Static and Modal Performances of Kenaf Fiber-reinforced Epoxy Composites for FPV Drone Structures

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Static and modal performances of kenaf fiber reinforced epoxy composites and their hybrid laminates were numerically evaluated for first-person view (FPV) drones. Seven laminate configurations were investigated, including full kenaf, carbon, and glass fiber composites, as well as kenaf–carbon and kenaf–glass hybrid systems with varying ply placements. Each ply contained a fiber weight fraction of ~30 wt.%. Finite element-based static structural and modal analyses were performed. Static analysis under realistic hover-loading conditions showed that the fully kenaf/epoxy frame exhibited a maximum von Mises stress of 1.20 MPa and a maximum displacement of 0.00352 mm, remaining well within safe structural limits while achieving the lowest mass (570 g). The carbon-skinned kenaf hybrid (C/K/K/C) reduced maximum stress and displacement by approximately 63% and 81%, respectively, compared to the full kenaf laminate, while maintaining a ~5% lower mass than the full carbon frame. Modal analysis revealed that the fundamental natural frequency increased from 11.9 Hz for the kenaf laminate to 13.6 Hz for the carbon–kenaf hybrid, approaching the carbon/epoxy frame value of 15.2 Hz. All kenaf-based and hybrid configurations exhibited natural frequencies well above dominant motor excitation ranges, indicating low resonance risk during FPV operation.

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INTRODUCTION

The rapid growth of first-person view (FPV) drone applications has intensified the demand for structural materials that combine light weight, high stiffness, vibration resistance, and crash durability. Conventional carbon-fiber and glass-fiber laminates, while widely adopted, are expensive, energy-intensive to produce, and they pose end-of-life disposal challenges, limiting their suitability for sustainable drone development. Carbon fiber production is highly energy-intensive, resulting in high manufacturing costs and a substantial carbon footprint, while glass fiber composites generate large volumes of manufacturing waste and end-of-life materials that are difficult to recycle (Sharma *et al.* 2025). Most synthetic fiber-reinforced composites are based on thermosetting polymers, making recycling and material recovery particularly challenging (Phan *et al.* 2026). Consequently, a considerable proportion of composite waste is still disposed of in landfills, highlighting the need for more sustainable reinforcement materials and improved end-of-life management strategies. Hence, there is a critical need for alternative, bio-derived composites with competitive mechanical and dynamic performance (Louhichi *et al.* 2026). In response to this challenge, this study aims to evaluate the performance of kenaf fiber reinforced epoxy composites for FPV drone structures. A finite element simulation of static and modal analyses was employed to establish their viability as sustainable replacements for carbon-fiber and glass-fiber based components. FPV drones operate under intense vibrational loads, abrupt maneuvers, and repeated crash events, making structural dynamics a crucial design factor. This shifts the focus from traditional tensile or bending evaluations toward modal behavior, damping characteristics, and structural integrity under multi-axis loading.

Recent studies based on unmanned aerial vehicles (UAV) have investigated carbon fiber–reinforced polymers (CFRP), aluminum (AL) alloys (*e.g.*, 6061and 7075) (Vosniakos *et al.* 2022), glass fiber–reinforced polymers (GFRP), Kevlar fiber composites (KFRP), and engineering plastics as primary drone frame materials because of their contrasting stiffness, weight, thermal, and structural performance characteristics (Hairi *et al.* 2023). Milenin (2025) demonstrated that frame material strongly affects FPV drone performance under extreme payloads. For instance, in 7-inch quadcopters carrying a 20 N payload, motors on a carbon-fiber frame exceeded 90 °C, whereas those on an aluminum 6061-T6 frame remained below 60 °C, showing an approximately 30 °C reduction and more uniform thermal distribution. Despite higher power consumption due to frame mass, the aluminum frame exhibited lower power demand under payload, fewer low-frequency vibration resonances, and Finite Element Method (FEM) predictions. This closely matched experimental motor temperatures (37 to 44 °C without payload; <60 °C with payload) confirming superior thermal regulation and dynamic stability. Zohaib Butt *et al.* (2021) performed a multi-objective structural optimization of five types of multi-rotor unmanned aerial vehicle (MR-UAV) quadcopter frames (“X”, “+”, “I”, “K”, and “Z”) using four materials (Al-alloy, CFRP, GFRP, and KFRP) under maximum aerodynamic loading with a factor of safety of 1.75, focusing on minimizing equivalent stress, total deformation, and improving fatigue life. Finite-element results showed that woven E-Glass fiber reinforced epoxy produced the lowest equivalent stress and deformation, followed by woven carbon fiber reinforced epoxy, while unidirectional kenaf fiber reinforced epoxy outperformed other CFRP variants. Overall, the “+” and “X” frame configurations were identified as the most structurally efficient designs for resisting peak external loads, providing optimal airframe material combinations for future MR-UAV development.

Li *et al.* (2024) conducted a comparative FEM-based structural analysis of quadcopter frames made from carbon fiber, aluminum alloy, plastic, and glass fiber under a uniform load of 4.905 N, focusing on total deformation, shear strain, and stress. The carbon fiber frame showed the lowest deformation ($\approx 1.55 \times 10^{-6}$ m), followed by Al-alloy (1.98×10^{-6} m) and glass fiber (2.37×10^{-6} m), while plastic exhibited the highest deformation (3.17×10^{-6} m) with maximum shear strain of 7.99×10^{-6} m/m. Overall, the results indicate that carbon fiber offers superior stiffness, whereas glass fiber provides a balanced trade-off between rigidity and flexibility, making both suitable candidates for quadcopter frame construction. Al-Hadithi and Alcón Flores (2025) presented a unique, integrated structural–operational validation of a sub-250 g FPV drone chassis, combining nonlinear static and transient FEM (including 5 m/s crash and 40 km/h impact scenarios) with real flight, firmware (Betaflight), Global Positioning System (GPS), and telemetry validation. The study demonstrated that a screwless, interlocking-frame design using Polyethylene Terephthalate Glycol-modified (PETG) for prototyping and carbon fiber for production can safely withstand accelerations up to 4.2 G, flight speeds of ~116 km/h, and achieve safety factors of ~5.3 (max thrust) and 1.35 (impact), establishing a comprehensive workflow that bridges simulation, materials strategy, and real-world UAV performance.

Natural fiber composites have gained attention in drone applications as alternatives to traditional materials due to their favorable strength-to-weight ratios and reduced environmental impact (Shahar *et al.* 2024). Senan *et al*. (2022) applied the analytic hierarchy process (AHP) to select optimal natural fiber composite filaments for drone frame structures, ranking five criteria where performance (0.337) was most influential, followed by environmental (0.311), cost (0.193), weight (0.086), and size (0.073). Among Polylactic Acid (PLA)/Jute (6.3%), Polypropylene (PP)/Harakeke (30%), and Polypropylene (PP)/Hemp (30%), PLA/Jute achieved the highest overall score (0.449), with superior tensile strength (0.417) and modulus (0.478), identifying it as the most suitable natural fiber composite for drone structural applications. Lopena and Millare (2022) evaluated salago fiber–reinforced composites as an alternative drone airframe material and found that, although glass fiber composites exhibited higher flexural and impact strength, salago composites offered a 4.8% lower density (1.19 g/cm^3) and a 7.9% higher heat deflection temperature (58.6 °C). Flight and drop tests demonstrated practical viability, as the salago-composite airframe flew successfully and protected onboard components after five drops from 2 m, confirming its potential as a sustainable alternative for UAV structures.

Lefebvre *et al.* (2022) examined flax/Elium composites for autonomous long-range drones and compared them to glass and carbon fiber/Elium composites. Finite Element Analysis (FEA) revealed lower resistance to compression for flax/Elium, with failure occurring prematurely compared to glass fiber structures, indicating the need for further optimization. Dev *et al.* (2022) investigated the mechanical and moisture absorption behavior of sugarcane bagasse fiber-reinforced epoxy composites for drone frame development. The researchers found that neat epoxy exhibited superior overall properties, while composites containing 4 wt% fiber showed improved tensile and flexural strength compared with lower fiber loadings. Their study also showed that alkali treatment reduced fiber weight and moisture absorption, highlighting the importance of optimizing fiber treatment, fiber length, and loading to enhance the performance of sugarcane bagasse/epoxy composites. Singsang *et al.* (2025) reported that hemp fiber–reinforced polypropylene composites with 45 wt.% fiber content achieved the highest Young’s modulus of 1170 MPa, approximately twice that of neat polypropylene, indicating improved stiffness for drone frame applications. However, tensile strength decreased with increasing fiber content, and the strain at break dropped to the range of 3.97 to 8.42% compared with 28.31% for pure polypropylene, showing reduced ductility. Despite this, the 45 wt.% composite exhibited impact strength close to polypropylene and withstood a simulated maximum stress of 1.64 MPa under a 0.64 N load, supporting its feasibility as an alternative lightweight material for drone structures.

Previous researchers have extensively applied finite element analysis (FEA) to study the mechanical behaviour and failure response of natural fiber-reinforced polymer composites. Harishbabu *et al.* (2026) investigated pineapple leaf fiber (PALF)/epoxy composites with fiber loadings of 0, 5, 10, 20, and 30 wt% using an integrated experimental–numerical approach. The Representative Volume Element (RVE) model accurately predicted the elastic modulus, showing close agreement with the experimental results and classical micromechanical models, including the Rule of Mixtures and Mori–Tanaka formulations. Additionally, the FEA predicted the tensile and flexural strengths with deviations of less than 10% from the experimental values, validating the robustness and reliability of the proposed numerical framework for mechanical performance prediction in natural fiber composites. For UAV related applications, Ganesan *et al*. (2024) designed and simulated a UAV landing gear using raw and alkali-treated *Borassus flabellifer* (BF) fiber–epoxy composites, applying a 100 N landing load in FEM to evaluate deformation, stress, and durability. The alkali-treated BF composite with ethylenediamine (EDA) curing agent (ABFEDA) showed superior performance, achieving a maximum deformation of ~1.50 mm, outperforming banana, sisal, coir, and jute epoxy composites, while maintaining acceptable water absorption and thermal stability.

Researchers increasingly combine natural fibers with synthetic reinforcements to balance sustainability, cost, and weight reduction with the high strength, stiffness, and durability required for UAV structures, achieving performance levels unattainable by natural fibers alone. Bawankar *et al*. (2025) demonstrated that silk–carbon–epoxy hybrid composites with 20 wt% to 30 wt% carbon fabric achieve an 8% to 11% density reduction and enable ~12% longer UAV endurance, while delivering tensile strength up to ~637 MPa, flexural modulus ~39.1 GPa, and interlaminar shear strength (ILSS) increasing from ~95 to ~430 MPa due to improved fiber–matrix adhesion. The hybrids exhibited high impact resistance (~162 kJ/m^2), reduced water absorption (down to 0.48%), satisfactory fatigue endurance (~60 MPa at 10^6 cycles), and enhanced damping (2.5% to 3.0%), confirming crash tolerance and aeroelastic stability. On the other hand, researchers incorporate plant-derived additives such as cellulose, lignin, chitosan, and chitin into polymer composites to enhance interfacial bonding, mechanical strength, wear resistance, moisture stability, and flame retardancy, while simultaneously reducing environmental impact and reliance on fully synthetic reinforcements. Prakash *et al*. (2023) developed a lightweight hemp fiber–polyester composite reinforced with green pea pod (*Pisum sativum*) lignin for defense-oriented UAV applications, demonstrating that 2.0 vol% lignin maximized mechanical performance with tensile strength ~128 MPa, tensile modulus ~4.24 GPa, flexural strength ~161 MPa, and flexural modulus ~5.92 GPa, along with a fatigue life of ~36,972 cycles at 25% ultimate tensile strength (UTS). Increasing lignin to 4.0 vol% significantly enhanced durability and safety, achieving a low specific wear rate of ~0.103 mm^3/Nm, coefficient of friction (COF) ~0.35, high hydrophobicity (contact angle ~107°), and a minimum flame propagation speed of 11.90 mm/min. These results highlight the potential of waste-derived lignin–hemp composites as sustainable, wear-resistant, and flame-retardant materials for UAV structures, morphing wings, and surveillance drones.

Johny *et al.* (2024) developed a coconut coir-based porous carbon/magnetic iron composite (CCPC/Fe) as a sustainable electromagnetic shielding material for UAV applications. The composite exhibited strong electromagnetic wave attenuation, achieving reflection loss values of −26.41 dB at 2 mm thickness and −36.68 dB at 4 mm thickness, indicating excellent shielding performance across a broad frequency range. These findings demonstrate the potential of CCPC/Fe as a lightweight, cost-effective, and eco-friendly material for improving electromagnetic compatibility in UAV systems. Another study by Prakash *et al.* (2023b) demonstrated development of a lightweight epoxy-based biocomposite for morphing wing and UAV applications using a 3D-printed lignin-ABS core reinforced with hemp and aluminized glass fiber epoxy skin. Their optimum composite (E2) achieved a tensile strength of 136 MPa, flexural strength of 168 MPa, compression strength of 155 MPa, Izod impact strength of 4.82 kJ/m², and interlaminar shear strength of 21 MPa. In addition, the E2 composite absorbed 20.6 J during impact testing, demonstrated fatigue life cycles of 33,700, 25,800, and 19,600 at 50%, 70%, and 90% UTS, respectively, and showed a fracture toughness (K_{Ic}) of 32.5 MPa√m with an energy release rate (G_{Ic}) of 0.76 MJ/m².

Kenaf (*Hibiscus cannabinus*), an industrial crop abundantly available in Malaysia, is a natural fiber with strong potential for UAV applications due to its high specific strength and stiffness, low density, renewability, and suitability for lightweight structural components (Misnon *et al.* 2025). Previous studies have demonstrated that kenaf-based laminates can be optimized through fiber orientation, chemical treatment, and hybridization, achieving mechanical properties comparable to certain glass-fiber composites. However, applications in UAVs, especially in high-demand FPV platforms remain limited. Chandran *et al.* (2025) investigated the use of kenaf fiber-reinforced polymer composite for quadcopter arm structures using finite element analysis, focusing on fiber orientation and cross-sectional design. Their results showed that the circular hollow tube provided the highest stiffness with the lowest deflection, while the 0°/30°/45°/30°/0° fiber orientation achieved the highest maximum stress (0.343 MPa), and the 0°/45°/0°/45°/0° configuration showed the lowest displacement. For hybrid studies, Huang *et al*. (2025) investigated kenaf/flax/glass fiber–reinforced hybrid composites for unmanned maritime vehicle (UMV) applications under 50 days of artificial seawater aging, combining mechanical testing with Analytic Hierarchy Process (AHP) ranking. The results showed that stacking sequence strongly influenced durability, with GKFKG retaining the highest tensile strength (86.8%) and flexural strength (88.4%), while consistency ratios in AHP remained < 0.1, confirming decision reliability. Overall, GKFKG ranked as the optimal configuration, followed by GFKFG, GKKKG, and GKGKG, demonstrating the synergistic potential of kenaf–flax–glass hybrids for sustainable marine composite structures. Abidin *et al.* (2021) investigated kenaf–glass fiber hybrid laminated composites for UAV wing profiles, fabricating GKG and KGK stacking sequences and evaluating their tensile behavior through experiments and ANSYS 18.2 FEA validation. The results showed good agreement between numerical and experimental stress–strain responses, with some deviation in deformation attributed to modeling and boundary-condition factors. In terms of structural performance, the GKG configuration exhibited superior strength, achieving a maximum tensile stress of 121.9 MPa, compared to 79.8 MPa for KGK, highlighting the influence of stacking sequence on hybrid composite efficiency.

Despite the growing interest in natural fiber composites for lightweight aerospace structures, there is a lack of systematic evaluation addressing the combined static, and modal responses of kenaf-epoxy laminates in FPV-grade drone configurations. Most previous studies have focused on the material characterization of natural fiber composites or their application in simple structural components, while relatively few have investigated complete UAV frame structures subjected to realistic structural and dynamic loading conditions. Furthermore, limited attention has been given to natural fiber composites such as woven kenaf fabric laminates and the influence of hybrid stacking sequences with synthetic fibers on the structural integrity and vibration characteristics of FPV drone frames. Comparative investigations involving pure kenaf, carbon, glass, and hybrid laminate configurations under identical modelling conditions are also scarce, making it difficult to establish the structural benefits of hybridization while maintaining sustainability. To address this gap, this study integrates finite element–based static loading, and modal analysis to quantify stiffness, vibrational behavior, and structural resilience of kenaf composite drone elements. The methodology provides a holistic mechanical–dynamic performance profile to benchmark against carbon-fiber standards. The outcomes are expected to support the development of eco-efficient FPV drone frames, widen the material selection landscape for UAV designers, and contribute toward sustainable engineering practices within the rapidly evolving drone industry.

MATERIALS AND METHOD

In this study, two primary types of finite element analyses (FEA) were conducted. Static analysis was performed to evaluate the stress distribution and deformation of the drone frame under representative operational loading conditions, while modal analysis was carried out to determine the natural frequencies and corresponding mode shapes of the structure. All finite element analyses in this study were performed using SOLIDWORKS 2022 Simulation module. Standard built-in solver settings were employed for both analyses. To ensure a fair and consistent comparison between different material systems, all simulations were performed using identical geometry, laminate thickness, mesh settings, boundary conditions, and mass distributions. Identical load magnitudes were applied for all static analyses, whereas no external loads were defined for the modal analyses, as natural frequencies and mode shapes are governed by the structure's stiffness, mass, and boundary conditions. Only the material properties were varied between cases, isolating the influence of material behavior on the static response and modal characteristics of the FPV drone frame.

Materials and Components

The primary natural reinforcement used in this study was woven kenaf fiber fabric. This was selected based on its favorable specific mechanical properties, renewability, low density, and increasing relevance in sustainable aerospace and UAV structural applications. The kenaf fabric was supplied by Lembaga Kenaf dan Tembakau Negara (LKTN), Kota Bharu, Malaysia, in a bidirectional woven configuration, providing balanced in-plane properties and improved load transfer compared to unidirectional natural fiber reinforcements. Prior to composite fabrication, the woven kenaf fabrics were oven-dried to remove residual moisture and subsequently treated with a 5 wt.% sodium hydroxide (NaOH) solution to improve fiber–matrix interfacial adhesion, as alkali treatment has been widely reported to enhance the mechanical properties of natural fiber-reinforced composites (Mahmud *et al.* 2026).

For comparative and hybrid performance evaluation, woven carbon fiber and glass fiber fabrics were also employed (Ma *et al.* 2022). Carbon fiber was selected due to its widespread use in FPV drone frames, offering high stiffness, strength, and excellent fatigue resistance, thereby serving as a benchmark material (Fantuzzi *et al.* 2024). In contrast, glass fiber was chosen for its lower cost, good damage tolerance, and common use in structural composite applications, providing a practical comparison material with moderate mechanical performance (Săftoiu *et al.* 2024).

The epoxy system used was Smooth-On EpoxAmite® 100 (Part A) with EpoxAmite® 102 Medium Hardener (Part B). Epoxy resin was selected as the matrix material for all composite laminates because of its superior mechanical properties, low shrinkage, good environmental resistance, and established use in aerospace and UAV applications. The low viscosity of uncured epoxy enables effective impregnation of woven kenaf fibers during fabrication while minimizing fiber distortion and breakage, thereby preserving the structural integrity and reinforcing efficiency of the fiber architecture (Atmakuri *et al*. 2020). In addition, epoxy resins exhibit excellent interfacial adhesion with cellulosic fibers due to their ability to form strong hydrogen bonding and mechanical interlocking with the hydroxyl-rich surfaces of natural fibers. This strong fiber–matrix interface promotes efficient stress transfer from the matrix to the reinforcement, leading to improved stiffness, strength, and structural stability.

Aluminum standoffs were used as structural spacers between composite plates and were applied consistently across kenaf, carbon fiber, glass fiber, and hybrid composite configurations to ensure comparable mechanical responses. Additionally, landing skids were designed and manufactured from Polyethylene Terephthalate Glycol-Modified (PETG) using additive manufacturing, owing to its ease of fabrication, adequate impact resistance, and suitability for UAV components (Chen and Chen 2026). According to Ratuningtyas *et al*. (2023), PETG outperformed PLA and ABS by exhibiting the highest safety factor under static loading and the lowest strain under drop-test conditions, making it the most suitable material for 3D-printed landing skids. The skids were positioned beneath the bottom frame and directly connected to the motor mounts to replicate realistic operational and landing conditions.

Drone Design and Assembly

The FPV drone frame was designed and assembled using a computer-aided design (CAD) software. The overall drone configuration and assembly details are illustrated in Fig. 1a.

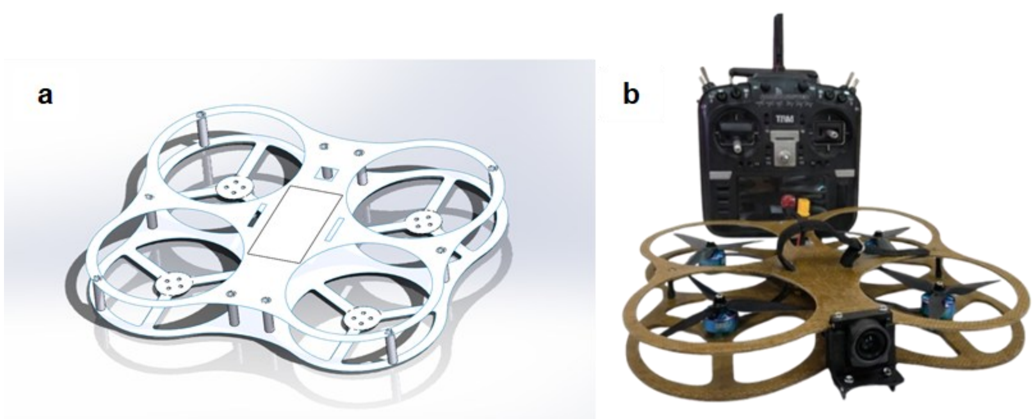


Fig. 1. (a) Drone configuration in CAD; (b) Working prototype with KKKK configuration

The composite parts, top and bottom frames were modelled as thin shell structures to enable explicit definition of the laminate stacking sequence on a ply-by-ply basis, which is essential for accurately capturing the anisotropic behavior of layered composite materials. This approach is also appropriate given that the laminate thickness is small compared to the in-plane dimensions of the frame. Based on the finalized design, a working prototype with KKKK configuration was fabricated, as shown in Fig. 1b.

For the working prototype, composite panels were produced using a controlled hand lay-up process followed by compression molding to ensure uniform fiber wet-out and consistent laminate thickness (Shahar *et al.* 2026a). After curing, the composite panels were precision-cut using waterjet machining according to the CAD design shown in Fig. 1a. Aluminum standoffs were employed to assemble the composite frame components, providing structural spacing and load transfer between plates. Subsequently, all essential electronic components, including motors, propellers, flight controller, GPS module, and onboard camera, were installed to complete the functional FPV drone assembly. Figure 2 shows the flow of prototype development with KKKK configuration.

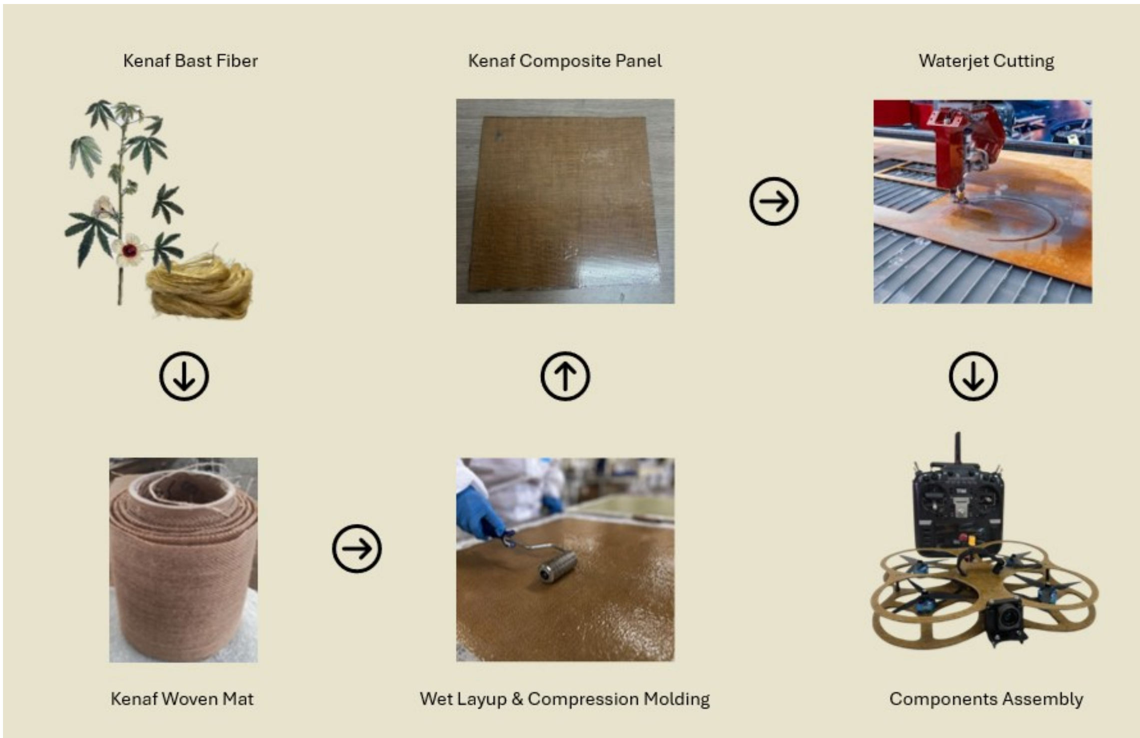


Fig. 2. Fabrication and prototype development

Boundary Conditions

For the static finite element (FE) analysis, mass distributions acting on the FPV drone frame were defined based on the self-weight of the structure and attached onboard components (Bvn and Agrawal 2023). Custom coordinate systems were defined at the locations of major components to enable accurate application of remote loads and masses, as shown in Fig. 3a (Bendtsen *et al.* 2021).

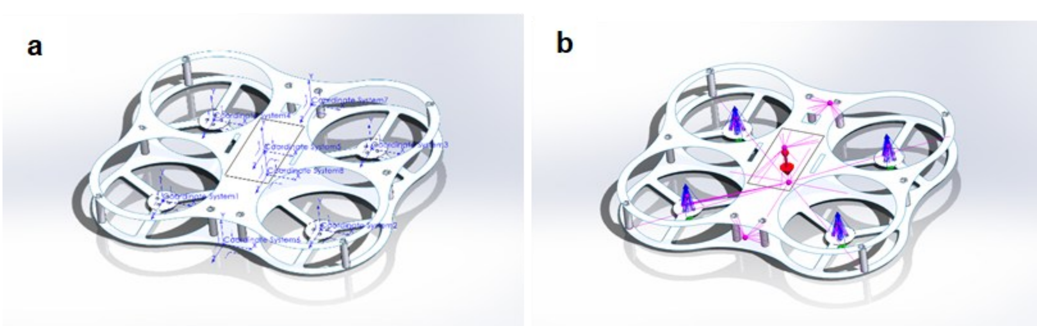


Fig. 3. (a) Custom coordinate system; (b) Static loading and constraint setup

Component masses were assigned using a remote mass approach, while gravity was applied as an external load. The onboard components were distributed on the frame according to the actual assembly layout. Motors (0.04 kg each), electronic speed controllers (ESCs, 0.03 kg), flight controller (0.01 kg), receiver (0.01 kg), and miscellaneous electronics (0.02 kg) were assigned to the bottom frame. A battery with a mass of 0.165 kg was positioned at the center of the top frame. The camera and its mounting (0.02 kg) were located at the front standoffs, while the video transmitter and its mounting (0.02 kg) were positioned at the rear standoffs of the frame.

Thrust loads were determined based on the manufacturer specifications of the Axisflying Brushless Motor 2207.5, 1860 KV, used in the FPV drone assembly. According to the manufacturer's data, each motor produces 622 g of thrust at 50% throttle, corresponding to approximately 6.1 N. A throttle setting of 50% was selected to represent hovering conditions, where the total thrust balances the all-up weight of the drone during steady flight. According to Giannakis and Savaidis (2016) and Kim *et al.* (2017), in UAV structural simulations, a factor of safety (FoS) of 1.5 is generally regarded as the minimum acceptable value based on conventional aerospace structural design principles, while values between 1.5 and 2.0 are commonly adopted for lightweight UAVs to accommodate uncertainties in loading, manufacturing, and material properties. Hence, to account for transient maneuvers, material variability, and modelling uncertainties, a safety factor of 1.5 was applied in this study, resulting in an effective thrust load of 9.15 N per motor. This loading condition provides a conservative yet realistic representation of operational stress without resorting to full-throttle assumptions. For the fixtures, a fixed constraint is applied to one arm of the frame, while roller–slider constraints were applied to the remaining three arms to prevent rigid body motion while allowing realistic deformation. The complete static loading and constraint configuration is illustrated in Fig. 3b. A mesh sensitivity analysis was conducted prior to the simulations to determine an appropriate mesh density that balanced numerical accuracy and computational efficiency. Based on the convergence results, the imported geometry was meshed with approximately 32,500 elements and 68,000 nodes for both static and modal finite element analyses (FEA). The element and node counts were kept consistent across all material configurations to ensure a fair comparison of the structural responses.

Material Assignment

The stacking sequence was carefully designed to ensure a fair comparison between kenaf fiber, carbon fiber, glass fiber, and hybrid composite laminates. The number of plies was controlled and fixed at four for all configurations, serving as the primary controlled variable in this study. All laminates were designed as quasi-isotropic layups [0/+45/−45/90], made possible using bidirectional woven fabrics, which provide balanced in-plane mechanical properties and minimize directional bias in static and modal analyses.

Woven kenaf, woven carbon fiber, and woven glass fiber fabrics were arranged in symmetric stacking sequences to reduce bending–twisting coupling and to ensure stable vibrational characteristics. Seven distinct laminate configurations were investigated to evaluate the influence of material composition and hybridization strategy: A full kenaf laminate, a full carbon fiber laminate, a full glass fiber laminate, and four hybrid laminates with synthetic fiber layers positioned either at the core or at the outer surfaces. This approach enabled assessment of how ply placement affects stiffness, load transfer, and natural frequency behavior in FPV drone structural applications. The arrangement of stacking sequences is listed in Table 1.

Table 1. Stacking Sequences of Quasi-Isotropic Woven Kenaf, Carbon Fiber, Glass Fiber, and Hybrid Laminates

Laminate Type	Stacking Sequence	Description
Kenaf/Epoxy Composite Frame	K / K / K / K	Fully woven kenaf fiber reinforced epoxy laminate
Carbon/Epoxy Composite Frame	C / C / C / C	Fully woven carbon fiber reinforced epoxy laminate
Glass/Epoxy Composite Frame	G / G / G / G	Fully woven glass fiber reinforced epoxy laminate
Kenaf–Carbon Hybrid	K / C / C / K	Hybrid laminate with carbon fiber core and kenaf outer layers
Carbon–Kenaf Hybrid	C / K / K / C	Hybrid laminate with carbon fiber outer layers and kenaf core
Kenaf–Glass Hybrid	K / G / G / K	Hybrid laminate with glass fiber core and kenaf outer layers
Glass–Kenaf Hybrid	G / K / K / G	Hybrid laminate with glass fiber outer layers and kenaf core

Note: K denotes woven kenaf fiber ply, C denotes woven carbon fiber ply, and G denotes glass fiber ply.

Table 2. Material Properties

Property	Unit	Kenaf/Epoxy (Woven)	Carbon/Epoxy (Woven)	Glass/Epoxy (Woven)
Elastic Modulus, E_X	GPa	6.5	65	25
Elastic Modulus, E_Y	GPa	6.5	65	25
Elastic Modulus, E_Z	GPa	3.0	8.0	7.5
Poisson's Ratio, v_{XY}	–	0.30	0.05	0.26
Poisson's Ratio, v_{YZ}	–	0.35	0.40	0.35
Poisson's Ratio, v_{XZ}	–	0.30	0.30	0.28
Shear Modulus, G_{XY}	GPa	2.0	4.5	4.0
Shear Modulus, G_{YZ}	GPa	1.2	3.5	3.2
Shear Modulus, G_{XZ}	GPa	1.2	3.5	3.2
Mass Density	kg/m³	1250	1600	2000
Tensile Strength, X	MPa	85	800	550
Tensile Strength, Y	MPa	80	750	520
Compressive Strength, X	MPa	70	600	450
Compressive Strength, Y	MPa	65	580	430
Shear Strength, XY	MPa	45	70	65
Yield Strength*	MPa	55	500	400
Material Damping Ratio	–	0.025	0.008	0.012
References		(Khalid *et al.* 2018; Suhaily *et al.* 2018)	"Failure analysis of V-notched carbon/epoxy composite plates" n.d.; Mastrogiannakis and Vosniakos 2020)	(Gunaryo *et al.* 2020)

* The material properties listed in this table represent average values due to inherent variability arising from differences in fiber morphology, manufacturing processes, and material heterogeneity.

Table 2 summarizes the orthotropic material properties assigned at the ply level for the woven kenaf/epoxy, carbon/epoxy, and glass/epoxy composite laminates used in the simulations. These properties were average values adopted from established literature and manufacturer datasheets for woven fabric composites and were selected to be representative of typical aerospace- and UAV-grade materials. The values were implemented consistently across all analyses to define the elastic, strength, density, and damping behavior of each ply within the laminate, enabling accurate numerical prediction of stiffness, stress distribution, and dynamic response. Each ply was designed to contain an approximate fiber weight fraction of ~30 wt.% to ensure consistency. Yield strength values were included as approximations to ensure numerical stability and convergence during finite element analysis, acknowledging that polymer matrix composites do not exhibit classical yielding behavior.

Static Analysis

Finite element analysis (FEA) was performed to evaluate the static structural response of the drone frame under loads representative of ground and hover operating conditions. The numerical model incorporated the self-weight of the frame and all mounted components, including the battery, motors, ESCs, flight controller, receiver, camera, and antennas. In addition, motor thrust was incorporated as externally applied loads at the motor mounting locations, defined through the boundary conditions to simulate hover equilibrium. Key parameters such as maximum von Mises stress, total deformation, and strain distribution were studied from the simulation to assess structural integrity and load-bearing capability. Material properties, laminate thickness, ply stacking sequence, mesh size, and boundary conditions were maintained consistently across all simulations to ensure a fair and direct comparison between material systems.

Modal Analysis

Following the finite element static analysis, three representative frame configurations were selected from the initial seven material systems for further dynamic evaluation based on their structural safety and stiffness performance. A finite element modal (frequency) analysis was conducted to determine the inherent dynamic characteristics of the selected drone frames. In this study, the assembled frame was modelled with all electronic components and propulsion units represented as rigidly attached remote masses, while no external loads or gravity were applied, allowing the extraction of the structure's natural frequencies and mode shapes independent of operational forcing. The modal simulations were performed using the same boundary conditions as the static analysis to represent the grounded operational state of the FPV drone and to ensure consistent comparison across material systems. For FPV drones, grounded modal analysis is appropriate because motor-induced vibrations are most critical during arming, idle, and throttle ramp-up on the ground, where resonance can damage electronics or cause video jitters, and this numerical approach is widely adopted in UAV and FPV studies. The first five natural frequencies were evaluated, with particular emphasis on the fundamental mode (Mode 1), which is typically associated with global arm bending and is most critical for FPV drone operation. The objective of this analysis was to assess whether the natural frequencies of the composite frames remain sufficiently separated from the dominant motor excitation frequencies encountered in its operational (on-ground) condition. A higher fundamental natural frequency is expected to reduce the risk of resonance, thereby improving vibration resistance, flight stability, and onboard sensor and camera performance.

RESULTS AND DISCUSSION

Static Analysis

The static analysis focused on quasi-static ground and steady-hover conditions, providing a baseline assessment of structural response under gravitational and thrust loading while excluding transient, aerodynamic, and impact effects. Table 3 summarizes the static analysis results by comparing maximum predicted von Mises stress, maximum displacement, maximum strain, and structural mass, which collectively indicate the strength, stiffness, deformation behavior, and weight efficiency of each FPV drone frame configuration. Based on these metrics, the carbon/epoxy frame ranked highest in performance, exhibiting the lowest predicted stress and displacement, followed by glass/epoxy, while the kenaf/epoxy frame recorded the highest predicted maximum stress, displacement and strain values due to its comparatively lower stiffness. The hybrid laminates fell between these extremes, with carbon-skinned hybrids outperforming glass-skinned hybrids and both offer clear improvements over the fully kenaf configuration. Overall, the predicted performance ranking based on combined stress and deformation response can be expressed as: carbon/epoxy > carbon–kenaf hybrid > glass/epoxy > glass–kenaf hybrid > kenaf–carbon hybrid > kenaf-glass hybrid > kenaf/epoxy.

Although the kenaf/epoxy frame exhibited higher predicted stress and deformation relative to synthetic composites, its maximum stress remains well below critical limits under the applied loading with a 1.5 safety factor, indicating that it still provides sufficient structural integrity while offering advantages in weight and sustainability.

Table 3. Results from Static Analysis

Material	Annotation	Maximum von Mises Stress (MPa)	Maximum Displacement (mm) ($\times10^{-3}$)	Maximum Strain ($\times10^{-5}$)	Mass (g)
Kenaf/Epoxy Composite Frame	KKKK	1.196	3.516	2.0	570
Carbon/Epoxy Composite Frame	CCCC	0.437	0.555	0.5	610
Glass/Epoxy Composite Frame	GGGG	0.585	1.131	0.7	650
Kenaf–Carbon Hybrid	KCCK	0.754	2.263	1.2	580
Carbon–Kenaf Hybrid	CKKC	0.449	0.665	0.7	580
Kenaf–Glass Hybrid	KGGK	0.906	2.786	1.4	610
Glass–Kenaf Hybrid	GKKG	0.635	1.254	0.9	610

The static analysis revealed performance gaps between the fully kenaf, carbon, and glass composite frames. Compared to the carbon/epoxy frame, the kenaf/epoxy frame exhibited a predicted approximately 174% higher maximum von Mises stress (1.20 MPa *vs*. 0.44 MPa) and a ~534% increase in maximum displacement (0.003516 mm *vs*. 0.000555 mm), reflecting its substantially lower stiffness. Relative to the glass/epoxy frame, kenaf/epoxy still showed a ~104% higher stress and a ~211% higher displacement, confirming that glass fiber provides a moderate but clear improvement over kenaf fiber. Moreover, according to the table, the kenaf/epoxy composite offered a clear mass advantage over both synthetic fiber systems, particularly against glass/epoxy composite. The kenaf/epoxy composite frame was approximately 6.6% lighter than the carbon/epoxy frame and 12.3% lighter than the glass/epoxy frame. This mass reduction highlights the potential of kenaf composites for lightweight UAV structures where reduced structural weight is critical for improving flight efficiency and payload capacity.

Figure 4 presents the static analysis results of the kenaf/epoxy composite FPV drone frame in terms of von Mises stress, displacement, and strain under representative operational loading. The von Mises stress distribution (Fig. 4a) shows that stresses are predicted to be generally low and well distributed across the frame, with peak values concentrated in the central region beneath the battery and at the aluminum standoff connections, where multiple loads are transferred between the top and bottom frames. These locations act as primary load paths, explaining the localized stress concentrations. The displacement contour (Fig. 4b) indicates that the maximum deformation occurs at the center of the frame, while the arms and motor mounting regions remain comparatively stiff, confirming that the overall structural integrity of the frame is maintained under static loading. The strain distribution (Fig. 4c) follows a similar trend to stress, with higher strain observed near the central plate and standoff interfaces, and low strain levels across the arms. Importantly, all stress and deformation values remain within the acceptable limits when evaluated with the applied safety factor, demonstrating that the kenaf/epoxy composite frame provides sufficient load-bearing capability for FPV drone applications while offering the added benefits of reduced environmental impact and material sustainability.

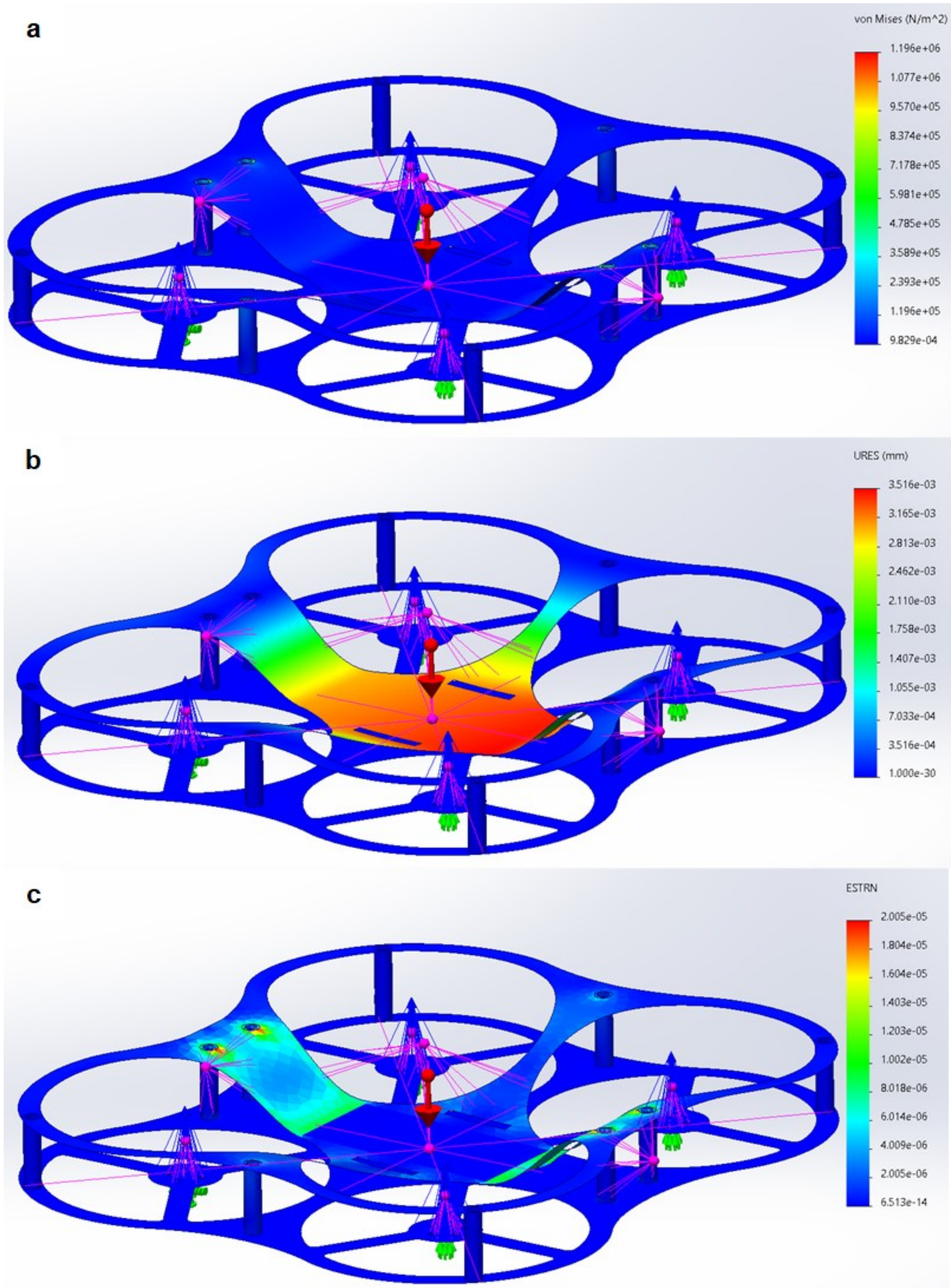
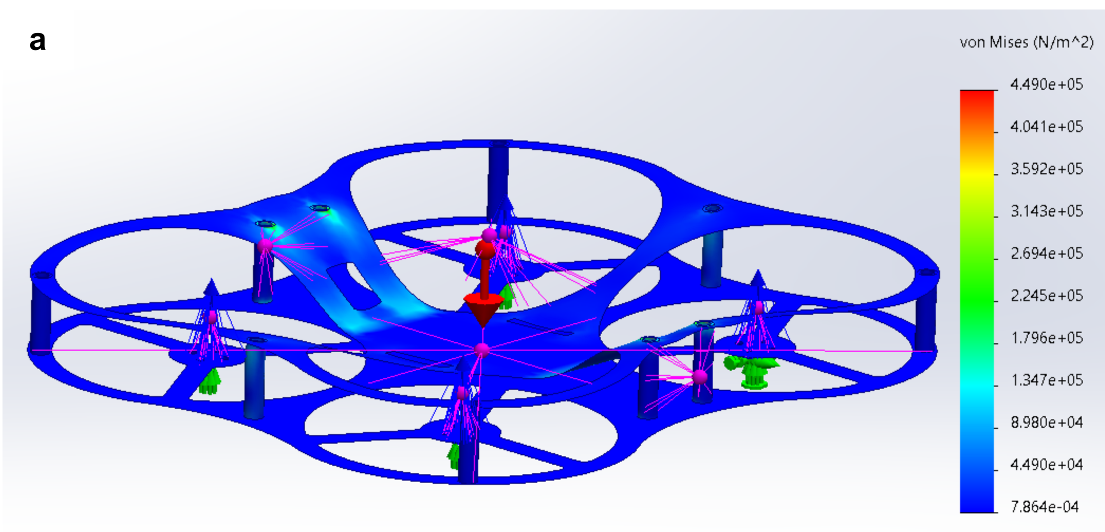


Fig. 4. Static analysis of kenaf/epoxy composite frame: (a) Von Mises stress; (b) Displacement; and (c) Strain

For the hybrid laminates, ply-sequencing played a dominant role in governing structural response. When compared directly with the pure kenaf/epoxy frame, all hybrid configurations demonstrated measurable predicted improvements. Stress reductions ranged from ~24% to ~63%, while displacement reductions ranged from ~21% to over ~81%, depending on the membrane material. Notably, the carbon-skinned hybrid approached the performance of the full carbon/epoxy frame, with only ~3% higher stress and ~20% higher displacement, but at a ~5% lower mass. This highlights the effectiveness of using combinations of reinforcing fibers, particularly with synthetic fiber skins, in bridging the performance gap between natural fiber composites and fully synthetic systems while maintaining weight efficiency and improved sustainability. The carbon-skinned hybrid (CKKC) composite reduced maximum predicted stress by ~63% and displacement by ~81% relative to the kenaf/epoxy frame, while maintaining nearly the same mass (580 g, ~2% higher than kenaf). In contrast, the kenaf-skinned hybrid (KCCK) achieved a smaller stress reduction of ~37% and a displacement reduction of ~36% relative to kenaf/epoxy. A similar trend was observed for glass-based hybrids: the glass-skinned configuration (GKKG) reduces stress by ~47% compared to kenaf/epoxy, whereas the kenaf-skinned hybrid (KGGK) achieved only a ~24% reduction. These results clearly indicate that placing stiffer synthetic fibers (carbon or glass) at the outer piles, where bending stresses are highest, significantly enhances load resistance and stiffness.

Singh *et al.* (2020) reported a maximum deformation of 5.84 mm concentrated at the outer edges of nylon-6 quadcopter arms and a peak von Mises stress of 6.27 MPa at the inner arm–based interface, with negligible stress in the grounded E-glass base plate due to full constraint. In contrast, the present study showed substantially lower deformation (0.00055 to 0.00352 mm) and stress levels (0.44 to 1.20 MPa) across kenaf, hybrid, and carbon composite FPV frames under comparable hover-type loading. The large difference reflects the higher stiffness of laminated composite frames and the use of distributed mass and thrust loading rather than fully grounded base plates. While the results from Singh *et al.* (2020) highlight arm-level flexibility in polymer frames, the current findings demonstrate that composite and hybrid laminates can provide superior stiffness and load distribution suitable for vibration-sensitive FPV applications. Figure 5 presents the static analysis results of the carbon–kenaf hybrid composite FPV drone frame, illustrating the von Mises stress, displacement, and strain distributions under operational loading.



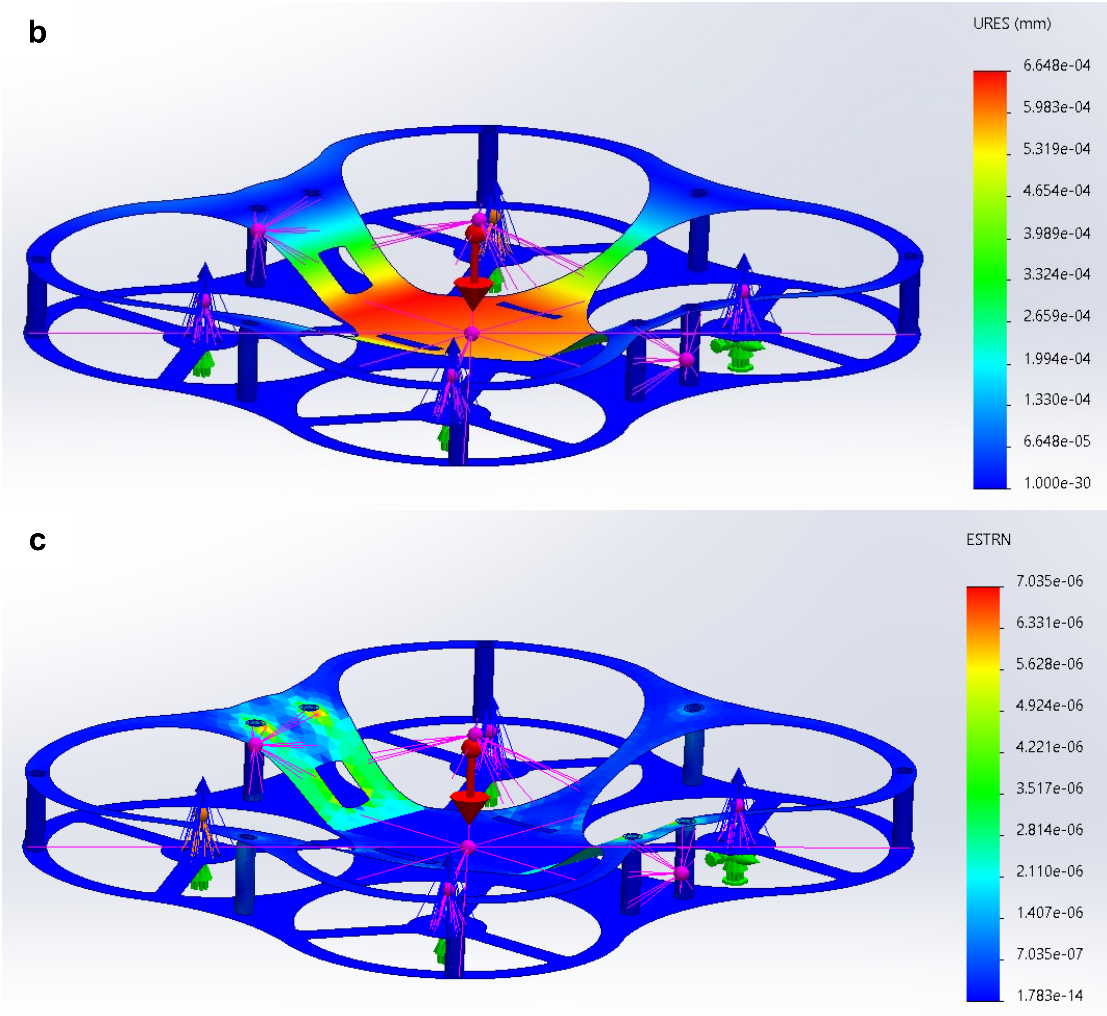


Fig. 5. Static analysis of carbon-kenaf hybrid composite frame: (a) Von Mises stress; (b) Displacement; and (c) Strain

The stress contour indicates that the predicted maximum stress remained localized primarily beneath the centrally mounted battery and around the aluminum standoff regions, similar to the kenaf/epoxy frame, but with noticeably reduced magnitudes due to the increased stiffness contributed by the carbon fiber plies. The displacement plot shows a clear reduction in overall deformation, with the central plate exhibiting the highest deflection while the arms and motor mounting regions remained comparatively rigid, reflecting improved load distribution in the hybrid laminate. The strain distribution followed the stress pattern, with localized strain concentrations near load transfer points and uniformly low strain across the arms.

Figure 6 shows the static analysis results of the glass–kenaf hybrid composite FPV drone frame in terms of von Mises stress, displacement, and strain distributions. The stress contour indicates that the maximum von Mises stresses are concentrated in the central region beneath the battery and around the aluminum standoff interfaces, consistent with the primary load transfer paths of the frame. Compared to the fully kenaf configuration in Fig. 4, the stress magnitude is reduced due to the higher stiffness of the glass fiber plies, though it remains higher than that of the carbon–kenaf hybrid (Fig. 5).

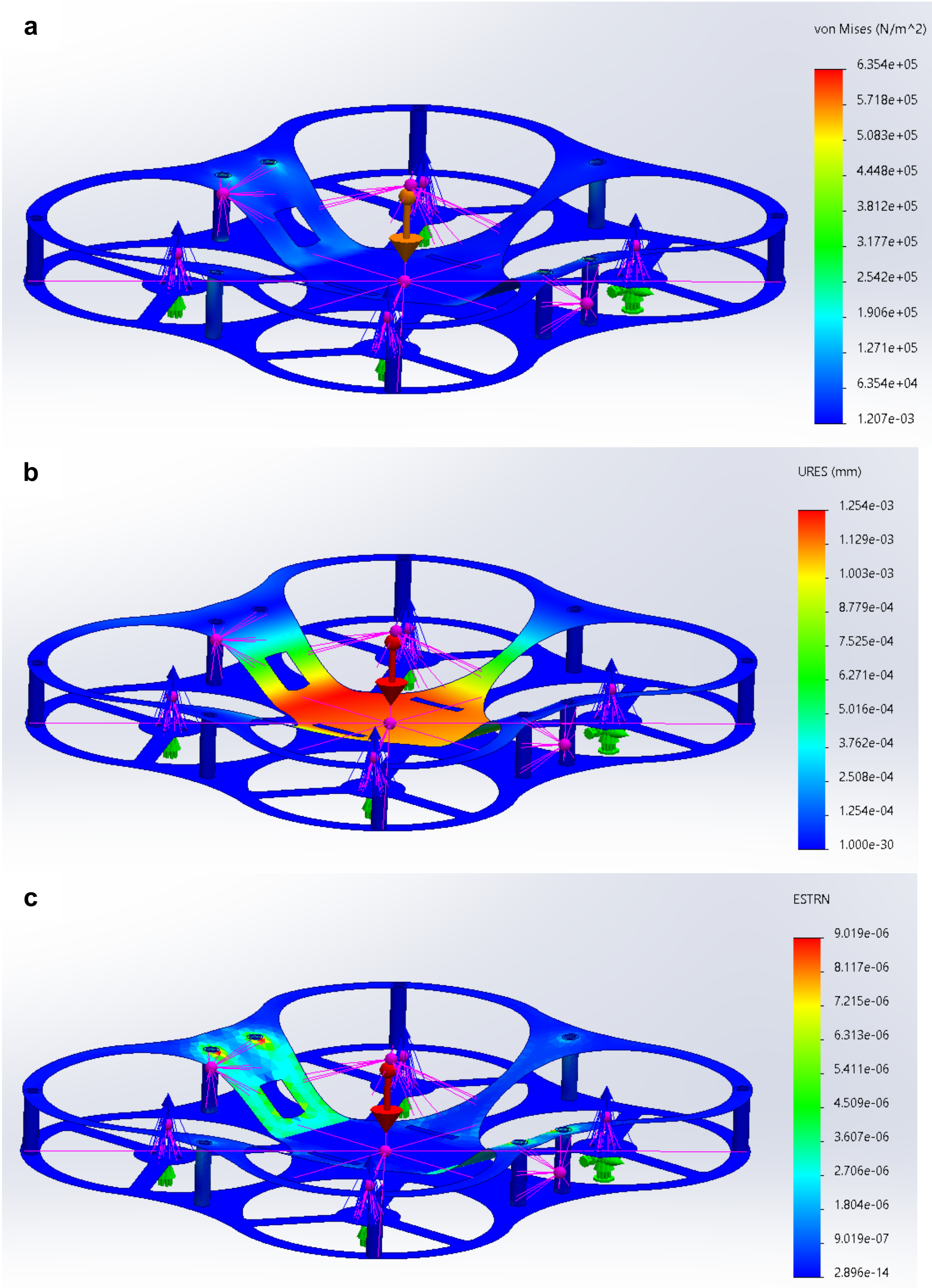


Fig. 6. Static analysis of glass-kenaf hybrid composite frame: (a) Von Mises Stress; (b) Displacement; and (c) Strain

The displacement plot reveals a noticeable reduction in central deflection relative to the kenaf-only frame, while the arms and motor mounting regions exhibit minimal deformation, indicating effective load sharing between the kenaf core and glass fiber skins. The strain distribution mirrors the stress pattern, with localized strain concentrations near the standoffs and low strain levels across the arms.

A comparative assessment of Figs. 4 to 6 highlights the progressive improvement in static structural performance achieved through hybridization of the woven kenaf/epoxy frame with synthetic fiber skins. The fully kenaf/epoxy frame (Fig. 4) exhibited the highest stress, displacement, and strain levels, with pronounced concentrations beneath the centrally mounted battery and at the aluminum standoff interfaces; however, all responses remain within safe limits under the applied loading and safety factor, confirming its suitability for low-to-moderate performance FPV applications where sustainability and weight reduction are prioritized. The carbon–kenaf hybrid frame (Fig. 5) demonstrates the most significant reduction in stress and deformation among the three, owing to the high stiffness of the carbon fiber outer plies, which effectively carry bending loads where stresses are highest. This configuration closely approaches the performance of a full carbon frame while maintaining reduced synthetic material content, making it ideal for high-performance FPV drones subjected to aggressive maneuvers, higher thrust levels, and increased payload demands. The glass–kenaf hybrid frame (Fig. 6) provides intermediate behavior, with lower stress and displacement than the fully kenaf frame but slightly higher than the carbon–kenaf hybrid, offering a cost-effective and damage-tolerant alternative suitable for general-purpose FPV platforms. When compared with other stacking sequences reported in Table 3, these three configurations are predicted to be particularly advantageous because they either maximize natural fiber usage (KKKK) or strategically place stiffer synthetic fibers as skins (CKKC and GKKG), optimizing bending stiffness and load distribution. As a result, they provide structurally efficient, vibration-resilient, and application-specific solutions for FPV drones operating under varying performance, cost, and sustainability requirements.

Modal Analysis

Based on the static analysis results, kenaf/epoxy laminate and hybrid laminate configurations that demonstrated reduced stress and displacement while maintaining low mass were selected for further dynamic evaluation through modal analysis. Modal analysis is critical for FPV drone structures, as it identifies the natural frequencies and shape modes of the frame, ensuring that structural resonances do not coincide with motor- and propeller-induced vibration frequencies that can degrade flight stability, damage electronic components, and reduce video quality. In this study, modal analysis was performed on the selected kenaf-based and hybrid frames using identical geometry, laminate thickness, boundary conditions, and mass distributions, with no external loads applied, allowing the intrinsic dynamic behavior of each material system to be directly compared. Although thrust and aerodynamic loads were not included, the modal analysis provides a baseline evaluation of the intrinsic dynamic behaviors of the frame, which is relevant to grounded conditions and serves as a reference for in-flight vibration assessment. The results in Fig. 7 show a clear and consistent increase in natural frequency from Mode 1 to Mode 5 for all material systems. This is expected, as higher modes correspond to stiffer deformation patterns with shorter effective wavelengths. For the kenaf/epoxy frame (KKKK), the first natural frequency was predicted as 11.88 Hz, increasing to 875.62 Hz at Mode 5. Although KKKK exhibits the lowest frequencies among all configurations, it still demonstrates a stable and progressive modal response, indicating sufficient global stiffness for FPV drone structures when operated away from resonance conditions. From a sustainability perspective, this highlights kenaf/epoxy as a viable low-frequency structural solution, particularly for lightweight and low-cost FPV platforms.

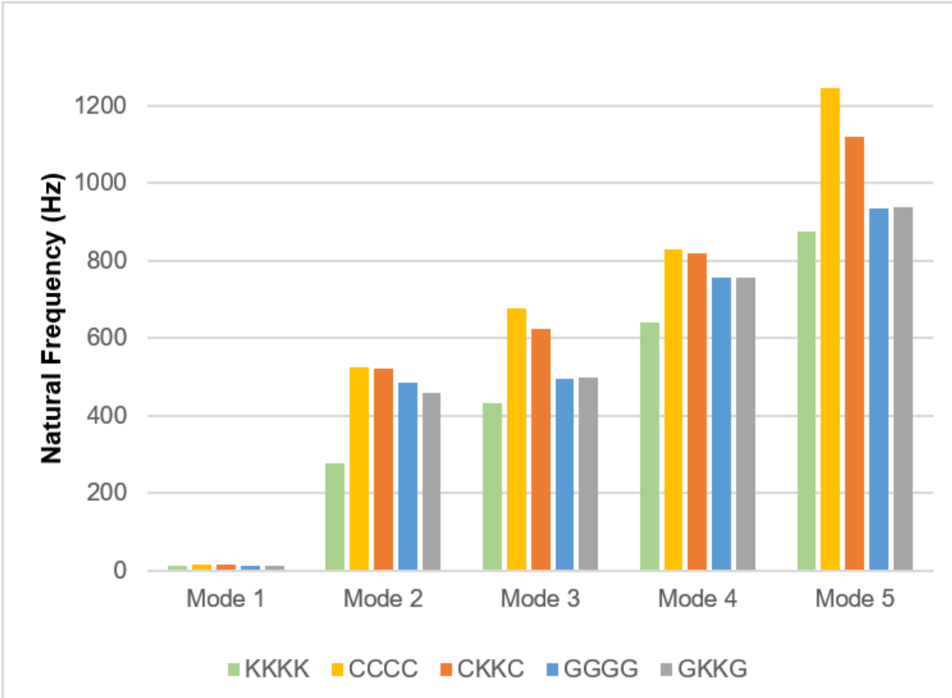
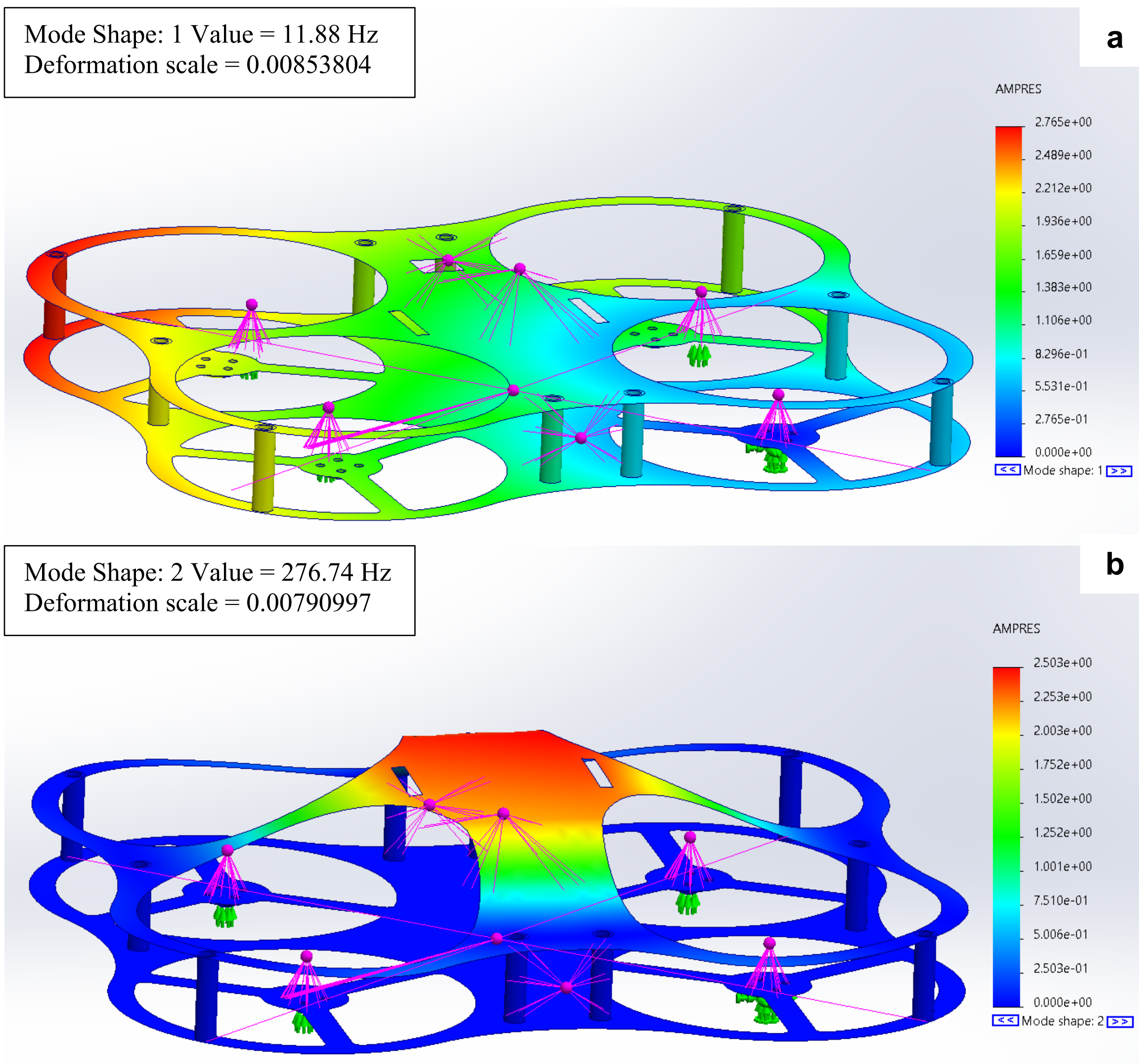


Fig. 7. Natural frequencies with respect to mode shapes

When compared with synthetic composites, the carbon/epoxy frame (CCCC) recorded the highest natural frequencies across all modes, with Mode 1 at 15.15 Hz and Mode 5 reaching 1247.5 Hz, reflecting its superior stiffness. Relative to CCCC, the kenaf frame showed reductions of approximately 22% in Mode 1 and 30% in Mode 5, which is consistent with the lower elastic modulus of natural fibers. The glass/epoxy frame (GGGG) was predicted to perform between carbon and kenaf, with Mode 1 at 12.44 Hz and Mode 5 at 933.8 Hz, offering moderate stiffness but at higher mass and lower sustainability benefits compared to kenaf-based systems. The carbon–kenaf hybrid (CKKC) increased the Mode 1 frequency to 13.65 Hz, representing a ~15% improvement over KKKK, while achieving 820.16 Hz at Mode 4 and 1120.8 Hz at Mode 5. Similarly, the glass–kenaf hybrid (GKKG) improved Mode 1 to 12.17 Hz and Mode 5 to 936.79 Hz, closely matching the performance of the full glass frame but with greater natural fiber content. These predicted results confirm that hybridization effectively enhances stiffness and vibration resistance while retaining the environmental advantages of kenaf.

Sundararaj *et al*. (2021) conducted modal analysis on several geometrical versions of a specialized drone frame manufactured using carbon fiber and ABS additive, designed to be self-sustaining through integrated solar cells and a chamber filled with lighter-than-air gas. Their results showed that carbon-fiber frames produced high Mode 1 natural frequencies (72 to 142 Hz), whereas ABS frames exhibited much lower values (14 to 32 Hz), demonstrating the strong influence of material stiffness and arm length on dynamic performance. Mode 1 is emphasized because it represents the global, most flexible deformation of the entire structure, and as the lowest natural frequency. It is the mode most likely to coincide with real-world excitation and therefore carries the greatest risk of resonance. In comparison, the FPV drone frames used in this study constructed from kenaf and hybrid laminates exhibited lower predicted Mode 1 frequencies (11.88 to 15.15 Hz), yet these remained far below the motor-induced excitation band of typical FPV drones. Since FPV motors generate vibration frequencies primarily between 500 and 6,000 Hz, the frame in Mode 1 values lie safely outside this band, indicating an extremely low resonance likelihood. Furthermore, unlike the findings of Sundararaj *et al*. (2021), who reported that longer-arm configurations that show early-failure tendencies and abrupt frequency shifts, the present hybrid designs (especially the CKKC laminate) are predicted to maintain stable, progressive modal behavior without dangerous jumps between modes. Overall, although Sundararaj's carbon frames are predicted to be stiffer in absolute numerical terms, the present kenaf-based hybrid structures offer safer vibration margins relative to FPV operating frequencies while simultaneously delivering enhanced sustainability.



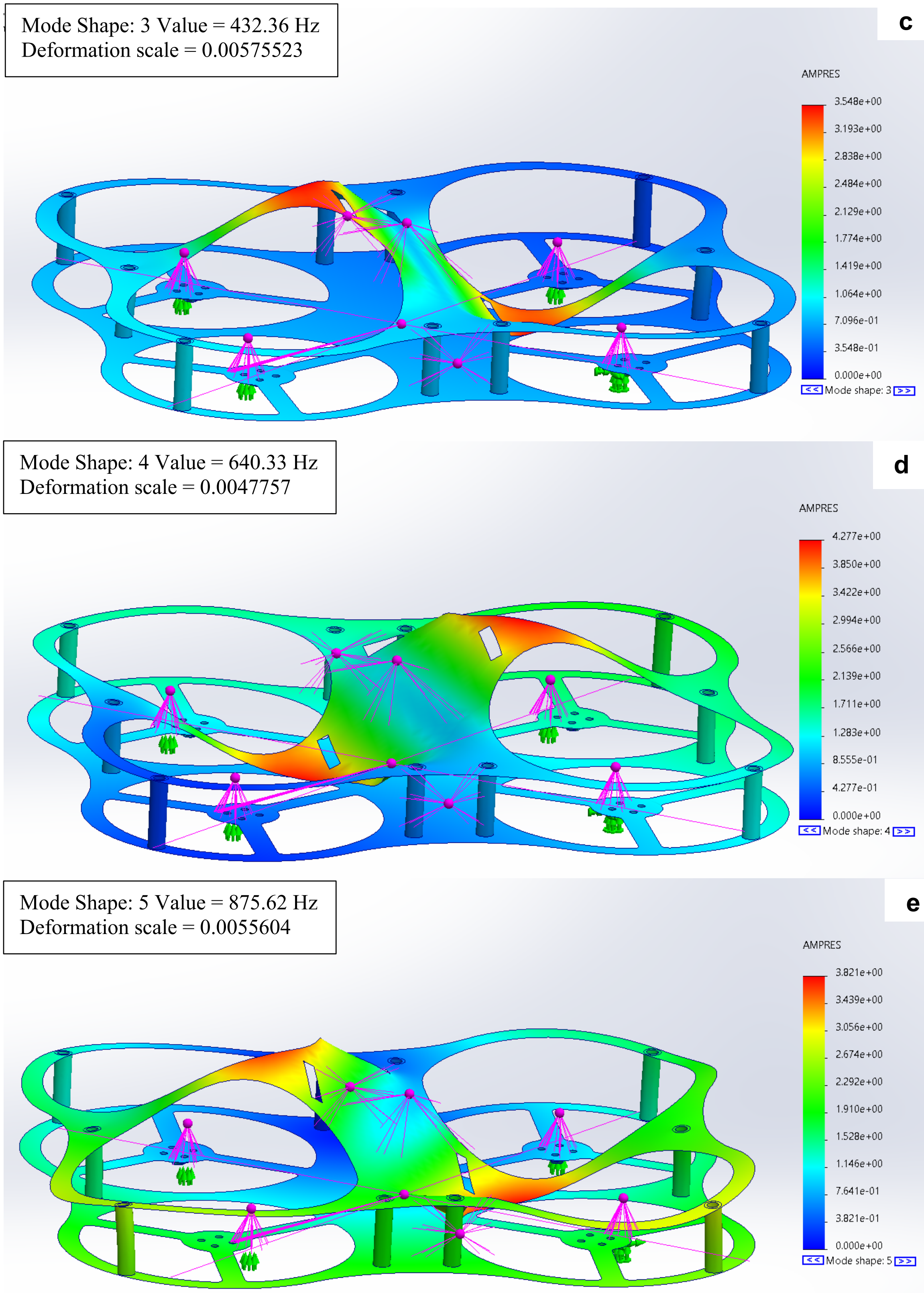
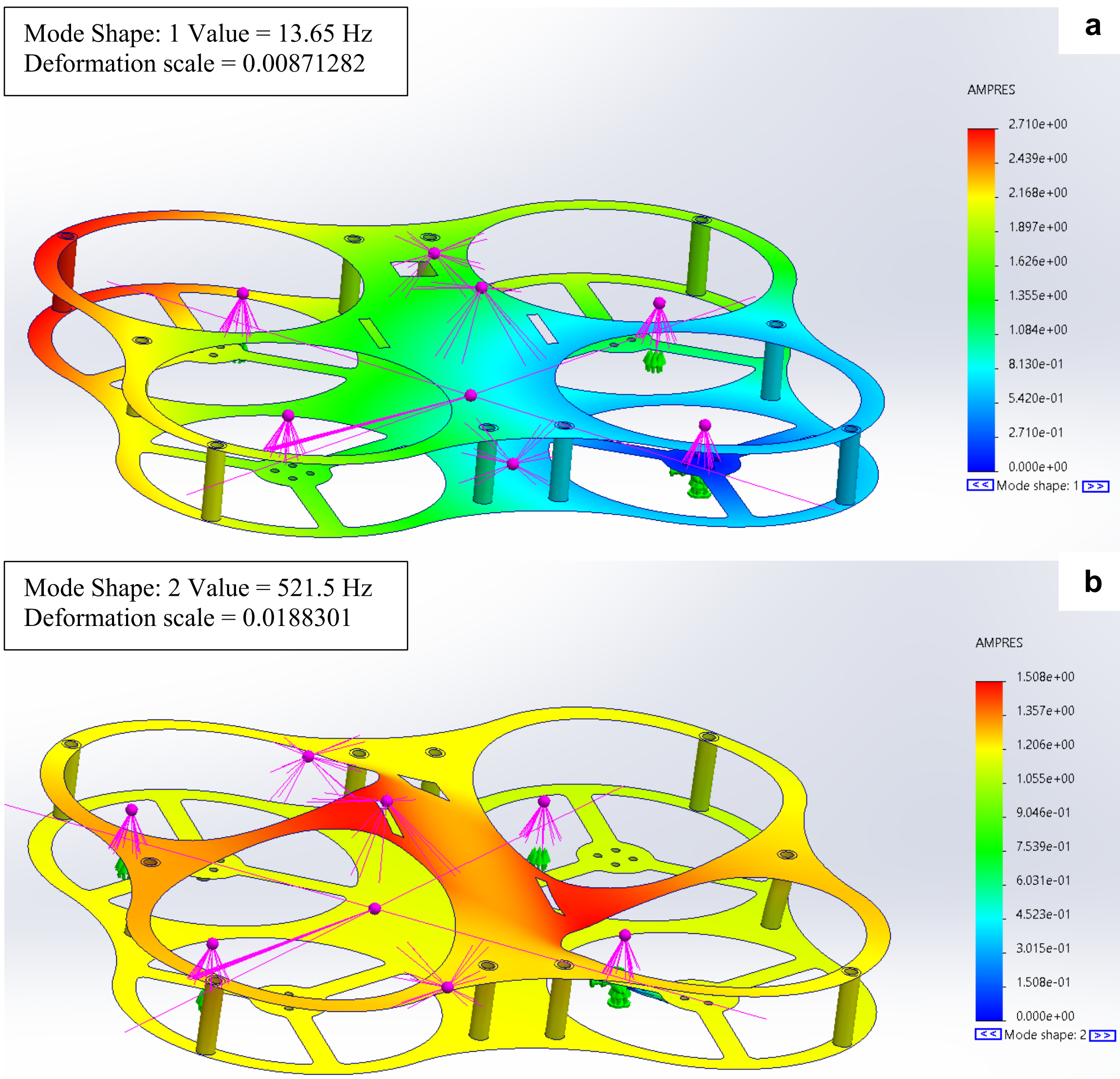


Fig. 8. Modal analysis of kenaf/epoxy composite frame (a-e): Modes 1-5

Figure 8 illustrates the first five mode shapes obtained from the modal analysis of the kenaf/epoxy composite FPV drone frame, highlighting the progressive dynamic deformation patterns of the structure. The KKKK configuration exhibited the lowest predicted stiffness among the three designs (CKKC and GKKG), resulting in more pronounced deformation at lower natural frequencies. Mode 1 demonstrates global bending of the entire frame, indicating its primary flexible direction and reflecting the relatively low flexural stiffness of kenaf fiber. Mode 2 reveals torsional twisting around the central body, showing how the frame reacts to asymmetric loading and rotor-induced disturbances. Mode 3 introduces lateral bending of the ducted ring structures, while Modes 4 and 5 highlight localized vibrations around the motor mounts and ring supports, areas that experience cyclic aerodynamic and thrust variations during flight. Overall, the evolution of these mode shapes demonstrates that the kenaf/epoxy frame was predicted to maintain stable global behavior at lower modes while higher modes are governed by localized structural features, confirming its suitability for FPV applications when operating away from resonance with motor-induced vibrations.



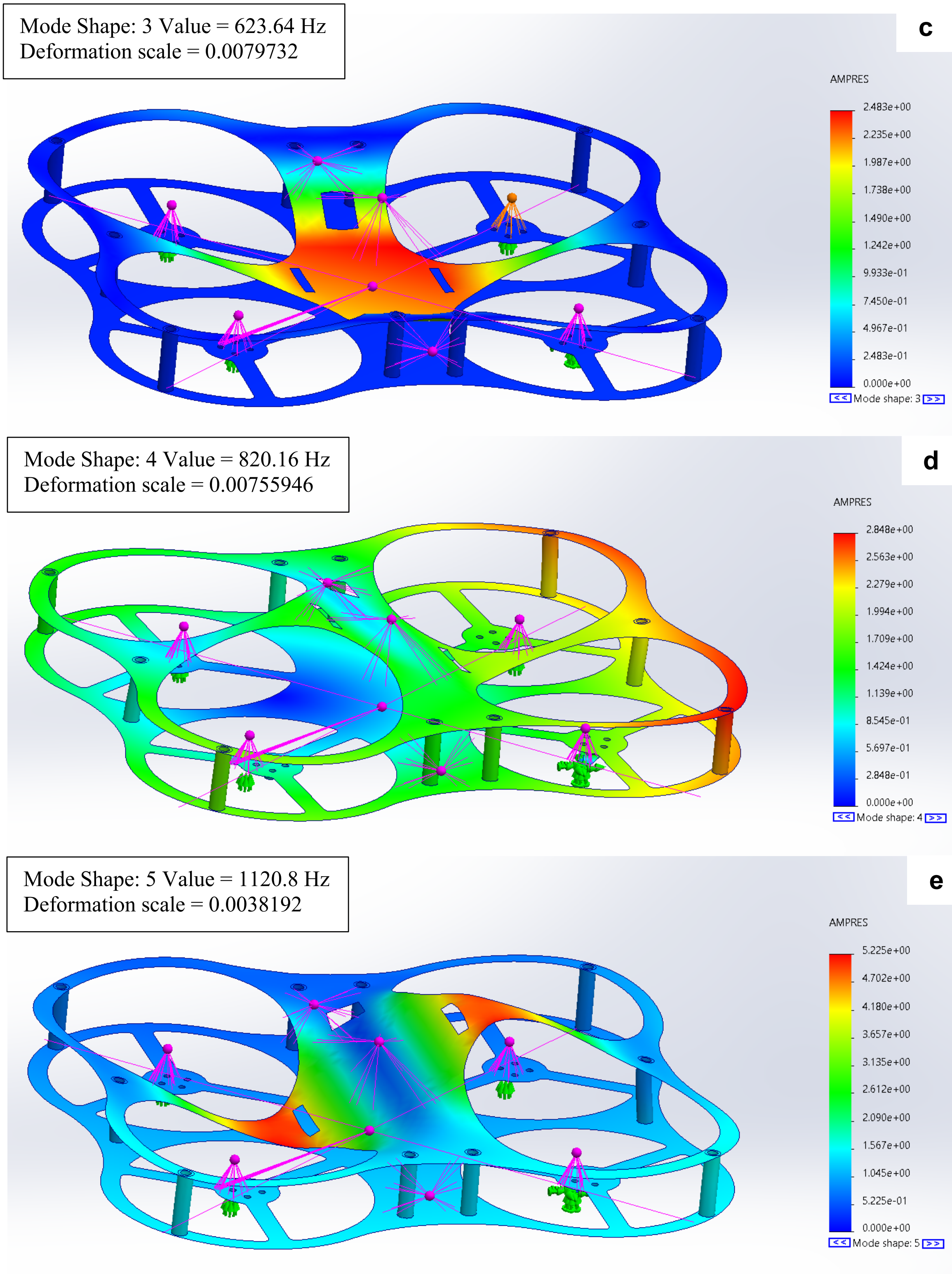
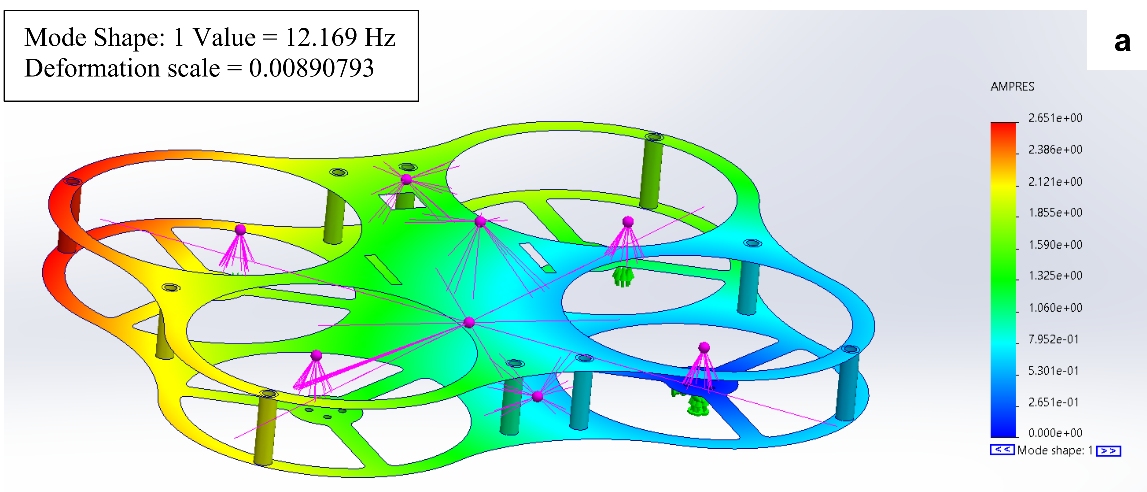
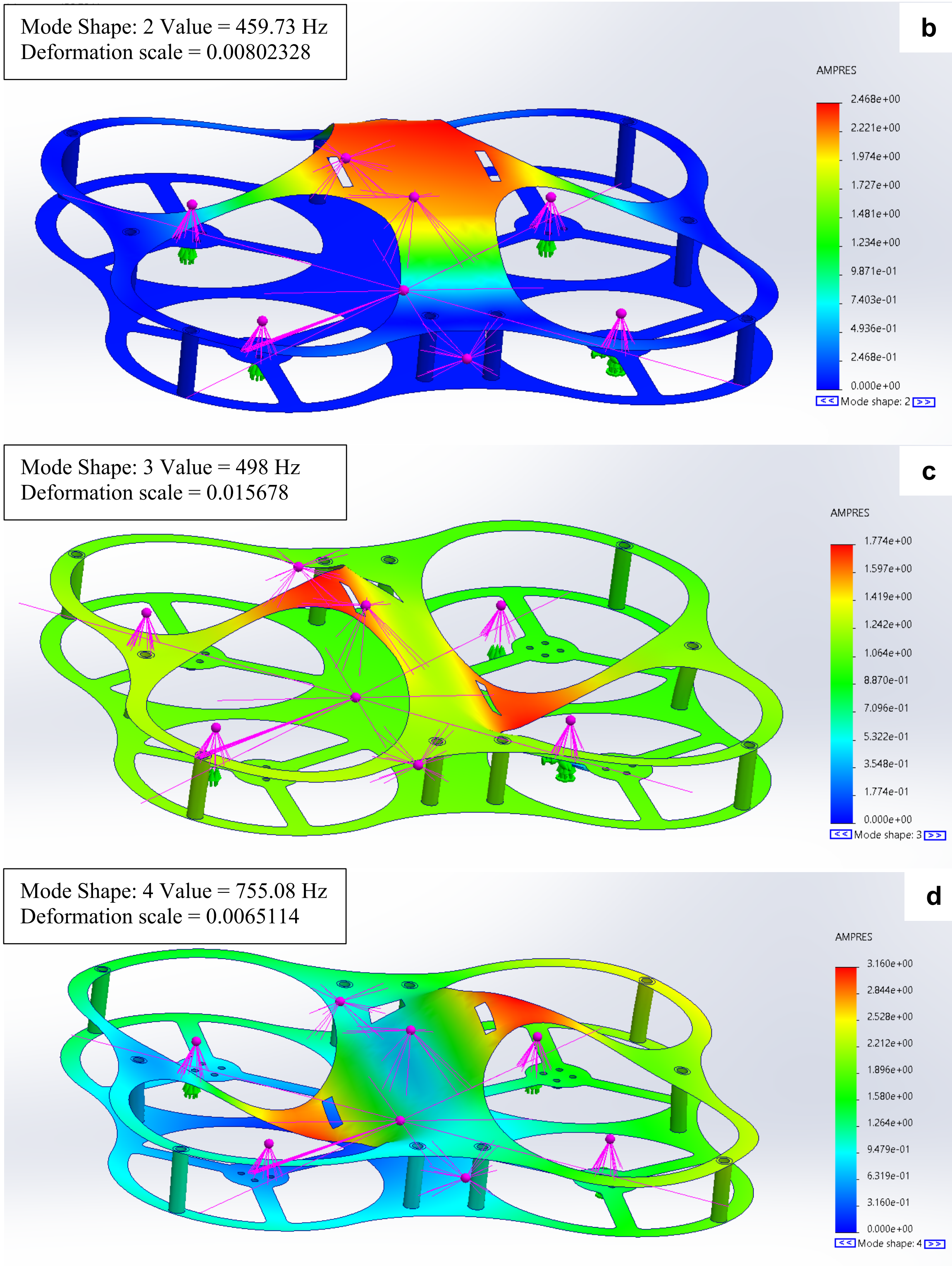


Fig. 9. Modal analysis of carbon-kenaf hybrid epoxy composite frame (a-e): Modes 1-5

Figure 9 shows the first five modal shapes of the CKKC hybrid epoxy composite drone frame, illustrating how the structure was predicted to deform at increasing natural frequencies. The analysis reveals that the hybrid laminate benefits from the stiff carbon fiber skins and the damping-efficient kenaf fiber core, producing a balanced dynamic response. In Mode 1, the frame undergoes global bending, indicating its most flexible direction under low-frequency excitation. Modes 2 and 3 display torsional and lateral bending patterns around the central body, reflecting how the CKKC configuration manages twisting loads generated by uneven rotor thrust. Modes 4 and 5 exhibit more localized deformations around the motor mounts and ducted rings regions typically sensitive to aerodynamic and rotor-induced vibrations. A study by Borah *et al.* (2022) reported that increasing the fiber volume fraction enhanced the fundamental natural frequency while reducing resonance amplitude, with carbon fiber composites exhibiting the highest dynamic performance and pineapple leaf fiber composites outperforming other natural fibers due to their superior stiffness and mechanical properties. Consistent with these findings, the present study demonstrated that hybridization of kenaf/epoxy laminates, particularly the carbon–kenaf configuration (CKKC), were predicted to significantly improve structural stiffness and increase the fundamental natural frequency while maintaining a lower structural mass and remaining outside the dominant motor excitation range, thereby reducing the risk of resonance.

Figure 10 shows the first five vibration modes of the GKKG hybrid epoxy composite frame, illustrating how the structure was predicted to respond dynamically due to the combination of stiff glass fiber skins and a lighter kenaf fiber core. The modal analysis indicates that the GKKG configuration exhibited slightly lower stiffness compared to carbon-based hybrids, leading to more pronounced deformation patterns in the early modes. Mode 1 reveals global bending of the frame, showing the primary flexible direction under low-frequency excitation. Mode 2 demonstrates a torsional twist around the central spine, influenced by the relatively lower in-plane stiffness of glass fiber compared to carbon. Mode 3 introduces lateral bending and twisting of the ducted rings, while Modes 4 and 5 highlight localized deformations near the arms and circular guards' areas susceptible to rotor-induced and aerodynamic vibrations.




Mode Shape: 2 Value = 459.73 Hz
Deformation scale = 0.00802328
b
AMPRES
2.468e+00
2.221e+00
1.974e+00
1.727e+00
1.481e+00
1.234e+00
9.871e-01
7.403e-01
4.936e-01
2.468e-01
0.000e+00
Mode shape: 2
Mode Shape: 3 Value = 498 Hz
Deformation scale = 0.015678
c
AMPRES
1.774e+00
1.597e+00
1.419e+00
1.242e+00
1.064e+00
8.870e-01
7.096e-01
5.322e-01
3.548e-01
1.774e-01
0.000e+00
Mode shape: 3
Mode Shape: 4 Value = 755.08 Hz
Deformation scale = 0.0065114
d
AMPRES
3.160e+00
2.844e+00
2.528e+00
2.212e+00
1.896e+00
1.580e+00
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Mode shape: 4

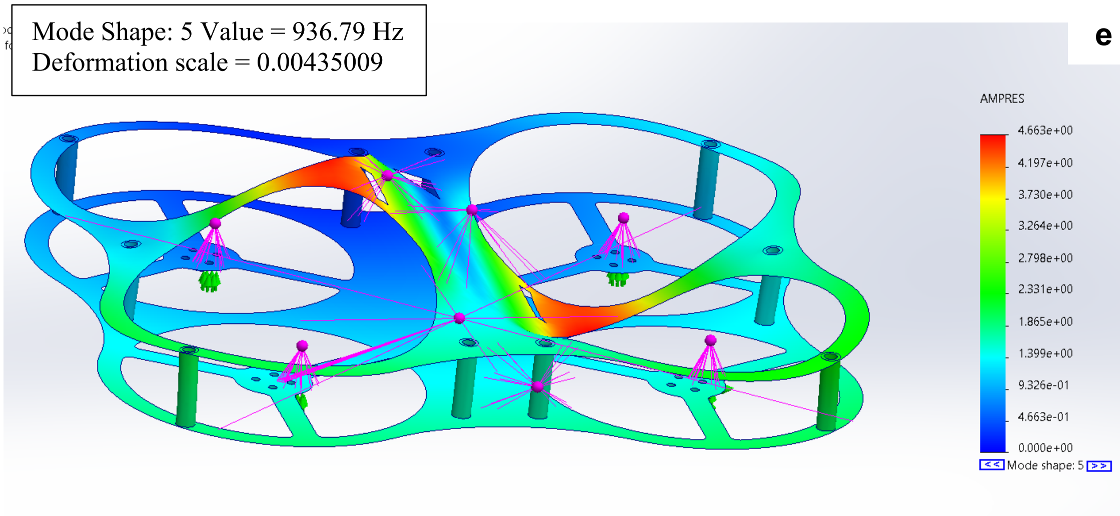

Fig. 10. Modal analysis of glass-kenaf hybrid epoxy composite frame (a-e): Modes 1-5

Based on the modal analysis in Figs. 8 to 10, in all frames, Mode 1 corresponds to global bending, Modes 2 and 3 involve torsion and lateral bending, and Modes 4 and 5 show localized deformations near the motor mounts and ducted rings. CKKC consistently exhibited the highest natural frequencies across all modes due to the high stiffness of carbon fiber skins, which effectively reinforce the kenaf core and produce a high stiffness-to-mass ratio, resulting in minimal deformation. GKKG shows intermediate frequencies, as glass fiber skins provide moderate stiffness, allowing slightly larger bending and twisting compared to CKKC. The KKKK was predicted to have the lowest frequencies, reflecting the low modulus of pure kenaf laminates, which makes the frame more flexible with larger deformations under similar modal excitations. Overall, the trend of CKKC > GKKG > KKKK in modal frequencies demonstrates that increasing the stiffness of the outer skins was predicted to significantly enhance vibration resistance, while the kenaf core contributes damping and lightweight support. From an FPV drone application perspective, motor-induced vibrations typically occur in the range of 100 to 300 Hz, depending on motor speed, propeller size, and operating conditions. All configurations showed Mode 2 frequencies well above this range, with KKKK at 276.74 Hz, CKKC at 521.5 Hz, and GKKG at 459.73 Hz, indicating that resonance with dominant motor vibrations is unlikely during normal flight. This is particularly important for FPV drones, where vibration isolation directly affects flight stability, onboard electronics, and video quality. Overall, while carbon/epoxy provides the highest dynamic performance, kenaf-based hybrid frames offer sufficiently high natural frequencies for FPV operation, making them attractive, sustainable alternatives that balance vibration performance, weight, and environmental impact.

Overall, the results demonstrated that woven kenaf composites, particularly when strategically hybridized with synthetic fiber skins, can achieve a favorable balance between stiffness, vibration resistance, weight efficiency, and sustainability, supporting their viability as eco-efficient alternatives for FPV drone structural applications. Future work should incorporate experimental validation through static loading and ground vibration testing to correlate numerical predictions with real FPV operating conditions.

FUTURE WORK

The present study was based primarily on finite element analysis (FEA) to evaluate the static and modal performance of kenaf/epoxy and hybrid composite FPV drone frames. Although the numerical models were developed using representative material properties, realistic loading conditions and direct experimental verification of the predicted structural responses have not yet been performed. This limitation should be considered when interpreting the results. Therefore, future work will focus on experimental validation through the fabrication of selected laminate configurations, followed by static loading tests, ground vibration (modal) testing, and flight-based vibration measurements. The experimentally obtained stress, deformation, and natural frequency data will be compared with the numerical predictions to assess model accuracy and refine the finite element models where necessary. Additional investigations under impact, fatigue, and crash-loading conditions will also be conducted to establish the long-term structural reliability of kenaf-based composite drone frames for practical FPV applications.

In addition to evaluating sustainable natural-fiber reinforcements, future research will also consider the environmental sustainability of the polymer matrix. While epoxy resin provides excellent mechanical performance for drone structures, they contribute to the environmental footprint of composite materials. Future studies will therefore investigate the use of bio-based and recyclable thermoplastic matrix systems in drone structures to reduce the overall environmental impact without compromising structural performance. Such developments would further enhance the sustainability of natural-fiber composite drone structures and support the transition toward more environmentally responsible aerospace materials.

Moreover, future studies will also investigate the integration of artificial intelligence (AI)-assisted modelling with embedded sensing technologies to enable real-time structural health monitoring and damage detection in kenaf-reinforced FPV drone frames (Shahar *et al.* 2026b). Machine learning algorithms will be developed to analyse sensor data, predict damage progression, estimate the remaining service life of the composite structure, and support predictive maintenance for improved flight safety and structural reliability.

CONCLUSIONS

This study numerically evaluated the static and modal performances of woven kenaf/epoxy, synthetic fiber, and hybrid composite laminates for FPV drone frame applications under realistic operational conditions.

1. The kenaf/epoxy frame was predicted to exhibit a maximum von Mises stress of 1.20 MPa and a maximum displacement of 0.00352 mm under hover-equivalent loading, remaining well within safe structural limits while achieving the lowest structural mass of 570 g.
2. Combined reinforcement with carbon and glass fibers significantly enhanced mechanical performance. When compared directly with the pure kenaf/epoxy frame, all hybrid configurations demonstrated measurable predicted improvements where stress reductions ranged from ~24% to ~63%, while displacement reductions ranged from ~21% to over ~81%, depending on the skin material.

3. Modal analysis showed that the predicted fundamental natural frequency increased from 11.9 Hz for the kenaf laminate to 13.6 Hz for the carbon–kenaf hybrid, approaching the carbon/epoxy benchmark of 15.2 Hz.
4. All kenaf-based and hybrid configurations exhibited natural frequencies well above dominant motor excitation ranges, indicating a low risk of resonance during FPV operation.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article.

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