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Design and Structural Performance Evaluation of a Lightweight CFRP-Based UAV Frame Using CAD Modelling and Finite Element Analysis

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Abstract

Unmanned aerial vehicles (UAVs) have gained significant attention in aerospace, industrial, agricultural, surveillance, and defence applications due to their capability to perform complex operations with reduced cost and improved safety. The structural frame of a UAV plays a critical role in determining its strength, stiffness, weight efficiency, and operational reliability. This research presents the design and structural performance evaluation of a lightweight quadrotor UAV frame using computer-aided design (CAD) modelling and finite element analysis (FEA). A three-dimensional parametric CAD model of the UAV frame was developed considering lightweight construction, load transfer capability, and structural reliability. Carbon fibre reinforced polymer (CFRP) was selected as the frame material due to its high strength-to-weight ratio and suitability for aerospace applications. The developed model was analysed under operational loading conditions through static structural, modal, and fatigue evaluations. A mesh convergence study was performed to ensure the accuracy and reliability of the numerical results, and an optimum mesh configuration was selected for subsequent analyses. The structural analysis revealed that maximum stress concentration occurred near the arm-to-central-body connection regions and motor mounting locations due to propulsion load transfer. The initial UAV frame exhibited a maximum von-Mises stress of approximately 276.9 MPa and maximum deformation of 0.807 mm, indicating satisfactory structural performance within the material strength limits. The developed simulation-based methodology provides an effective approach for evaluating lightweight UAV structures and establishing a foundation for further multi-objective optimization involving weight reduction, stiffness improvement, and fatigue performance enhancement.

Keywords: *UAV, Lightweight structure, CFRP, CAD, CAE*

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I. Introduction

Unmanned aerial vehicles (UAVs) have emerged as one of the most rapidly developing technologies in aerospace and mechanical engineering due to their extensive applications in civil, industrial, agricultural, environmental monitoring, surveillance, logistics, and defence sectors. Unlike conventional aircraft, UAVs operate without an onboard human pilot and can perform complex missions with improved accessibility, reduced operational cost, and enhanced safety in hazardous environments. The continuous advancement in sensors, communication systems, control algorithms, battery technologies, and lightweight structural materials has significantly expanded the capabilities of UAV platforms [1], [2].

The structural design of a UAV plays a crucial role in determining its overall performance, stability, endurance, and reliability. The frame structure acts as the primary supporting component that carries essential subsystems such as motors, electronic control units, batteries, landing mechanisms, and payloads. During operation, UAV frames experience various mechanical loading conditions, including static loads due to self-weight and payload, dynamic loads generated by propulsion systems, aerodynamic forces, and cyclic loads caused by repeated flight operations. Therefore, UAV structures must possess adequate strength, stiffness, and fatigue resistance while maintaining minimum possible weight [3].

Lightweight structural design has become one of the most important research areas in UAV development because structural mass directly influences flight duration, payload carrying capability, and energy consumption. A reduction in structural weight allows efficient utilization of available battery power and improves overall mission performance. However, excessive weight reduction without proper mechanical evaluation may result in insufficient stiffness, increased vibration response, and reduced structural durability. Therefore, achieving an optimum balance between weight reduction and mechanical performance remains a significant engineering challenge.

The development of advanced materials such as aluminium alloys, carbon fibre reinforced polymers (CFRPs), and polymer-based composites has provided new opportunities for lightweight UAV design. These materials offer improved specific strength, stiffness-to-weight ratio, and fatigue resistance compared with conventional structural materials. However, effective utilization of these materials requires proper understanding of their mechanical behaviour under different loading conditions [4].

Traditional UAV design approaches based mainly on experimental development require significant time and resources. The advancement of computer-aided design (CAD), computer-aided engineering (CAE), and numerical optimization techniques has enabled engineers to evaluate and improve structural designs through virtual simulation. These approaches allow prediction of stress distribution, deformation behaviour, vibration characteristics, and fatigue life before manufacturing, thereby reducing development cost and improving design reliability [5].

Raymer [6] discussed aircraft conceptual design methodologies and highlighted that structural weight reduction is a fundamental requirement for improving aerospace performance. The study emphasized that efficient structural design requires simultaneous consideration of material selection, geometry, manufacturing constraints, and operational requirements. Although UAVs are smaller than conventional aircraft, similar design principles are applicable because structural efficiency strongly affects their performance.

The increasing complexity of UAV applications has resulted in the development of advanced design methodologies based on simulation-driven optimization. Hassanalian and Abdelkefi [7] reviewed UAV classifications, applications, and design challenges and reported that structural optimization is one of the key factors influencing UAV efficiency and reliability. The authors highlighted that future UAV development requires integration of mechanical design, materials engineering, and computational optimization approaches.

1.1 Lightweight Structural Design of UAV Frames

The UAV frame is the primary load-bearing structure responsible for maintaining the relative position of different components and transferring operational loads throughout the system. The frame must provide sufficient structural rigidity to maintain dimensional stability while resisting external forces generated during flight. Since UAVs generally operate under limited energy resources, reducing structural weight has become a critical design objective.

Lightweight structural design involves minimizing material usage while maintaining required mechanical performance. The strength-to-weight ratio is considered one of the most important parameters in aerospace structural applications because it determines the ability of a structure to withstand applied loads relative to its mass. A lightweight UAV frame with improved specific strength can provide longer flight duration, increased payload capacity, and improved manoeuvrability.

The design of UAV structures involves several competing requirements. Increasing structural thickness may improve strength and stiffness but results in additional weight. Similarly, reducing material thickness may decrease mass but can increase deformation and fatigue susceptibility. Therefore, optimization-based design approaches are required to achieve a balanced solution between structural performance and weight reduction.

Filippone [8] investigated advanced aircraft performance characteristics and reported that lightweight structural design significantly contributes to improved aerospace efficiency. The study emphasized that structural optimization should consider both mechanical performance and operational requirements.

Jackson [9] studied lightweight structural concepts for small aerospace systems and reported that efficient structural design requires optimization of geometry, material distribution, and load transfer mechanisms. The study highlighted that improper structural design may lead to stress concentration regions and premature failure.

UAV frames are subjected to multiple loading conditions during operation. Static loads originate from the weight of onboard components and payload, while dynamic loads are generated by rotating motors, propellers, and aerodynamic disturbances. Additionally, repeated flight cycles introduce cyclic loading, which may result in fatigue damage over extended periods. Therefore, a reliable UAV frame design requires evaluation under static, dynamic, and fatigue loading conditions.

The development of lightweight structures has also been influenced by advanced manufacturing techniques. Additive manufacturing and composite manufacturing methods provide opportunities for producing complex geometries with reduced material consumption. However, these approaches require detailed numerical analysis because manufacturing defects, anisotropic behaviour, and material uncertainties may affect structural performance.

Khosravani and Reinicke [10] investigated composite materials for aerospace applications and reported that advanced materials provide significant benefits in reducing structural weight. However, the authors emphasized that proper structural analysis is necessary to ensure reliability under real operating conditions.

Modern UAV structural design therefore requires an integrated methodology involving CAD modelling, finite element analysis, and optimization techniques. Such approaches enable designers to evaluate multiple design alternatives and identify optimum configurations without extensive experimental trials.

II. Literature Review

The UAV frame acts as the primary structural component that supports various subsystems, including motors, batteries, electronic control units, sensors, landing systems, and payload components. During operation, the frame experiences different types of mechanical loading conditions, including static loads due to component weight, dynamic loads caused by propulsion systems, aerodynamic forces, and cyclic loads generated during repeated flight operations. Therefore, UAV frame design requires an optimum balance between lightweight characteristics, structural strength, stiffness, vibration resistance, and fatigue durability.

Traditional UAV development approaches relied heavily on experimental fabrication and physical testing. Although experimental methods provide accurate performance evaluation, they require significant time, resources, and manufacturing efforts. The advancement of computational techniques such as computer-aided design (CAD), computer-aided engineering (CAE), finite element analysis (FEA), and optimization algorithms has enabled researchers to develop simulation-based design methodologies. These approaches allow evaluation of structural performance before manufacturing and provide opportunities for improving design efficiency.

Raymer [11] investigated aircraft conceptual design methodologies and highlighted that structural weight reduction is one of the most important considerations in aerospace engineering. The study reported that lightweight structural designs improve fuel efficiency, payload capability, and overall aircraft performance. Although UAVs operate at a smaller scale compared with conventional aircraft, similar design principles are applicable because structural efficiency directly influences flight performance.

Hassanalian and Abdelkefi [12] presented a comprehensive review of UAV classifications, applications, and design challenges. The authors discussed different UAV configurations and highlighted that structural design, propulsion efficiency, and weight optimization are critical factors affecting UAV performance. The study emphasized that future UAV development requires integrated approaches combining mechanical design, materials engineering, and computational optimization.

Chao et al. [13] investigated autonomous UAV systems and reported that mechanical reliability is essential for achieving stable flight performance. The authors highlighted that structural stiffness and vibration characteristics directly influence flight control accuracy and operational stability. The study suggested that numerical analysis methods should be incorporated during the design stage to evaluate structural behaviour under realistic operating conditions.

Gupta et al. [14] investigated simulation-based design optimization techniques for lightweight aerospace structures and reported that computational approaches reduce development time and improve structural performance. The authors demonstrated that combining numerical analysis with optimization algorithms allows designers to evaluate multiple design alternatives and select improved structural configurations.

The increasing complexity of UAV applications has resulted in the requirement for advanced structural design methodologies. Modern UAV frames must not only withstand operational loads but also provide adequate dynamic stability and fatigue resistance. Therefore, integrated approaches involving CAD modelling, CAE simulation, and multi-objective optimization have become essential for achieving high-performance UAV structures.

Lightweight material development has also contributed significantly to UAV advancement. Materials with high specific strength, high stiffness-to-weight ratio, and improved fatigue resistance enable designers to reduce structural mass while maintaining mechanical reliability. Aluminium alloys, carbon fibre reinforced polymers (CFRPs), and advanced polymer materials are widely investigated for UAV frame applications.

Campbell [15] studied advanced composite manufacturing processes and reported that composite materials provide significant advantages in aerospace structures due to their superior mechanical properties and lightweight characteristics. The study highlighted that composite materials allow designers to achieve improved structural efficiency through optimized fibre orientation and laminate configuration.

Soutis [16] investigated fibre-reinforced composite materials used in aerospace applications and reported that carbon fibre reinforced polymer composites provide excellent strength-to-weight ratio and fatigue performance. However, the author emphasized that composite structures require advanced numerical methods because their anisotropic behaviour and damage mechanisms are more complex compared with metallic materials.

Davis [17] investigated aluminium alloys and reported that materials such as Al 6061 and Al 7075 provide favourable combinations of strength, density, corrosion resistance, and manufacturability. These characteristics make aluminium alloys suitable for UAV structural applications where moderate cost and reliable mechanical performance are required.

Mouritz [18] studied aerospace materials and explained that structural performance depends not only on material properties but also on manufacturing techniques, geometry, and loading conditions. The study emphasized that modern lightweight design requires an integrated approach considering materials, design parameters, and operational requirements.

Ngo et al. [19] reviewed additive manufacturing technologies and reported that advanced manufacturing techniques provide opportunities for producing lightweight structures with complex geometries. The authors highlighted that additive manufacturing enables rapid prototyping and design flexibility; however, mechanical limitations of polymer-based materials must be considered during structural applications.

Therefore, the existing literature indicates that UAV structural development requires a combined approach involving lightweight material selection, optimized geometry, numerical simulation, and performance evaluation. The following sections discuss previous research related to lightweight UAV structures, CAD/CAE-based analysis, fatigue behaviour, and optimization techniques.

III. Methodology

The UAV frame considered in the present study is based on a quadrotor configuration because of its simple structural arrangement, high stability, and extensive application in small and medium-sized UAV systems. The frame acts as the primary supporting structure and provides attachment locations for motors, electronic components, battery systems, and payload modules.

The structural design of the UAV frame was developed considering the requirements of lightweight construction, adequate stiffness, and mechanical reliability. The frame consists of a central body section connected with four supporting arms, where the propulsion motors are mounted at the outer ends. The central body provides support for the battery and electronic components, while the arms transfer the thrust forces generated by the motors to the main structural body.

During UAV operation, the frame experiences different mechanical loads due to gravitational forces, payload weight, motor thrust, and flight-induced vibrations. Therefore, the structural design must provide sufficient load-carrying capability while maintaining minimum mass. The geometric configuration was selected considering the requirement of uniform load distribution and reduction of stress concentration regions.

The important design considerations for the UAV frame include structural integrity, minimum material usage, ease of manufacturing, and compatibility with numerical optimization. The developed model allows modification of important geometric parameters during the optimization process, enabling evaluation of different structural configurations.

3.1 CAD Modelling Procedure

The three-dimensional CAD model of the UAV frame was developed using a parametric modelling approach. The use of parametric modelling allows modification of design parameters without recreating the complete geometry, which is essential for optimization-based design development. The model was created by defining the major structural dimensions and functional requirements of the UAV frame shown in figure 3.1.

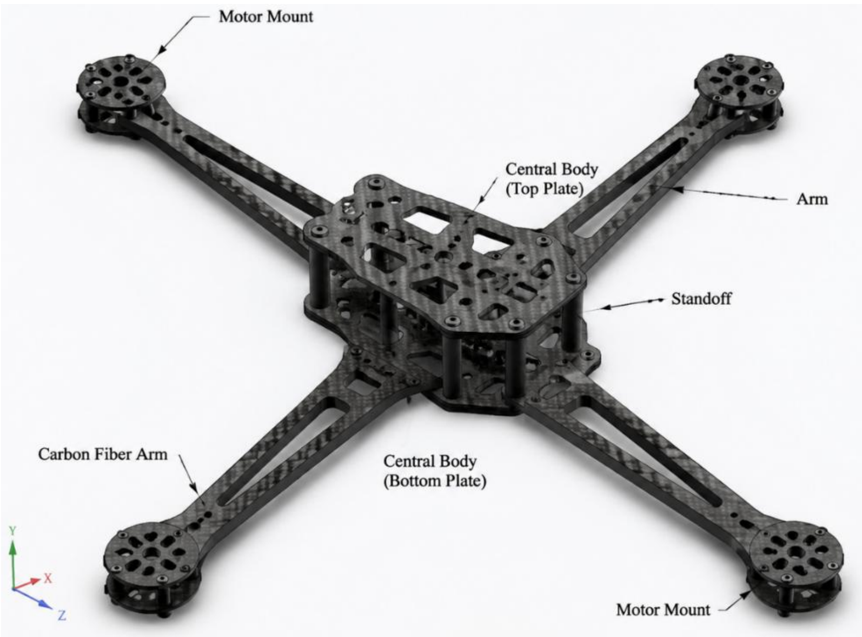

Figure 1: CAD model of the initial lightweight UAV frame

The CAD development process involved the creation of the central frame structure, supporting arms, motor mounting regions, and connecting features. The geometry was developed considering the structural requirements and expected load transfer behaviour during operation. The final assembly model represents the complete UAV frame configuration and provides accurate geometric information for finite element analysis.

The major geometric parameters considered during modelling include frame dimensions, arm length, arm width, structural thickness, and motor mounting dimensions. These parameters influence the overall stiffness, mass distribution, and stress response of the structure. Therefore, they were considered important design variables during the optimization process.

The developed CAD model was verified for geometric accuracy before being transferred to the CAE environment. The model provides a realistic representation of the UAV frame and enables detailed investigation of structural behaviour under different loading conditions.

3.2. Material Selection

Material selection is a critical aspect of UAV frame design because the selected material directly influences structural weight, stiffness, strength, and fatigue performance. The ideal material for UAV applications should possess high specific strength, adequate stiffness, low density, good fatigue resistance, and compatibility with available manufacturing processes.

In the present study, carbon fibre reinforced polymer (CFRP) has been considered as the structural material for the UAV frame due to its excellent mechanical properties and widespread application in lightweight aerospace structures. CFRP materials provide superior strength-to-weight ratio compared with conventional metallic materials and are capable of achieving significant weight reduction while maintaining structural performance.

The mechanical properties required for numerical simulation include density, Young's modulus, Poisson's ratio, tensile strength, yield strength, and fatigue properties. These properties were assigned in the CAE environment to accurately predict structural, modal, and fatigue behaviour.

The selection of CFRP enables investigation of lightweight structural performance and provides a suitable basis for multi-objective optimization. The material properties used for numerical simulation are presented in Table 1.

Table 1: Mechanical properties of selected UAV frame material

Material Property	Value
Density	1600 kg/m³
Young's modulus	70 GPa
Poisson's ratio	0.30
Tensile strength	600 MPa
Yield strength	450 MPa
Fatigue strength	250 MPa

IV. Results and Discussion

4.1 Finite Element Model Validation and Mesh Convergence Analysis

The accuracy and reliability of finite element analysis largely depend on the quality of the numerical model, particularly the mesh density used for discretization of the structure. An inappropriate mesh size may lead to inaccurate prediction of stress distribution and deformation behaviour, whereas an excessively refined mesh increases computational time without significant improvement in solution accuracy. Therefore, a mesh convergence study was performed before conducting detailed structural, modal, and fatigue analyses to determine an appropriate mesh density for the UAV frame model.

The developed CAD model was discretized using three-dimensional tetrahedral elements because of the complex geometry of the UAV frame consisting of thin arms, central mounting plates, and motor support regions.

The mesh was refined in critical areas such as arm-to-body connections and motor mounting locations, where higher stress gradients were expected due to load transfer and geometric discontinuities.

The mesh convergence analysis was carried out by gradually reducing the element size and evaluating the variation in important response parameters, including maximum equivalent von-Mises stress and total deformation. Four different mesh densities were considered to determine the influence of element size on the numerical results. The analysis was performed under identical loading and boundary conditions for all mesh configurations.

The initial coarse mesh with an element size of 5 mm resulted in comparatively higher variation in stress prediction due to insufficient representation of local stress gradients. As the mesh density was increased, the predicted stress and deformation values showed gradual stabilization. Further refinement beyond the selected optimum mesh size resulted in negligible variation in the obtained results, indicating that the solution had reached mesh-independent behaviour.

The variation of maximum stress and deformation with respect to different mesh densities is presented in Figure 2**.** The results indicate that the maximum variation between the final two mesh configurations was within an acceptable range, confirming that further mesh refinement would not provide significant improvement in numerical accuracy.

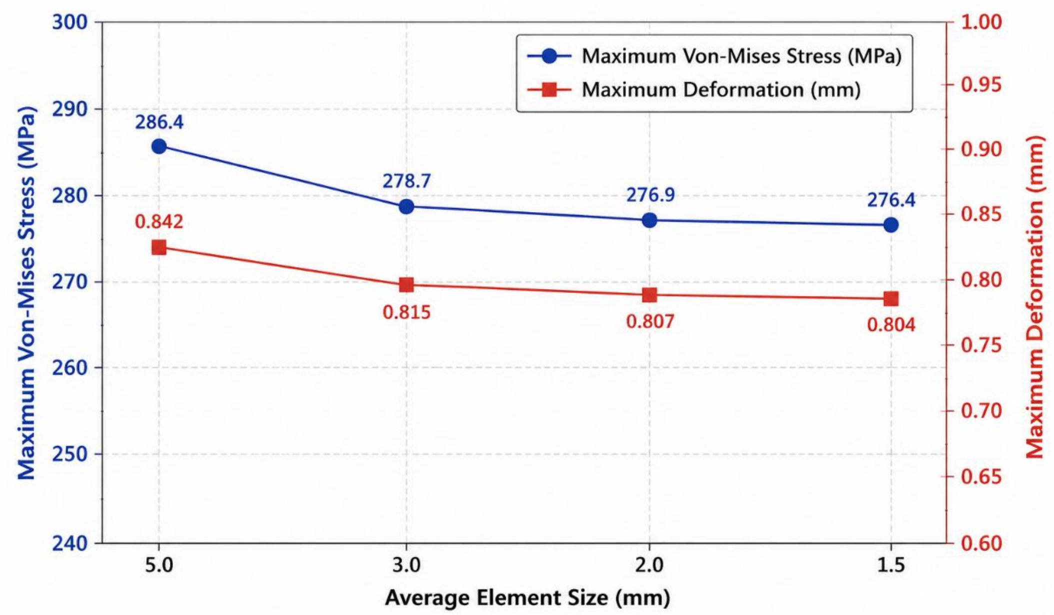

Figure 2: Mesh convergence analysis of UAV frame showing variation of maximum stress and deformation with element size

The quantitative results obtained from different mesh configurations are presented in Table 2**.** The mesh with an average element size of 2 mm was selected for subsequent analyses because it provided an appropriate balance between computational efficiency and accuracy. This mesh configuration consisted of approximately 85,420 elements and 142,680 nodes, providing sufficient resolution for capturing structural behaviour while maintaining reasonable computational requirements.

Table 2: Mesh convergence results for different mesh densities

Mesh Size (mm)	Number of Elements	Number of Nodes	Maximum Stress (MPa)	Maximum Deformation (mm)
5.0	28650	48920	286.4	0.842
3.0	56380	94750	278.7	0.815
2.0	85420	142680	276.9	0.807
1.5	128760	214350	276.4	0.804

The mesh convergence results demonstrate that refinement from 5 mm to 2 mm significantly improved the stability of the predicted structural response. However, further refinement from 2 mm to 1.5 mm resulted in only minor changes in stress and deformation values, with less than 1% variation. Therefore, the 2 mm mesh configuration was considered sufficiently accurate and was adopted for all subsequent structural, modal, and fatigue simulations. The validated finite element model provided a reliable foundation for further performance evaluation of the UAV frame. The selected mesh ensured accurate prediction of stress distribution, deformation behaviour, vibration characteristics, and fatigue response while maintaining computational efficiency. The structural, modal, and fatigue analysis results obtained using this validated model are discussed in the following sections.

4.2 Structural, Modal and Fatigue Analysis Results

The mechanical performance of the developed UAV frame was evaluated through integrated structural, modal, and fatigue analyses using the validated finite element model. These analyses were performed to understand the load-bearing capability, dynamic response, and durability characteristics of the initial UAV frame configuration. Since UAV structures are subjected to combined static, dynamic, and cyclic loading conditions during operation, simultaneous evaluation of these parameters is necessary for developing a reliable lightweight structure.

The structural analysis was initially performed to evaluate the stress distribution and deformation behaviour under the applied operational loads. The results obtained from static structural analysis were further used as the basis for modal and fatigue evaluation. Modal analysis was carried out to determine the natural frequencies and corresponding mode shapes of the frame, while fatigue analysis was performed to estimate the service life under repeated loading conditions.

The combined results obtained from these analyses provide a comprehensive understanding of the structural limitations of the initial UAV frame and help identify the areas requiring improvement during the optimization process.

4.3 Static Structural Analysis Results

Static structural analysis was performed to evaluate the response of the UAV frame under operational loading conditions. The applied loads represent the combined effect of structural weight, payload, and propulsion forces acting on the frame during flight operation. The analysis was conducted using the optimized mesh configuration obtained from the mesh convergence study.

The structural response was evaluated in terms of equivalent von-Mises stress and total deformation. The von-Mises stress distribution provides information regarding the regions experiencing maximum mechanical loading and helps determine the possibility of material yielding. The deformation distribution indicates the stiffness behaviour of the structure and provides information regarding the dimensional stability of the frame.

The equivalent von-Mises stress distribution obtained from the analysis is shown in Figure 3**.** The results indicate that the maximum stress occurs near the arm-to-central-body connection regions and motor mounting locations. These regions experience higher stress concentration because they transfer the propulsion forces generated by the motors to the main structural body. In contrast, the central plate region exhibits comparatively lower stress levels due to better load distribution.

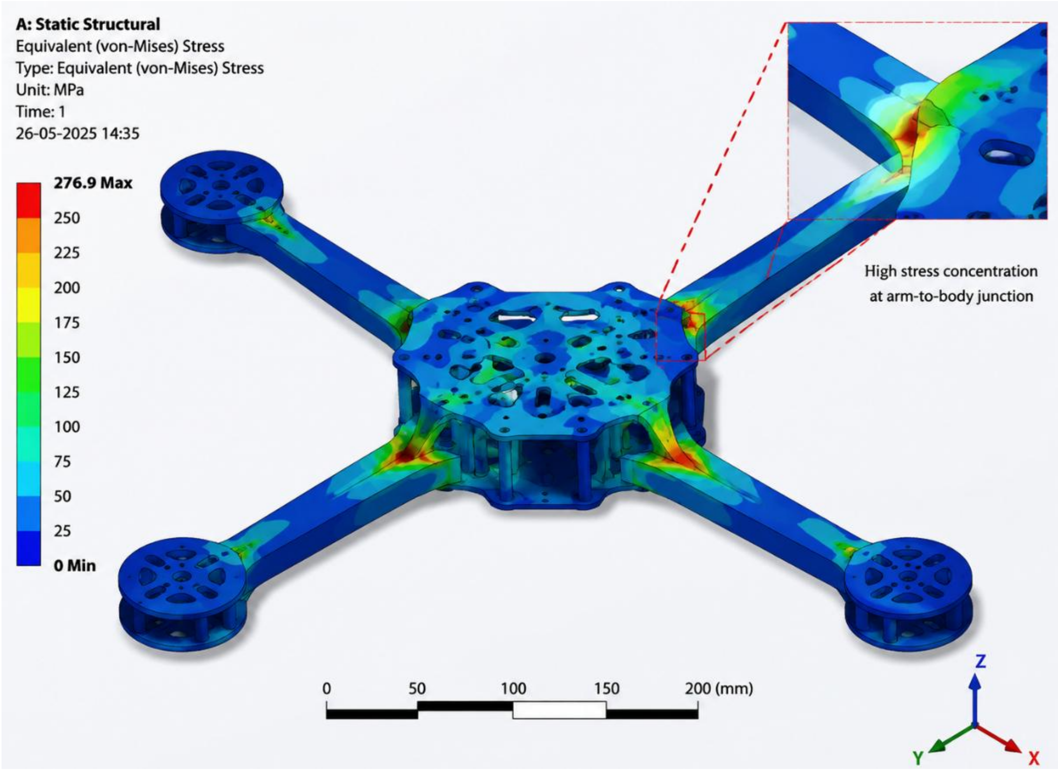

Figure 3: Equivalent von-Mises stress distribution of initial UAV frame under operational loading

The maximum equivalent stress obtained for the initial UAV frame was found to be approximately 276.9 MPa, which remains below the allowable tensile strength of the selected CFRP material. This indicates that the initial design possesses adequate structural strength under the applied loading conditions. However, the concentration of stress near the arm junction regions suggests that these locations are critical and require consideration during the optimization process.

The total deformation distribution of the UAV frame is presented in Figure 4. The maximum deformation was observed at the outer ends of the UAV arms near the motor mounting locations. This behaviour occurs because the arms act as cantilever-like structures subjected to motor-generated forces. The central region exhibits minimum deformation due to higher structural stiffness.

Figure 4: Total deformation distribution of initial UAV frame

The maximum deformation obtained from the analysis was approximately 0.807 mm**,** indicating that the structural displacement is within an acceptable range and does not significantly affect the functionality of mounted components. However, reduction in deformation remains an important optimization objective because improved stiffness contributes to better vibration resistance and operational stability.

The structural analysis results demonstrate that the initial UAV frame satisfies the basic strength requirements; however, improvement is possible through modification of geometric parameters. The identified stress concentration regions and deformation behaviour provide important guidelines for the subsequent multi-objective optimization process.

V. Conclusion

The present study investigated the design and structural performance evaluation of a lightweight UAV frame using CAD modelling and finite element analysis. A parametric three-dimensional CAD model of a quadrotor UAV frame was developed by considering the requirements of minimum weight, adequate stiffness, and structural reliability. Carbon fibre reinforced polymer (CFRP) was selected as the structural material due to its superior specific strength and suitability for lightweight aerospace applications.

A validated finite element model was developed through mesh convergence analysis to ensure accurate prediction of structural behaviour. The results demonstrated that a mesh size of 2 mm provided an appropriate balance between computational efficiency and numerical accuracy, with negligible variation observed after further refinement. The validated model was subsequently used for structural evaluation under operational loading conditions.

The static structural analysis showed that the maximum stress concentration occurred near the arm-to-central-body junction and motor mounting regions because these areas experience significant load transfer from propulsion forces. The maximum equivalent von-Mises stress was obtained as approximately 276.9 MPa, while the maximum deformation was found to be approximately 0.807 mm. These values remained within the allowable mechanical limits of the selected CFRP material, indicating that the developed UAV frame possesses sufficient structural strength and stiffness for operational applications. The study demonstrates that CAD-based modelling combined with finite element simulation provides an effective methodology for analysing and improving lightweight UAV structures before physical manufacturing. The identified critical stress regions provide important design guidelines for future improvements. Further work can focus on multi-objective optimization of geometric parameters, weight reduction, vibration suppression, and fatigue life enhancement to achieve improved UAV performance and durability.

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