

# Design and Comparative Finite Element Analysis of Aluminium and Carbon Fibre Drone Chassis

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**Abstract:** Stiffness, strength, and vibration properties are the result of the design of multirotor UAVs' structures and thus of their flight efficiency. This is of particular importance for precision agriculture applications, where it is desirable to have very lightweight airframes that are also sufficiently stiff and damage-tolerant to counteract thrust loads and operational noise. In this work, we design and analyse a modular four-arm quadcopter frame using finite elements. A 3D frame model is developed and statically analysed in ANSYS 2025 R/2 for two different materials, namely the aluminum alloy and the carbon-fibre-reinforced polymer (CFRP). A typical hover load case (12.5 N per arm thrust, including the effect of self-weight) is also addressed under the same geometry and boundary conditions. The maximum stress concentration for both configurations is observed at the central hub. The deformation of the aluminum frame reaches a maximal value of 1.28 mm and the maximum von Mises stress is over 55 MPa, leading to a safety factor higher than four. In comparison, the CFRP frame exhibits a pair of much smaller deformations of 0.32 mm, which is around 75% improvement in stiffness with a similar stress value (~54.6 MPa). These results validate the excellent stiffness-to-mass performance of CFRP, while aluminium should still be considered as a competitive and cheaper alternative for soft manufacturing conditions.

**Keywords:** Quadrotor chassis, Finite element analysis, Modular UAV design.

## 1. Introduction and Background

Unmanned aerial vehicles (UAVs) have garnered widespread interest in civil, industrial, and scientific applications due to their flexibility, fast deployment and wide range of applicability under harsh environments. Out of the multirotor configurations, the quadcopter stands out for vertical take-off and landing, mechanical simplicity and high manoeuvring capability [1]. These capabilities enable applications such as precision agriculture, infrastructure inspection and surveillance, etc. The overall design of such UAVs, including the body frame, is crucial to improving the overall integrity, stability and performance of a system and requires careful material selection and structural optimisation in order to reduce stress induction, deformation generation and operational lifespan [2-3]. Finite element analysis (FEA) has become an essential tool in developing load-bearing structures in this process, allowing engineers to simulate the response of drone frames to loads and loading conditions, thereby optimising their designs for performance and strength [4]. Accordingly, this work seeks to add to this knowledge by offering a comparison of the finite element analysis results between Aluminium alloy and carbon-fibre-reinforced polymer (CFRP) as materials used in quad-copter frames so that engineers can have a better understanding of the structural performance of these materials to make an optimal choice of material for different applications [5].

The major load-carrying member of a quadrotor is the structural frame that carries the propulsion, avionics, batteries, payload, and landing gear, as well as makes the arm-to-arm symmetric transmission of thrust and external loads. The frame is subjected to the forces generated from inertial, gravitational, aerodynamic and landing processes simultaneously, and its structural performance directly affects the payload ability, flight endurance time, vibration responding property and mission safety. Insufficient load transfer and less than ideal geometric design patterns have resulted in break-inducing stress concentrations at critical areas such as arm-to-hub connections and motor mounts, where crashes often occur in multirotor-UAVs [6].

The mass-stiffness trade-off is among the key problems in designing a quadcopter frame. Reduced weight yields better thrust/weight ratio and energy efficiency, while low stiffness leads to increased deformations, degradation of the natural frequencies, and lack of control due structural flexibility coupling with flight dynamics. The majority of quadrotor UAVs adopt for its symmetry and uniform thrust allocation a X-configuration with four arms spaced 90° apart for its symmetry and uniform thrust allocation [7]. Main structural design parameters are: motor-to-motor distance, arm length, cross-sectional shape and area, and hub dimensions. The motor-to-motor distances of the 4–5-inch propeller drones range between 210 and 280 mm, so as to trade off the space for the propeller to rotate and airframe stiffness. Recent optimisation works showed that advanced arm shapes, such as tapered or aerofoil inspired, can enable reductions in structural mass of 15-25% while also reducing stress concentration and moving natural frequency away from the main excitation band [8].

Selection of material is a decisive factor for mechanical performance, mass efficiency and vibration response. Aluminium alloys such as 6061-T6 and 7075-T73, are extensively employed owing to their isotropic behaviour, corrosion resistance, the ease of machinability and cost effectiveness. To overcome these limitations, CFRP composites are increasingly used in high-performance UAVs. In particular, thermosetting carbon fibre composite reinforced with epoxy) CFRP has an extraordinarily high specific stiffness and strength (fibre-direction elastic modulus of 120–300 GPa) at very low density (~1600 kg/m<sup>3</sup>) [9]. Yet, even with the complications of anisotropy and cost barriers, etc., CFRP still offers large gains from the viewpoint of stiffness to weight ratios, and vibration characteristics. Alternative materials, such as glass-fibre-based polymers and additively manufactured polymers, deliver inexpensive or speed prototyping but somewhat lower stiffness and strength.

The finite element analysis (FEA) has emerged as a widely used tool in preliminary development of the quadcopter frame design. Static structural analysis of combined thrust and gravity loading is performed to identify deformation, stress distribution, and factor of safety for critical areas before fabrication. The modal analysis also supports the vibration assessment by predicting natural frequencies and mode shapes, which are used to estimate resonance risks due to rotor-induced excitations [10].

It has been reported that the mass saving of CFRP frames was 30-40% from aluminium with similar or even better stiffness and vibration behaviour. In this respect, the current paper presents a comparison of FEA for aluminium and CFRP quadcopter frames having the same geometry and boundary conditions. The deformation, stress fields, stiffness, and vibration properties are tested by static structural and modal analysis [10]. The study is restricted to linear elastic material response during hover and free vibration, neglecting aerodynamic and control system effects, in order to provide a pure structural and materials perspective for the purpose of early-stage UAV design.

## 2. DESIGN AND METHODOLOGY

### 2.1 Chassis Geometry, Configuration, and Mass Definition

The structure of the quadrotor is based upon a central hub, 4 curved arms with motor mountings and landing gear struts, and with interfaces for avionics, battery and payload. A parametric 3D CAD model was created based on typical multirotor design practices with uniform arm lengths, hub symmetry and sufficient propeller clearances for a similar size of the avionics. A symmetrical X-configuration was chosen to obtain symmetry thrust allocations and steady flight dynamics for micro-UAV precision agriculture tasks.

Stiffness, payload clearances and mass design constraints were used to guide the shape of the arm and hub thickness through a series of refinements to make it manufacturable. The structural philosophy is based on a composite main frame with aluminum fittings and motor mounts, using local polymers for non-compact brackets [11]. 10-inch BLDC motors, mounted at the arm-ends with appropriate radial and axial distance to minimise aerodynamic interactions and ground-effect losses.

Sr No	Name of Component	Estimated Weight (Gm.)	No of Items	Approximate Weight (Gm)
1	Chassis	390	01	390
2	Battery	380*	01	380
3	Motor	110*	04	440

4	Propeller	14*	04	56
5	Flight Controller	165*	01	165
6	ESC	24*	04	96
7	Payload/Sensor	439*	01	439
Total Approximate Weight		1966		

\* Weight of standard components available in the market

**Table 1: total take-off mass (maximum take-off weight, MTOW) is determined by summing the contributions of all structural and functional components**

The payload includes an AI vision system for self-heading navigation, and there is an OAK-D camera mounted under the centre plate. The camera system also adds about 439 g to the payload mass. The maximum allowable take-off mass (MTOW) of the MAV, which is taken as Eq.5 data listed in Table 1, is 1966g.

## 2.2 Propulsion System and Thrust Requirement

The propulsion system includes four similar BLDC motors with 10-inch propellers. A T/W of 2.5 is chosen for sufficient manoeuvrability; the total thrust required is  $\approx 48.2$  N

$T_{total} = 2.5W \approx 2.5 \times 1.966 \text{ kg} \times 9.81 \text{ m/s}^2 \approx 48.2 \text{ N}$  This is equivalent to a hover scrolling thrust of 12.5 N per arm, which agrees well with the 800 kV class motor used in conjunction with 10" propellers. The flight controller is the Pixhawk 2.4.8, and each motor is powered by a 30 A ESC. Using a lithium polymer battery of 5000 mAh capacity, which has a total battery mass of approximately 380 g.

## 2.3 Material Properties

Two frame materials are considered: aluminum alloy 6061-T6 and CFRP. The aluminium is modelled with isotropic and linear elastic material, whereas the CFRP is modelled with an orthotropic, linearly elastic laminate having principal lay-ups along the axes of the arms. The material properties are summarised in Table 2.

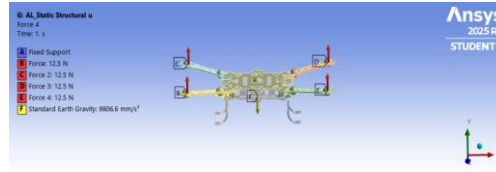
Material Properties	Aluminium alloy	Carbon-fibre-reinforced polymer
Density	2700 kg/m <sup>3</sup>	1500 kg/m <sup>3</sup>
Young's modulus	69 GPa	290 GPa
Poisson's ratio	0.33	0.33
Yield strength	275 MPa	600 Mpa
Material model	Linear elastic, isotropic	linear elastic, orthotropic

**Table 2: Material properties of Aluminium and carbon fibre reinforced polymer**

The aluminum and CFRP frame mass extracted from a CAD model are about 913 g and 554 g, respectively, resulting in substantial weight savings compared to keeping high directional stiffness [10].

## 2.4 Loading and Boundary Conditions

For this hover condition, static structural analysis was performed, which is analogous to the initial design point of multirotor UAV frame. Four upward 12.5 N forces were acting on motor mounts together with the gravity acceleration  $g = 9806.6 \text{ mm/s}^2$ . That operated the whole chassis volume. The applied loading and boundary conditions are shown in Figure 1.



**Fig.1: Static Structural Loading and Boundary Conditions Applied to the Quadcopter Chassis**

The chassis was modelled with 10-node quadratic tetrahedral elements. A universal element size of approximately 2.5 mm was employed with local refinement to 1.0 mm in high stress gradient areas. The final finite element model has approximately 35,000 elements equally for aluminium and CFRP, with good enough accuracy at little computational cost.

### 2.6 Analysis Type and Solution Procedure

Linear static structural analysis was performed in ANSYS Mechanical 2025 R2. A linear elastic material response and geometric non-linearity were considered, being reasonable for hover level loading. The continuum model may be formulated by the following homogeneous equilibrium equation.

$$[K]\{u\} = \{F\}$$

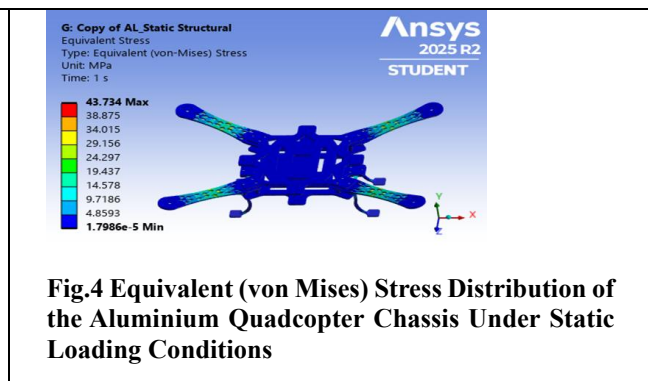
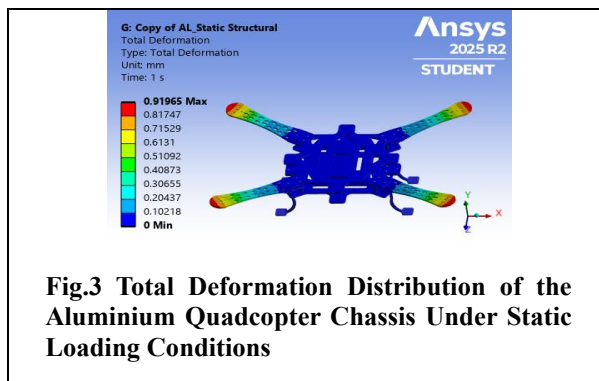
where  $[K]$  is the global stiffness matrix,  $\{u\}$  is the nodal displacement vector, and  $\{F\}$  represents the applied load vector [2]. The ANSYS direct sparse solver, PARDISO, was used with default settings of convergence. Output measures were total deformation, von Mises stress and principal stresses, with standard solution times of 2–3 min per geometry.

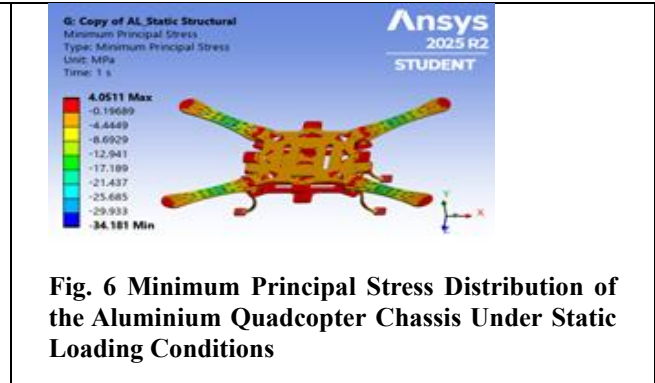
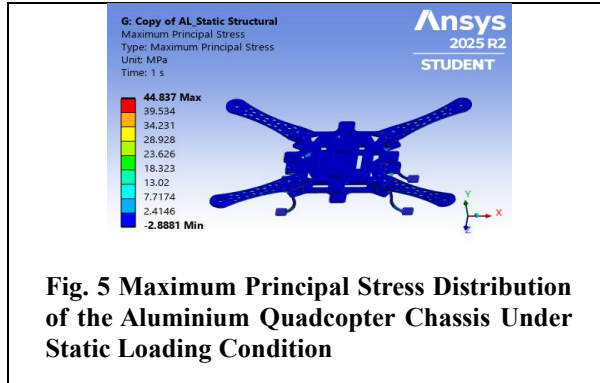
## 3. RESULTS AND DISCUSSION

### 3.1 Static Analysis Results for Aluminium Chassis

#### 3.1.1 Total Deformation

The overall deformation represents the general stiffness of the aluminium frame of the quadcopter. As shown in Fig. 3, the largest deformation is 0.91965 mm at the point of the free ends of arms of the XMBs, and hardly any deformation on the central hub. This is typical of cantilever-type loading in the presence of thrust forces. The deformation is small compared to the arm length, meaning the mechanical stiffness of each arm will be high enough for stable hover and low risk of misalignment of motors or high transmission vibration. Similar values of deformation have been reported for aluminium UAV frames in the literature [10].





### 3.1.2 Equivalent (von Mises) Stress

The static loading resulting from Mises stress distribution is presented in Fig. 4. The maximum stress of 43.734 MPa appears primarily at the arm–hub joints, near motor mounting locations and sudden changes in geometry as a result of bending moment on gyroscopic thrusting due to loading. This value is well below the yield strength of aluminium ( $\approx 250$  MPa) and therefore represents a great safety margin and an elastic structural regime. Comparable stress trends were reported in previous FEA studies of aluminium UAV designs [12].

### 3.1.3 Principal Stress Analysis

The highest principal tensile stress reaches 44.887 MPa, mainly at the top surface of the arms near the hub, as shown in Fig. 5. The lowest principal compressive stress is  $-34.181$  MPa and appears on the lower arm surfaces and central hub area (Fig. 6). Both tensile and compressive stresses are well below the strength limits of aluminum, so there is little risk of crack initiation, buckling, or compression instability under static hover loading [13].

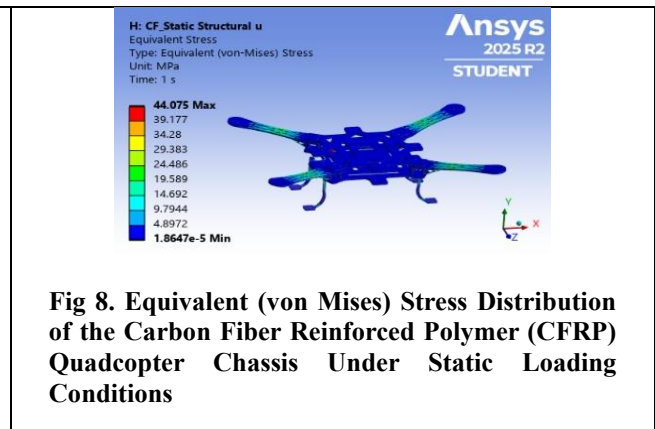
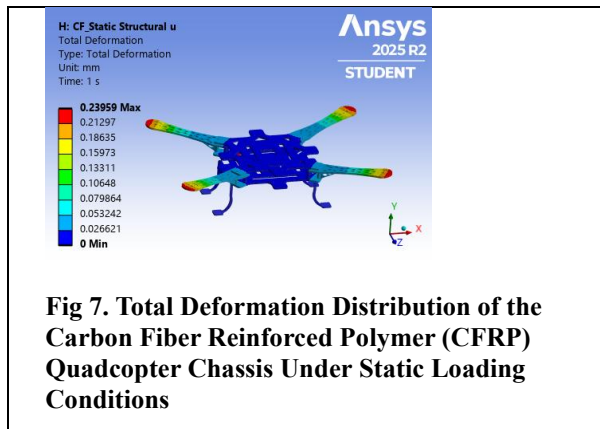
### 3.1.4 Factor of Safety and Failure Assessment

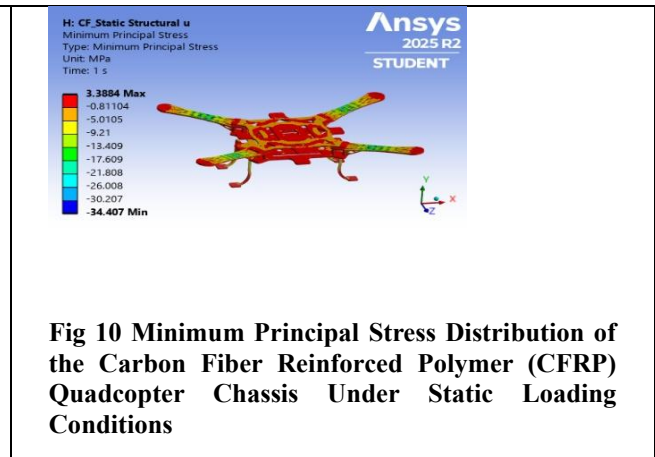
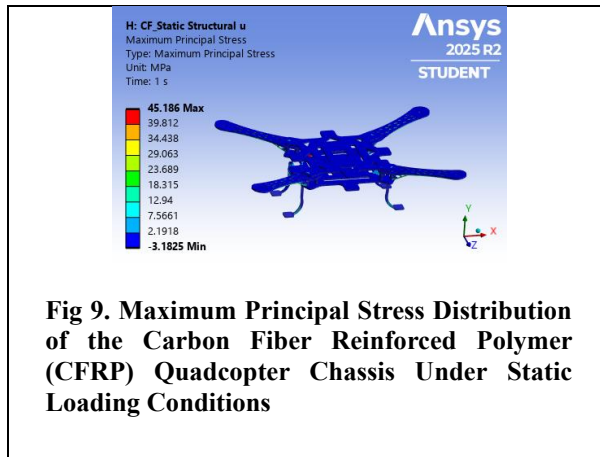
A conservatively low yield strength value of 250 MPa, the aluminium chassis achieves von Mises FoS of about 5.7, indicating far superior safety margins than required in traditional UAV design (FoS = 2–3). The material and failure tests found that plastic deformations, fracture or buckling behaviour under static loading will not occur in the sample according to the von Mises and maximum principal stress criteria. The aluminium frame is thus structurally sound and can be subjected to additional modal, fatigue and impact studies [14].

## 3.2 Static Analysis Results for Carbon Fiber Chassis

### 3.2.1 Total Deformation

The CFRP chassis is much stiffer and has a maximum deformation of 0.239 around the motor mounts (Figure 7). The low deformation level reduces propeller misalignment and the transfer of vibrations, which ultimately enhances flight stability and sensor precision. This reaction emphasises carbon fiber's excellent modulus to weight ratio vs. metal frames [15].





### 3.2.2 Equivalent (von Mises) Stress

The equivalent stress distribution of the CFRP frame is shown in Fig. 8. Maximal von Mises stress is 44.075 MPa, focused at the arm–hub junctions and motor mounting holes, identically with the aluminium case. These stress values are much lower than the normal tensile strength of CFRP (500–1000 MPa), showing a high safety margin and successful redistribution of stresses.

### 3.2.3 Principal Stress Analysis

The largest principal tensile stress is 45.186 MPa in the vicinity of the arm roots closest to the central hub (Fig. 9), and the minimum principal compressive stress is –34.407 MPa mainly on lower arm surfaces and central plate (Fig. 10). Both values are within the safe levels for CFRP laminates, which indicates very little risk of fiber breakage, matrix cracking or compressive failure with static loading. This can then be interpreted as a high factor of safety, equal to or greater than the > 15 values found in other drone composite and aluminium alloy structural elements[16].

### 3.2.4 Factor of Safety and Failure Assessment

With a conservative tensile strength of 500 MPa, the CFRP chassis attains a von Mises factor of safety in the vicinity of 11.3 and clearly has a significant margin against dynamic, fatigue and impact loading. Failure is assessed by use of maximum stress and Tsai–Hill criteria, which also show that the factor of safety was well beyond the critical limits. The small deformation and compressive stress show an extremely low de-lamination or buckling could occur in hover.

## 4. Comparative Analysis

According to the evaluation, for given hover loading, direct comparative assessments between standard aluminium and carbon fiber quadcopter frames indicate evident material-specific performance disparities. The maximum deformation of the aluminium chassis is 0.91965 mm, and that of CFRP is much lower at 0.239 mm, resulting in a higher stiffness for the carbon fibre by ~74%. Less deformation results in better flight stability and reduces motor derails to a minimum.

Both configurations exhibit the same peak von Mises stress levels (approximately 44 MPa) due to stresses at the arm-hub junctions. But the structural safety margins are not the same because of material strength inequalities. In addition, the factor of safety of aluminium frame is about 5.7, which satisfies static operation requirements for UAV, while the CFRP1 frame’s factor of safety is significantly higher than that of aluminum frame, implying excellent resistance to dynamic and fatigue loading. aluminum, relatively inexpensive and easy to fabricate for medium-performance UAVs, while carbon fiber has higher stiffness, lower deformation and larger safety factors than aluminum material for the selection of high-performance and endurance-critical requirements.

The comparative static structural results are summarised in Table 3.

Parameter	Aluminium Chassis	Carbon Fiber Chassis	Key Observation

Maximum deformation (mm)	0.91965	0.239	Carbon fiber shows ~74% lower deformation.
Maximum von Mises stress (MPa)	43.734	44.075	Stress levels are comparable.
Maximum principal stress (MPa)	44.887	45.186	Similar tensile stress distribution
Minimum principal stress (MPa)	-34.181	-34.407	Comparable compressive behaviour
Allowable strength (MPa)	250 (yield)	500 (conservative tensile)	Carbon fiber has a much higher strength limit
Factor of safety (von Mises)	~5.7	~11.3	Carbon fiber provides ~2× higher safety margin
Structural stiffness	Moderate	Very high	Carbon fiber significantly stiffer
Suitability	Cost-effective UAVs	High-performance UAVs	Material selection depends on the mission

**Table 3 comparative static structural results of both materials Conclusion**

In this work, a finite element comparative static structural analysis of aluminum alloy with carbon-fibre reinforced polymer (CFRP) quadcopter chassis has been carried out under the same hover loading conditions. Deformation, stress distribution and factor of safety were analyzed as structural responses.

In the aluminium, there was a maximum deformation of 0.91965 mm, with maximum von Mises stress values of 43.734 MPa and primary principal stress values in tensile and compressive were 44.887 MPa and -34.181 MPa respectively. Considering a material yield strength of 250 MPa and for an aluminium frame, this resulted in an approximate value of factor safety to be equal to approximately 5.7, which proved the elastic behaviour and structural safety during hover.

A CFRP chassis demonstrated higher stiffness with the maximum deformation of 0.239 mm, which was about a ~74% decrease from the aluminium counterpart. The highest equivalent stress was 44.075 MPa, and the principal stresses were 45.186 MPa and -34.407 MPa. According to a conservative allowable tensile strength of 500 MPa, the CFRP frame succeeded in achieving its factor of safety of about 11.3, which was higher than the metal frame by far, in terms of load-carrying capacity and endurance life.

As the dimensions and loading were identical, both materials had a similar stress profile while they showed different deformation behaviour. Aluminium alloy also shows promise as a structurally safe and economical candidate for moderate performance platforms.

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