Fort Worth, Texas, area. This success has underscored the transformative potential of drones in modernizing logistics[4]. The adoption of delivery drones is gaining global attention as businesses recognize their efficiency in overcoming challenges such as navigating densely populated areas and reaching remote areas. Drone technology is expected to continue advancing, strengthening its role as a critical component of the global logistics network. Advances have driven innovation in key drone components such as navigation

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systems, batteries, sensors, and mechanical parts like engines and propellers. These components include propellers, which are essential for flight and stability[5], [6]. In addition to providing lift, propellers also control direction and speed. Propeller designs and specifications vary widely depending on the drone type and payload. Delivery drones have larger, stronger propellers to support heavier loads. Optimal propeller performance is crucial to drone functionality, as issues such as deformation or cracking can lead to instability and eventual failure[7]. Drone propellers must withstand a variety of dynamic forces during operation, including lift, shear stress, centrifugal torque loads, and air pressure fluctuations influenced by wind speed and direction[8]. Load cycling contributes to material fatigue over time, which can lead to cracking and structural failure. Fatigue loading is crucial for improving propeller durability, safety, and rotational performance. Analysing how propellers respond to repeated deformations and stresses requires sophisticated methodologies that can handle the complexity of varying loads and geometries[9]. One approach uses the Finite Element Method (FEM). FEM uses numerical analysis to solve complex differential equations, both Ordinary Differential Equations (ODEs) and Partial Differential Equations (PDEs), which are difficult to solve analytically. FEM is used to find structural deformation loads, stress analysis, fatigue loading, and dynamic simulations[10]. Research into drone propeller loading, FEM includes detailed simulations of how propellers deform and fatigue under various loading conditions. Critical stress points prone to cracking and failure can be identified, optimizing propeller design in terms of geometry and material selection[11]. The result is safer, lighter, and more efficient propellers. Advanced composite materials such as carbon fiber are used in drone propeller design. Known for its high strength-to-weight ratio, carbon fiber can withstand significant stress without adding weight to the drone[11], [12].

The direction-dependent anisotropic nature of materials makes their behaviour more complex than that of conventional homogeneous materials, requiring a more in-depth and accurate approach for structural analysis. The Finite Element Method (FEM) is crucial because it can comprehensively model material behaviour, including stress, elasticity, plastic deformation, and fatigue. The use of FEM allows for more realistic predictions of structural responses to various loading conditions encountered during operation, rapid advances in materials science and simulation techniques have also contributed to improvements in drone reliability and performance. This has made drones increasingly important in various sectors, particularly logistics, surveillance, and other modern industries. Studies on this topic remain underexplored. There is a significant research gap, particularly in previous studies that have addressed propeller-driven drones under various loading conditions. Most studies have not yet thoroughly examined the influence of anisotropic material properties on structural response under complex load

conditions, further research is needed to fill this gap in order to produce more accurate analyses and support the development of more optimal and reliable drone designs[13]. Propeller efficiency significantly impacts drone energy performance. High-performance propellers increase lift, decrease battery consumption, and contribute to improved flight stability. For cargo delivery, this aspect is crucial, enabling drones to travel longer distances while carrying optimal payloads[14]. Utilizing FEM simulations provides an opportunity to assess propeller performance prior to production and deployment, reducing the likelihood of operational failures and minimizing repair costs[15]. Advances in drone technology depend not only on electronics and control systems, but also on mechanical components, with propellers being crucial[16]. Incorporating FEM simulations to analyse propeller fatigue and deformation is crucial during the design phase. Errors at this stage can pose serious safety risks to drone operations. The analysis ensures that the propellers can withstand a wide range of flight conditions and loading scenarios, improving operational reliability and safety[17], [18]. The research focused on evaluating the propeller performance under various loading conditions, identifying critical areas susceptible to cracking, and offering design recommendations aimed at improving safety, efficiency, and durability. The findings provide a valuable resource for advancing drone technology, particularly in the freight delivery sector, where high performance and robust structural safety are crucial.

2 Methodology

This study analyses the deformation, stress distribution, safety factor, and fatigue life of carbon fiber drone propellers using the Finite Element Method (FEM).

2.1 Literature review

A literature review was conducted to establish a theoretical foundation and define loading parameters regarding drone propeller design, carbon fiber material properties, fatigue failure mechanisms, and FEM-based structural analysis of rotating components[18], [19]. The literature review described includes standards for composite materials, methods for modelling propeller geometry, approaches to aerodynamic loading, and numerical simulation techniques. Developments from this literature review are crucial in establishing geometry, material properties, and simulation parameters.

2.2 Propeller geometry and modelling

The propeller geometry was designed using CAD software, following the exact dimensions of the drone propellers analysed in the study. The propeller design was carefully crafted to ensure reproducibility. The use of key geometric parameters is explained in the following dimensional details.

Main propeller geometric parameters:

- a) Number of blades: 2
- b) Blade length (hub to tip): ± 230 mm
- c) Chord length at blade root: ± 35 mm
- d) Chord length at blade tip: ± 20 mm
- e) Maximum blade thickness: ± 3 mm
- f) Pitch angle at blade root: $\pm 25^\circ$
- g) Pitch angle at blade tip: $\pm 10^\circ$ (linear twist)
- h) Hub diameter: ± 30 mm
- i) Hub thickness: ± 10 mm

The CAD model for the propeller serves as the basis for the FEM simulation analysis, which allows for the freezing, stress distribution, and fatigue behaviour of the propeller in this study.

2.3 Material properties

The propeller is made of a carbon fiber composite material. In the numerical analysis and to ensure consistency, the material is modelled as a homogeneous isotropic substance[20]. Relevant material properties are sourced from published studies and can be found in the composite material data. The following data and material properties were used in the simulation:

- a) Young's modulus, $E = 70$ GPa
- b) Poisson's ratio, $\nu = 0.30$
- c) Density, $\rho = 1600$ kg/m³
- d) Equivalent yield strength = 600 MPa
- e) Fatigue behaviour: S–N curve adopted from carbon fiber composite literature under constant-amplitude loading

This study explicitly uses the isotropic assumption as a parameter constraint, to obtain simulation complexity and results in layer-level orthotropic modelling using FEM.

2.4 Finite Element Modelling

The simulation used ANSYS Workbench 2023 R1 to perform static and structural fatigue analysis[21].

Hardware Specifications:

- a) Processor (CPU): Intel Core i7-12700H (14 cores, 20 threads, up to 4.7 GHz)
- b) RAM: 32 GB DDR4
- c) Graphics Card (GPU): NVIDIA GeForce RTX 3060 6 GB
- d) Storage: 1 TB NVMe SSD
- e) Cooling System: Built-in cooling system (laptop/workstation)

Software Specifications:

- a) Operating System: Windows 11 Pro 64-bit
- b) Simulation Software: ANSYS 2023 R1
- c) Module Used: ANSYS Mechanical – Static Structural
- d) Solver: Program Controlled (ANSYS default solver)

Important details regarding the FEM modelling are as follows:

- a) The element type used was a 3D solid tetrahedral element (SOLID187).
- b) An initial mesh size of approximately 2.5 mm was applied.

- c) Local mesh refinement was implemented in the hub and blade root regions.
- d) A mesh independence study was conducted, considering mesh sizes of 3.5 mm, 2.5 mm, and 1.5 mm.
- e) Mesh convergence was achieved at a mesh size of 2.5 mm, with the resulting variation remaining below 5%.

2.5 Boundary conditions and rotational speed

The boundary conditions are precisely and precisely defined in propeller testing. The propeller area is modelled as a fixed support, which indicates a fixed attachment to the drive shaft. The propeller rotational speed is determined as follows:

- a) Rotational speed: 5,000 RPM

Calculation of the centrifugal effect due to rotation is activated in the simulation for the calculation of the inertial forces acting on the propeller during FEM testing in Ansys version 2023.

2.6 Loading scenarios

In the loading condition, the calculation is based on the total mass of the entire drone and the load variations. Maintaining the consistency of units in Newton (N), all mass conversion values into force use the gravitational acceleration constant, $G = 9.81$ m/s². Then the loading can be seen as follows:

- a) Base drone load: $3.6 \text{ kg} \times 9.81 \text{ m/s}^2 = 35.316$ N
- b) Additional load of 0.5 kg: $4.1 \text{ kg} \times 9.81 \text{ m/s}^2 = 40.2$ N
- c) Additional load of 0.75 kg: $4.35 \text{ kg} \times 9.81 \text{ m/s}^2 = 42.7$ N

The thrust force in this study is distributed evenly across the blade surface in a direction perpendicular to the plane of rotation. The effect of aerodynamic pressure is balanced and represented as an equivalent statistical load, for the centrifugal force resulting from the rotational motion is calculated directly in this study.

2.7 Solver settings and analyses

The simulation was performed using ANSYS Mechanical Solver, which was configured with the following parameters to solve the results and obtain the research results:

- a) Large deformation: enabled
- b) Solver type: Program Controlled
- c) Convergence criteria: default ANSYS settings

The main output parameters of the research measured include other maximum cooling, mises stress distribution, safety factor, and fatigue life using the stress-life (S-N) method.

2.8 Results analyses

The simulation results are used to determine key areas on the propeller, particularly focusing on the blade base

and blade tip areas. The results of load variations on noise, maximum stress, safety factor, and fatigue life are assessed in detail[21]. Using existing research and the insights gained, design recommendations and operational constraints are suggested to improve the safety and concealment of the propeller during actual flight operations.

3 Results and discussion

This study focuses on examining the structural behaviour of carbon fiber drone propellers under various loading scenarios using the Finite Element Method (FEM). With the choice of parameters including maximum resolution, stress distribution, and safety factor, serving as indicators of the structural integrity of the propeller[22]. Fatigue performance is evaluated by risk and potential factors by considering stress concentration and safety factor values, considering that S–N curve data and the definition of specific load cycles are not included in this study.

3.1 Quantitative Summary of Simulation Results

For a clear comparison of the loading scenarios, the primary simulation results are quantitatively outlined in Table 1.

Table 1. Summary of FEM Results for Different Loading Scenarios

Total Load (kg)	Force (N)	Maximum Deformation (mm)	Critical Location	Minimum Safety Factor
3.6	5.88	14.933	Blade tip	0.51341
4.1	6.6967	17.007	Blade tip	0.45079
4.35	7.105	18.044	Blade tip	0.42489

Calculation and simulation results show that higher applied loads result in higher maximum climates and lower minimum safety factors. In studies and loading scenarios, the propeller blade tip consistently emerged as the achievable critical point.

3.2 Deformation Response of the Propeller

3.2.1 Baseline Load of 3.6 kg

At a base load of 3.6 kg (see Figure 1), the simulation results show a minimum height of 0 mm and a maximum height of 14,933 mm. The propeller area exhibits the lowest point, with the highest point at the blade tip. These results are based on classical structural mechanics theory, which predicts that structures such as cantilevers subjected to distributed loads experience the greatest deflection at the free end. While the propeller design successfully withstands the base load, this repetition has the potential to cause stress concentrations, especially under repeated loading during flight operations.

At a load of 3.6 kg, the simulation shows low-quality areas on the propeller, highlighted in blue, while higher-stress areas appear at the blade tips. The stress distribution indicates that the blade tips are a critical

point likely to experience stress concentrations during drone operation. As the load increases by 0.5 kg, bringing the total to 4.1 kg, the maximum loading increases to 17,007 mm. The stress distribution, particularly at the blade tips, appears to be significant in this study, indicating that the additional load has a significant effect on areas susceptible to fatigue. The simulated contour colors also shift, making high-voltage areas more prominent and indicating potential overvoltage at those points, as depicted in Figure 1.

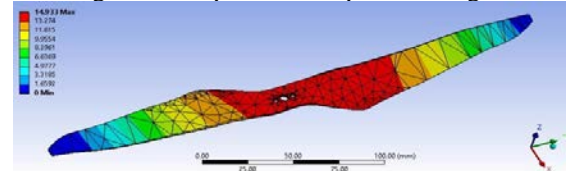


Fig. 1. Deformation of 3.6 kg

Analysis of Figure 1 shows the drone propeller experiencing acceleration under a force of 5.88 N, corresponding to the drone's weight of 3.6 kg. Simulations show that the area of the propeller subjected to this load is marked in blue, indicating a minimal signal at 0 mm. The propeller structure remains largely stable with negligible elongation. The maximum temperature is 14,933 mm, a simulation result of specific points on the propeller experiencing temperatures below the specified force. This highlights the importance of stopping, as repeated stress during the flight cycle can cause material fatigue and stress concentrations[23].

The simulation results were puzzling, and a factor of safety analysis was performed to determine the propeller's resistance to repeated deformation and material failure. Variations in the factor of safety across different regions of the propeller were observed. A critical point was identified at one end, shown in red, with a factor of safety value of 0.51341, indicating an increased likelihood of cracking under repeated loading. The orange areas indicate a safety factor between 1 and 5, indicating moderate risk; the green areas range from 5 to 10; and the blue areas from 10 to 15, indicating areas with relatively higher safety. The distribution of these forces and safety factors is crucial for determining areas susceptible to cracking[23].

This understanding is necessary and crucial for design improvement, as it allows for reinforcement of critical components and adjustment of the propeller geometry to achieve a more even load distribution. Finite element method (FEM) simulations serve as the basis for optimizing propeller design, improving durability, performance, and safety during operation while reducing the risk of material failure due to fatigue, as shown in and illustrated in Figure 2.

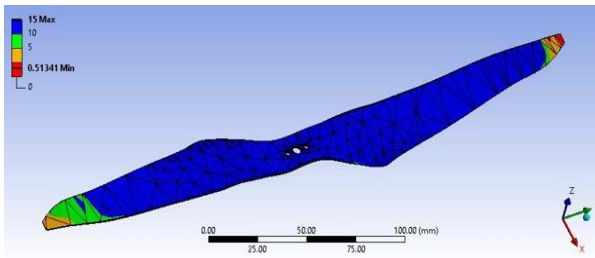


Fig. 2. safety factor

Figure 2 shows the distribution of safety factors across the different drone propeller variations in each segment. The FEM simulation of the colors effectively depicts the safety level at specific points on the propeller. One of the propeller tips is marked in red, indicating the lowest safety factor of 0.51341. This indicates that the area is most vulnerable and has the potential to crack or fail under repeated loads. Such conditions underscore the importance of prioritizing design and material reinforcement at the propeller tip to reduce the risk of damage. The opposite side of the propeller tip is shown in orange, which corresponds to a safety factor range between 1 and 5. While this zone is relatively less critical than the area marked in red, it remains below the ideal safety threshold and still requires observation.

3.3 Additional Load of 0.5 kg

When the total applied load is increased to 4.1 kg, as illustrated in Figure 3, the observed maximum height increases to 17,007 mm, representing an increase of approximately 13.9% compared to the baseline load condition. The resulting propeller structure demonstrates relatively high sensitivity to load variations. The profile remains largely consistent with the baseline scenario, showing resolution primarily at the blade tips. Design consistency for the propeller's geometric configuration is a critical factor influencing the localization of recurrence, as changes in the applied load primarily affect the extent and magnitude of recurrence.

The subsequent analysis includes simulations of a drone propeller subjected to a total load of 4.1 kg, which corresponds to a force of 6.6967 N acting on the carbon fiber material. These simulations highlight the propeller's structural response to this additional load relative to the baseline load condition. A graphical representation of the results illustrates the visible shape changes in the propeller, with the region of minimal resonance depicted in blue[24]. The region experiencing maximum recurrence shows an improvement compared to the simulation under the 3.6 kg load, and safety factor assessment identifies critical stress concentrations at the tip of the wire blade, where the safety factor decreases proportionally with increasing load. identification of potential failure zones, as a basis for conducting a comprehensive design evaluation aimed at ensuring the structural integrity and overall performance of the drone propeller system. See Figure 3 for detailed visualization.

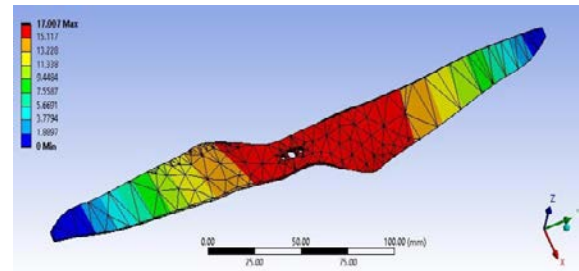


Fig. 3. Deformation 0.5

Figure 3 shows the deformation of a drone propeller under a force of 6.6967 N, corresponding to a total load of 4.1 kg. The simulation results show the propeller section subjected to this loading condition represented by blue shading. The color in the simulation results indicates that the minimum deformation in the propeller is 0 mm, with most regions remaining structurally stable and exhibiting negligible length changes. The maximum deformation reaches 17.007 mm, indicating an increase relative to the simulation with a lower base load of 3.6 kg. The results indicate that points on the propeller deform under the additional force, a phenomenon worthy of concern due to its potential to cause stress concentrations and material fatigue over time.

The simulation provides a factor of safety analysis of the propeller to evaluate areas susceptible to cracking under the loading conditions. While the factor of safety distribution pattern remains comparable in the lower load simulation, the factor of safety values at critical locations have decreased as a consequence of the increased load. This decrease underscores the importance of recognizing critical areas at higher risk of material damage and structural failure due to the overall effect of applied deformation and stress. to provide critical information for design improvements and ensure long-term performance and reliability of the propeller.

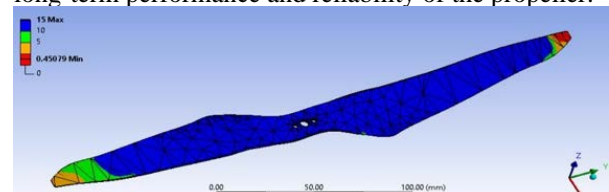


Fig. 4. Safety Factor

Figure 4 shows the distribution of safety factors across the drone propeller, showing significant variation across sections. A red zone appears at one end of the propeller, with the lowest safety factor at 0.45079, the most critical area with a high potential for cracking under repeated loading[25]. This value is the result of a baseline simulation, indicating that an additional 0.5 kg load significantly increases the likelihood of material failure at this point. The propeller, on the other hand, is colored orange, with a safety factor of 2. This area is relatively safer than the critical red zone, but it still warrants consideration because its safety factor remains below the level considered very safe. A green section appears after the orange section, indicating a safety factor of 6, indicating a reasonably high level of reliability under the applied load. The propeller surface is depicted in blue, corresponding to a safety factor of 6,

reflecting excellent structural integrity and minimal risk of failure.

The distribution of safety factors provides valuable insights for propeller design. The output at critical points with low safety factors, and modifying the propeller geometry can help distribute the load more evenly, reducing the risk of fatigue cracking and increasing overall durability.

3.4 Additional Load of 0.75 kg

Under the highest load condition of 4.35 kg (Figure 5), the maximum deformation was 18,044 mm, marking an increase of approximately 20.8% compared to the baseline load. The propeller structure is approaching its elastic performance threshold. While the minimum deformation remains 0 mm in most regions, the consistent increase in maximum deformation highlights the significant bending effects. In practical use, such deformation can impact aerodynamic efficiency and flight stability, particularly under cyclic loading scenarios[26].

The increase in maximum deformation to 18,044 mm indicates that areas of the propeller are subjected to greater stress due to increased forces. Repeated deformation can lead to stress concentrations, potentially triggering fatigue-related damage and reducing material life. Deformation analysis and simulations also revealed the distribution of the propeller's factor of safety. The increased loading conditions resulted in a further decrease in the factor of safety at critical points compared to the previous simulation, increasing the risk of cracking and structural failure at the propeller tip. Although other regions exhibit higher factors of safety, the critical points remain a focus area for design optimization.

This data on deformation and the distribution of the factor of safety provides a solid basis for refining the propeller design. Adjusting geometry and material selection can help address identified vulnerabilities. By analysing stress patterns and critical areas in detail, engineers can improve the propeller's resilience under varying drone operating conditions, enhancing the component's safety, performance, and durability (Figure 5).

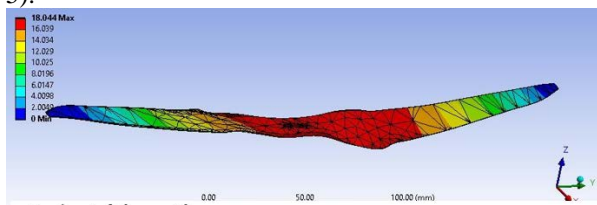


Fig. 5. Deformation 0.75

Figure 5 shows the deformation results of the drone propeller with a force of 7.105 N, equivalent to a total load of 4.35 kg. The simulation results of the entire propeller area under load are represented by the color blue, the minimum deformation value is 0 mm. The blue region is mostly the surface of the propeller, which maintains stability and shows negligible elongation. The maximum deformation is 18,044 mm, indicating an

improvement compared to the results obtained under the previous load conditions[27], [28]. Observations at the points of the propeller experience significant deformation due to the increase in load. Deformation is an important factor to consider, it can cause the formation of stress concentrations and exacerbate fatigue phenomena, potentially reducing the operational life of the propeller. The simulation provides a distribution of safety factors across the propeller, depicted in Figure 6.

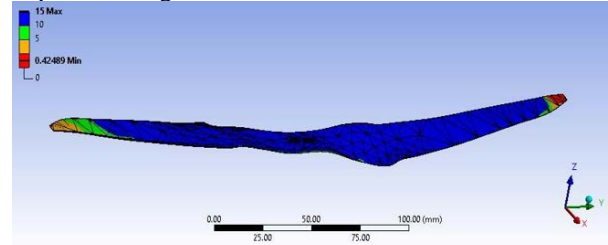


Fig. 6. safety factor deformation force 7.105 N

Figure 6 shows the safety factor represented through color variations across the propeller's various sections. The red section at one end of the propeller indicates the lowest safety factor, measured at 0.42489. This identifies the most critical point, where repeated loading can cause cracking. The opposite end is colored orange, indicating a safety factor of 2, making it relatively safer than the critical red zone. Within the orange area, a green section appears, representing a safety factor of 6, indicating a higher level of stability. The majority of the propeller is depicted in blue, with a safety factor of 10, indicating this region's high resistance to applied loads. This deformation distribution and safety factor are crucial in determining areas susceptible to cracking and improving propeller design. By identifying zones with lower safety factors, this simulation emphasizes how increasing loads affect propeller deformation and operational safety. Finite element method (FEM) analysis is used to ensure the durability, performance, and safety of drones prior to use.

3.5 Safety factor analyses

3.5.1 Safety Factor Distribution at Baseline Load

A basic load of 3.6 kg (Figure 2) calculated the minimum safety factor as 0.51341 at the blade tip. This value is below the static safety threshold ($SF \geq 1$), indicating that the structure can operate in critical conditions if the load is applied repeatedly and experiences dynamic fluctuations. Other areas of the propeller exhibit higher safety factor values, indicating that most of the structure remains relatively safe under these specific loading conditions.

3.5.2 Effect of Load Increase on Safety Factor

With total loads of 4.1 kg and 4.35 kg, the minimum safety factor decreases further to 0.45079 and 0.42489, respectively (Figures 4 and 6). This decrease reflects an inverse relationship between the applied load

and structural safety. This is a result of linear elastic theory, which states that stress increases proportionally with the applied force. Higher loads directly decrease the safety factor, thereby increasing the likelihood of structural failure.

3.5.3 Literature-Based Discussion and Fatigue Implications

Simulation results consistently show the blade tip as the most critical region regarding deformation and safety factors. Previous research on composite blades and drone propellers has shown that stress concentrations primarily occur at the blade tip due to bending moments and load distribution effects, as reported in previous studies [26], [28].

While fatigue is discussed in this study, it is important to clarify that the analysis remains qualitative. Fatigue evaluation is based on three primary considerations:

- a) significant stress concentrations observed at the blade tip,
- b) safety factor values below one, and
- c) the probability of repeated loading during drone operation.

To achieve comprehensive quantitative predictions of fatigue life, future investigations should incorporate material S–N curve data, employ mean stress correction methods such as the Goodman or Gerber approaches, rigorously define load cycles, and employ more realistic boundary conditions and advanced modelling techniques that account for fiber orientation effects. This research goes beyond the scope of the current study and is proposed for further in-depth research.

4 Conclusion

A structural study of a carbon fiber drone propeller under various loading conditions using the Finite Element Method (FEM) was conducted. Numerical results show that changes in load significantly affect the propeller's deformation and safety factor. Increasing the applied load causes a proportional increase in the maximum deformation and a decrease in the minimum safety factor, indicating a narrower structural safety range [26], [29].

The propeller blade tip is the most critical area under various loading conditions. This is indicated by the highest deformation and stress values, which occur due to the dominance of bending forces. The maximum deformation increased from 14.933 mm at a load of 3.6 kg to 18.044 mm at a load of 4.35 kg, indicating that the increased load directly affects the blade's structural response. The minimum safety factor decreased from 0.51341 to 0.42489, indicating that the propeller structure is approaching its critical limit as the working load increases. While this study has provided an initial overview of structural behaviour and potential material fatigue, the analysis is still qualitative. Quantitative fatigue life evaluation is not possible due to data limitations, such as the lack of S–N curves, mean stress

correction models, and specific loading cycle definitions. The results of this study are more appropriately viewed as a static analysis that provides an initial indication of the potential fatigue risk in the propeller structure. For further research development, it is recommended to conduct a more comprehensive fatigue analysis involving more complete material data, including S–N curves and cyclic loading parameters that are representative of actual operating conditions. Further research can also include blade design optimization, the use of alternative materials with better fatigue resistance, and experimental validation to improve the accuracy of the simulation results. It is hoped that a safer, more reliable propeller design with a longer service life will be obtained under various operational conditions.

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