Croatian Society
for Materials
Protection

Metalurgija/Metallurgy

Vol. 65 No. 2 / 2026

Experimental Characterization of Materials for Structural Airframe Elements of a Multirotor UAV

Petar Piljek [1,*], Denis Kotarski [2], Zdenka Keran [1] and Matija Krznar [1]

https://doi.org/10.64486/m.65.2.7

[1] University of Zagreb Faculty of Mechanical Engineering and Naval Architecture, Ivana Lucica 1 10000 Zagreb, Croatia; petar.piljek@fsb.unizg.hr, zdenka.keran@fsb.unizg.hr matija.krznar@fsb.unizg.hr
[2] Karlovac University of Applied Sciences, Department of Mechanical Engineering, Trg J. J. Strossmayera 9, 47000 Karlovac; denis.kotarski@vuka.hr
* Correspondence: petar.piljek@fsb.unizg.hr

Type of the Paper: Article
Received: September 2, 2025
Accepted: November 29, 2025

Abstract: This work presents a cost-efficient experimental framework for characterizing structural materials used in rotor arms of multirotor UAVs. A set of specimens, including FDM-printed PLA and PETG with varying wall thicknesses and infill percentages, and CFF-printed Onyx reinforced with fiberglass, was evaluated against a commercially established reference (S500). Static deflection tests revealed that increasing the wall number and infill in PETG specimens reduces deflection at the expense of mass, with the selected PETG design achieving ~30 % lower deflection and ~20 % lower mass than the commercial airframe. CFF specimens showed superior stiffness but were considerably more expensive and required significantly longer production times. The study demonstrates that low-cost experimental testing provides useful mechanical data, supporting the design of lighter, structurally efficient rotor arms.

Keywords: multirotor UAV; rotor arm; additive manufacturing, experimental characterization

1. Introduction

Advances in engineering materials and manufacturing technologies have significantly contributed to the development of modern mechatronic systems, enabling lighter, more efficient, and structurally optimized components across various engineering fields. These advancements have also substantially accelerated the evolution of aerial robotic systems, where material selection and structural design play an essential role in achieving high performance, reliability, and operational safety. Among different aerial platforms, multirotor unmanned aerial vehicles (UAVs) have become widely adopted in civilian, industrial, and research domains due to their high maneuverability, vertical take-off and landing capability, and relatively simple mechanical configuration. Their versatility has been demonstrated in applications such as autonomous wind turbine blade inspection using LiDAR-equipped UAVs [1], navigation in complex electromagnetic or magnetic environments [2], and precise dynamic flight tracking enabled by modern autopilot systems [3].

From a hardware perspective, multirotor UAVs consist of propulsion units mounted on a structural airframe, powered by lithium-polymer batteries, and supported by onboard sensors and control electronics to ensure stable and autonomous flight. Their design requires careful integration of propulsion, energy, and control elements to achieve the desired performance, endurance, and reliability. Established methodologies for system sizing, component selection, and performance evaluation are presented in the literature [4]. Recent works highlight low-cost and modular UAV concepts for versatile applications, including custom platforms developed for controller tuning and experimental validation [5]. From the structural design standpoint, advances in design methodologies have introduced generative design and simulation tools for structural optimization [6]. In parallel, the use of composite and additively manufactured (AM) materials has enabled lightweight and application-tailored UAV airframes [7], underscoring the increasing importance of structural design in improving overall flight efficiency and performance. With the growing adoption of AM in UAV development, desktop 3D printers have become attractive low-cost fabrication options, offering access to a wide range of affordable polymer materials, and can even be adapted to process high-performance thermoplastic polymers [8].

This study addresses the characterization of materials used for manufacturing structural airframe elements of multirotor UAVs, with particular emphasis on rotor arms. Although recent research increasingly employs design tools for UAV structural optimization, existing simulation-based approaches generally assume homogeneous and isotropic material behavior, which therefore do not provide sufficient accuracy for AM elements. The primary contribution of this work is a methodological cost-efficient experimental framework, presented to determine relevant mechanical properties of AM structural elements. The proposed approach enables practical, application-oriented material characterization that accounts for manufacturing-induced effects, supporting more informed design decisions in low-cost and customizable UAV production. The findings provide a basis for improving lightweight and reliable multirotor airframe structures, particularly when AM is employed.

2. Structural Design and Comparative Analysis

The propulsion-supporting airframe parts of a multirotor UAV represent critical load-bearing structural elements whose characteristics directly influence the dynamic behavior of agile aircraft. These parts can be divided into elements that form the central structure and the rotor arms, which extend outward and support the propulsion units. Among these components, the rotor arms experience the highest mechanical demands. The electric motors are mounted at the outer ends of the rotor arms, where the rotating propellers generate thrust forces and drag torques, as schematically shown in Figure 1, while the inner ends of the arms are attached to the central structure of the UAV, which must effectively absorb and transfer these loads.

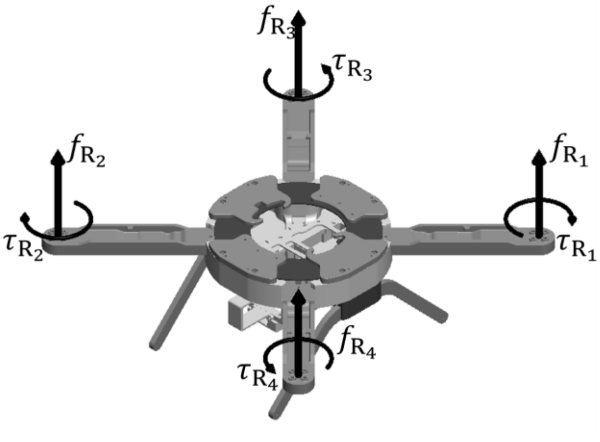

Figure 1. Schematic representation of multirotor UAV airframe parts.

The rotor arm must provide sufficient stiffness to limit deflection under thrust loads, while remaining lightweight to minimize the overall mass of the UAV. Material selection and structural configuration largely depend on the size and performance requirements of the platform. For small multirotor platforms, particularly in the hobby and entry-level segment, airframes are predominantly manufactured from plastic composites due to their low weight and low production cost. These frames are commonly produced by injection molding and reinforced with carbon rods to increase stiffness, as seen in widely used models such as the DJI F450 [9] and the

https://doi.org/10.64486/m.65.2.7

S500 airframe [10]. Aluminum airframes are also present in this size category [11] but are less common. In racing-oriented and high-agility FPV-class UAVs, carbon-fiber frames represent the dominant solution due to high stiffness, low mass, and robustness under frequent impacts [12]. At the heavy-lift end of the spectrum, multirotor platforms rely increasingly on carbon-fiber structural elements to achieve a high strength-to-weight ratio, as shown in [13]. While these conventional approaches remain standard for large production series and commercially established airframes, AM is increasingly adopted for low-volume, customizable UAV builds. AM enables functional integration and rapid iteration of rotor arm designs, offering new possibilities in product complexity [14] that are difficult or impractical to achieve using conventional manufacturing methods.

In low-cost production scenarios, where minimizing manufacturing expenses and enabling design flexibility are key requirements, Fused Deposition Modeling (FDM) AM technology naturally emerges as a suitable alternative to conventional fabrication methods. FDM technology enables rapid prototyping and cost-efficient small-batch production of rotor arms. The 3D model of the analyzed rotor arm, together with the electric propulsion unit thrust force characteristic, is shown in Figure 2. The thrust data were acquired following the methodology presented in [15]. The legend identifies the types of propeller, motor, and battery, respectively. Since thrust represents the dominant load acting on the rotor arm during flight, its magnitude has a direct impact on structural elements. Unlike aluminum structures, where material properties are largely predefined, the mechanical performance of FDM-printed parts strongly depends on the selected printing parameters. Designers can easily adjust parameters such as wall thickness, infill density and pattern, layer height, and print orientation, all of which influence stiffness, strength, and failure behavior of the printed part. As a result, the structural characteristics of the rotor arm are not only defined by its CAD geometry but also by process-specific parameters, making the design–manufacturing relationship more tightly coupled. An essential objective in increasing the overall efficiency of the UAV system is to reduce mass while maintaining the required structural properties of the rotor arm.

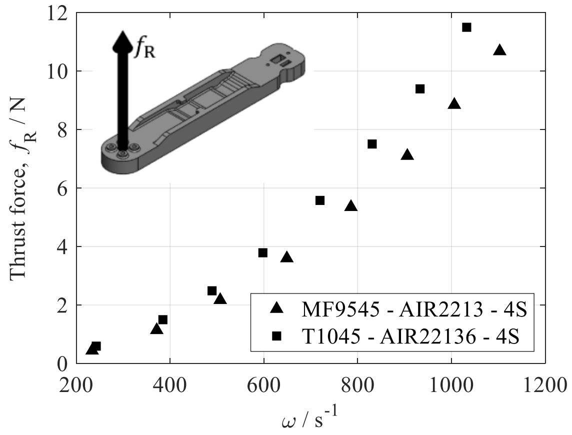

Figure 2. 3D model of the rotor arm and the electric propulsion unit thrust force characteristic.

3. Experimental Characterization of Additively Manufactured Rotor Arms

For the experimental evaluation, a set of rotor arm specimens was selected to benchmark different AM approaches against a commercially established reference. As a baseline, the S500 airframe rotor arm, an injection-moulded polymer component reinforced with a carbon rod, was included as the reference setup. FDM-printed specimens manufactured from polylactic acid (PLA) and polyethylene terephthalate glycol (PETG) were produced to assess the influence of structural parameter selection. PLA was included for comparison purposes only, as despite its favourable stiffness, it is not suitable for rotor arm prototyping due to its limited UV resistance and low heat-deflection temperature. PETG specimens were therefore tested with varying wall thicknesses and infill percentages to evaluate the effect of structural parameter selection on mechanical performance.

Finally, a CFF-manufactured rotor arm reinforced with continuous fiberglass is included to enable a performance comparison between conventional FDM and CFF, providing insight into potential benefits for structurally demanding UAV components.

The key characteristics of all tested specimens are summarized in Table 1. For the FDM-produced specimens, slicing was performed in Bambu Studio for fabrication on a Bambu Lab P1S printer. Figure 3 shows the complete 3D geometry alongside the sliced representations, highlighting the internal infill structure and wall configuration. For these specimens, a gyroid infill pattern was used for all materials. Printing was conducted at the following temperatures: PLA at 220 °C nozzle and 55 °C bed, and PETG at 255 °C nozzle and 70 °C bed.

For the CFF-manufactured specimen, preparation was performed in the Markforged Eiger slicer for printing on a Markforged Onyx Pro system. The Onyx specimen utilized a triangular infill pattern and was printed at 275 °C nozzle temperature for the Onyx filament and 255 °C for the fiberglass reinforcement, while the printing bed remained unheated.

Table 1. Key characteristics of tested specimens.

Setup	Manufacturing Technology	Material	FDM parameters		Mass	Printing time
			Infill / %	Wall count	g	min
1	Injection molded	Polymer with reinforced carbon rod	–	–	44.9	–
2	AM – FDM	PLA	20	2	28.1	61
3	AM – FDM	PETG	20	2	29.9	62
4	AM – FDM	PETG	20	4	35.4	67
5	AM – FDM	PETG	30	4	39.6	80
6	AM – FDM	PETG	30	5	42.5	82
7	AM – CFF	Onyx reinforced with fiberglass	37	2	37.7	442

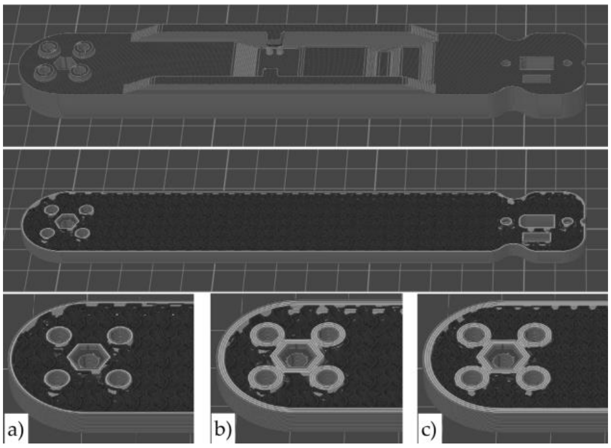

Figure 3. 3D model of rotor arm with sliced views showing gyroid infill and wall structure: (a) 2 walls with 20 % infill, (b) 4 walls with 20 % infill, and (c) 4 walls with 30 % infill.

The static deflection tests were performed using a dial gauge-based measurement system. The rotor arm was clamped upside down in a fixture to replicate the loads it experiences when mounted on a multirotor UAV. Load points were applied at the motor mounts, and deflection was measured 130 mm from the clamping point, directly opposite the applied load along the rotor arm, as shown schematically in Figure 4. A dial gauge (Kaefer, 0.01 mm resolution) was mounted on the fixture to capture deflection, while weights were applied beneath the arm. For each specimen, 10 measurements were taken with weights ranging from 300 g to 1200 g in increments of 100 g. In total, 29 specimens were experimentally tested, and all measurement data were manually recorded in a measurement matrix. The results are presented for a total of seven setups, as summarized in Table 1. The maximum standard deviation observed across all specimens, calculated from at least three repeated measurements for each load step, was 0.092 mm. This value is considered negligible relative to the total deflection magnitudes and therefore does not affect the comparative conclusions.

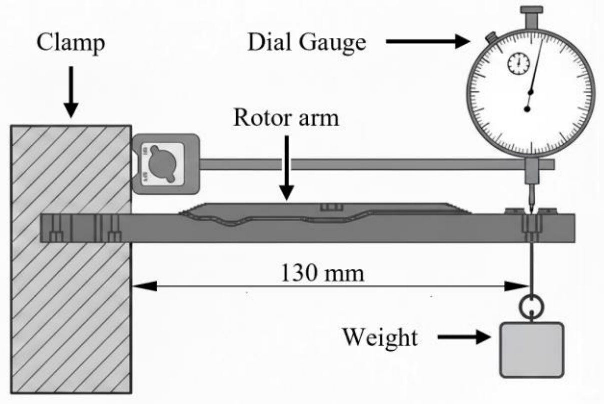

Figure 4. Schematic representation of the experimental setup.

The experimental measurement data were processed and visualized using the MATLAB software package. Figure 5 presents the static deflection results for all seven rotor arm setups considered in this study. Although the PLA specimen exhibited the highest mechanical performance, it is unsuitable for UAV airframes in outdoor conditions because of its poor UV stability and low heat-deflection temperature. In practice, the rotor arm carries a BLDC motor that heats up during operation, and PLA is prone to softening and loss of stiffness under such thermal loads. The CFF-manufactured setup is suitable for outdoor usage and exhibits better mechanical performance compared to the reference setup (commercial DJI S500 airframe). However, its production cost is substantially higher, the material itself is an order of magnitude more expensive, and the required printing time is approximately six times longer, which limits its suitability for low-cost, rapid-prototyping applications.

Compared to the commercial setup, the PETG configurations achieved notable improvements. As expected, increasing the number of walls and the infill percentage in the PETG specimens resulted in higher mass and a corresponding reduction in deflection. Within the PETG group, although setup 3 exhibited the most favorable mass-to-deflection ratio, its two-wall structure does not provide sufficient local stiffness in the motor-mount region, where concentrated compressive loads occur. Setup 4 was therefore selected for prototype fabrication because its four-wall configuration offers significantly improved structural robustness with only a moderate mass increase while still achieving substantially lower deflection, approximately a 30 % reduction, and lower overall mass, roughly 20 % less than the commercial reference. In practical operation, the reduced static deflection and lower mass of the selected PETG configuration provide measurable benefits for multirotor UAV performance. Due to its higher stiffness, the PETG arm produces a smaller bending-induced tilt of the thrust vector, resulting in slightly improved thrust alignment. Additionally, the 40 g total mass reduction for a quadrotor lowers the required hover thrust, leading to a modest decrease in power consumption.

https://doi.org/10.64486/m.65.2.7

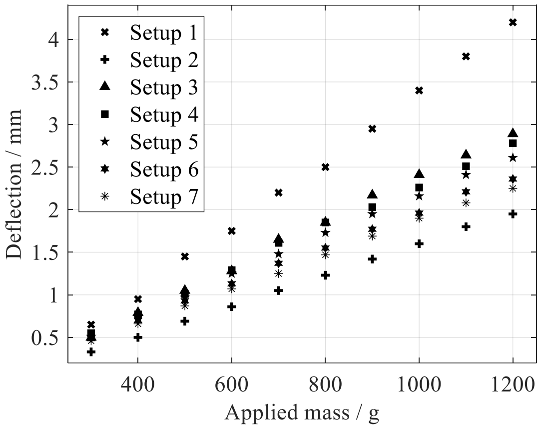

Figure 5. Measured static deflections for all seven rotor arm setups.

4. Conclusions

This study presented a cost-efficient experimental framework for characterizing rotor arms of multirotor UAVs, enabling practical evaluation of FDM and CFF technologies in structural element production. The results demonstrated that PETG specimens allow meaningful tuning of stifness and mass through adjustment of wall thickness and infill density. The chosen PETG design achieved significantly lower deflection and reduced mass compared to the commercial airframe elements. CFF Onyx parts exhibited superior stiffness, but with substantially higher cost and longer production time, making them suitable only for applications where structural performance clearly outweighs manufacturing constraints.

The findings also show good potential for commercial use. Commercially, desktop 3D printing enables affordable low-volume production without expensive molds, allowing for quick design iterations and on-demand spare parts. Furthermore, the reduction in mass achieved by the optimized PETG parts helps lower the drone's power consumption, leading to better flight efficiency. The proposed test method also helps engineers define specific printing settings that guarantee repeatable and predictable mechanical behavior, which is essential for selling reliable commercial products.

In conclusion, these results show that low-cost experimental testing provides useful data for designing lighter, structurally efficient rotor arms and supporting optimized UAV airframe development.

Acknowledgments: This research was funded and supported by the European Union through the project "Advancing Autonomy: A Concept for a Multipurpose Ground-Aerial Robotic System (cAMGARS)" (Grant Agreement ID: NPOO.C3.2.R3-I1.05.0357).

References

[1] M. Car, L. Markovic, A. Ivanovic, M. Orsag, and S. Bogdan, "Autonomous Wind-Turbine Blade Inspection Using LiDAR-Equipped Unmanned Aerial Vehicle," *IEEE Access*, vol. 8, pp. 131380–131387, Jul. 2020, https://doi.org/10.1109/ACCESS.2020.3009738

[2] D. Martinović, S. Bogdan, and Z. Kovačić, "Mathematical Considerations for Unmanned Aerial Vehicle Navigation in the Magnetic Field of Two Parallel Transmission Lines," *Applied Sciences*, vol. 11, no. 8, pp. 3323, Apr. 2021, https://doi.org/10.3390/app11083323

[3] S. Kusmirek, V. Socha, T. Malich, L. Socha, K. Hylmar, and L. Hanakova, "Dynamic Flight Tracking: Designing System for Multirotor UAVs With Pixhawk Autopilot Data Verification," *IEEE Access*, vol. 12, pp. 109806–109821, Aug. 2024, https://doi.org/10.1109/ACCESS.2024.3441115

[4] A. Rezaei, F. Vahedi, A. Talaeizadeh, and A. Alasty, "A Practical Algorithm for Multirotor System Design and Evaluation," in *Proc. 11th RSI Int. Conf. on Robotics and Mechatronics (ICRoM)*, Tehran, Iran, 2023, pp. 165–170, https://doi.org/10.1109/ICRoM60803.2023.10412467

[5] M. Waliszkiewicz, K. Wojtowicz, Z. Rochala, and E. Balestrieri, "The Design and Implementation of a Custom Platform for the Experimental Tuning of a Quadcopter Controller," *Sensors*, vol. 20, no. 7, pp. 1940, Mar. 2020, https://doi.org/10.3390/s20071940

[6] V. Andries and S.-M. Zaharia, "Generative Design, Simulation, and 3D Printing of the Quadcopter Drone Frame," *Applied Sciences*, vol. 15, no. 9, pp. 9647, Aug. 2025, https://doi.org/10.3390/app15179647

[7] A.V. Azarov, F. K. Antonov, M. V. Golubev, A. R. Khaziev, and S. A. Ushanov, "Composite 3D Printing for the Small Size Unmanned Aerial Vehicle Structure," *Composites Part B: Engineering*, vol. 169, pp. 157–163, May 2019, https://doi.org/10.1016/j.compositesb.2019.03.073

[8] J. Kessler, K. Draganová, K. Semrád, and M. Filko, "Modification of the 3D Printer for the Processing of the High-Performance Thermoplastic Polymers in the Production Process of Transport System Components," *Metalurgija*, vol. 62, no. 3–4, pp. 412–414, Jul. 2023. [Online]. Available: https://hrcak.srce.hr/301005 [Accessed: Oct. 10, 2025]

[9] DJI, "DJI F450 ARF Kit V5 Flame Wheel," Build Your Own Drone. [Online]. Available: https://www.buildyourowndrone.co.uk/dji-f450-arf-kit-v5-flame-wheel [Accessed: Oct. 13, 2025]

[10] Holybro, "Holybro S500 V2 Airframe Kit (510074)," SpexDrone. [Online]. Available: https://spexdrone.com/products/holybro-s500-v2-airframe-kit-510074 [Accessed: Oct. 13, 2025]

[11] HobbyKing, "HobbyKing X550 Glass Fiber Quadcopter Frame 550mm," HobbyKing. [Online]. Available: https://hobbyking.com/en_us/hobbyking-x550-glass-fiber-quadcopter-frame-550mm.html [Accessed: Oct. 13, 2025]

[12] F. A. A. Mamani, G. B. C. Malcoaccha, M. A. B. Quicaño, L. G. P. Gutierrez, G. A. E. Espinoza, E. S. Espinoza, and A. O. Salazar, "Design, assembly, and tuning of a multipurpose FPV drone: A flexible and low-cost alternative," *Hardware X*, vol. 23, pp. e00672, Sep. 2025, https://doi.org/10.1016/j.ohx.2025.e00672

[13] D. Kotarski, P. Piljek, M. Pranjić, and J. Kasać, "Concept of a Modular Multirotor Heavy Lift Unmanned Aerial Vehicle Platform," *Aerospace*, vol. 10, no. 6, pp. 528, Jun. 2023, https://doi.org/10.3390/aerospace10060528

[14] "A guide to additive manufacturing," ed D. Godec, et. al., Cham, Switzerland: Springer Cham, 2023, https://doi.org/10.1007/978-3-031-05863-9

[15] P. Piljek, D. Kotarski, and M. Krznar, "Method for Characterization of a Multirotor UAV Electric Propulsion System," *Applied Sciences*, vol. 10, no. 22, art. 8229, Nov. 2020, https://doi.org/10.3390/app10228229