

Carbon fiber reinforced polymer and polyethylene terephthalate glycol carbon comparison for quadcopter frame application

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ABSTRACT

Unmanned aerial vehicles are widely used in various fields of application. Due to their low weight requirements and favorable strength properties, UAVs are primarily manufactured from CFRP (carbon fiber reinforced polymer), however, 3D printing technology also appears to be a promising technique for the production of such structures. This article presents a comparison of two materials that can be used to manufacture a small, high-performance UAV. The drone frame was selected as the research object. In order to determine the basic mechanical properties of the proposed materials, samples were made from CFRP using the vacuum bagging method and from PETG (polyethylene terephthalate glycol) Carbon filament. The samples and frame elements made of PETG Carbon were manufactured using a Prusa i3 MK3 printer. Tensile and impact tests were conducted to evaluate the mechanical properties of the materials. CFRP demonstrated 16 times higher tensile strength and 10 times higher Young's modulus compared to PETG Carbon. In the Charpy impact test, CFRP demonstrated 72% higher surface impact strength and 121% higher edge impact strength than PETG Carbon. For the flight tests, the quadcopter frame was made of PETG Carbon due to its simpler production process and approximately 7.5% lower density compared to CFRP. These properties were prioritized due to the intended use of the unmanned aerial vehicle being tested. A commercial CFRP frame was used for comparative flight tests. After assembling the drones, test flights were conducted.

Keywords: mechanical properties, unmanned aerial vehicles, carbon fiber reinforced polymer, 3D printing

INTRODUCTION

Currently, unmanned aerial vehicles (UAVs) are widely utilized across numerous sectors of the economy, finding applications in areas such as agriculture, industry, forestry, energy infrastructure, border protection, law enforcement, military operations, and even sports. They are used, among others, for atmospheric research, monitoring areas during floods and fires, patrolling international borders, inspecting high-voltage power lines, providing telecommunication relay services, as well as conducting rescue and search missions [1–5].

In the military sector, UAVs are employed for reconnaissance, surveillance, and fire support, as well as in special operations and combat missions. They are also used for force protection, supply transport, and strike missions, while ongoing technological advancements enable the development of loitering munition concepts and so-called intelligent swarms. The recreational market is also gaining increasing importance, particularly FPV (first person view) flights and commercially available drones, which, owing to modern automatic stabilization systems and satellite navigation technologies, are becoming easy to operate and accessible to a wide range of users.

Development trends in the field of UAVs include further miniaturization of structures, the advancement of drone swarm concepts involving cooperation in combat or rescue missions, as well as increased system autonomy. Increasing emphasis is being placed on extending UAV flight endurance, including research into ground-based laser power transmission and hybrid power systems. As a result, UAVs are becoming increasingly autonomous and capable of performing complex tasks, ranging from environmental monitoring to reconnaissance missions [6–8].

Since the early days of aviation, engineers have sought materials that combine low weight with high strength, stiffness, and reliability. The history of aircraft construction demonstrates the use of a wide range of materials, from wood and metal alloys to composite materials, which currently dominate modern aerospace structures. Engineering materials used in structural applications should exhibit strength properties appropriate for their intended use [9, 10]. One example of a study involving the numerical strength analysis of an aluminum support platform for an unmanned aerial vehicle is presented in [11].

Similarly to manned aircraft, unmanned aerial vehicle structures primarily employ composite materials due to their low density combined with high mechanical strength [12,13]. Specialized test stands equipped with strain gauges for measuring structural loads are used in strength testing of composite drone structures [14–16]. For testing the strength of aerospace materials or components, it is also possible to use a conventional universal testing machine [17], the digital image correlation (DIC) method [18], or a combination of both approaches [19].

3D printing has recently gained significant popularity in unmanned aviation due to the widespread availability of printers and filaments with diverse material properties. Reinforced filaments are thermoplastic materials modified with short carbon, aramid, or glass fibers, as well as metal or ceramic particles. The most commonly used filaments include PLA (polylactic acid) [20], PETG (polyethylene terephthalate glycol) [21], ABS (acrylonitrile-butadiene-styrene) [21], ASA (Acrylonitrile Styrene Acrylate) [22], and TPU (Thermoplastic polyurethane) [23]. Filaments themselves generally exhibit relatively low mechanical properties [21, 24], however, reinforcement significantly improves their strength and stiffness while maintaining low density. Interesting properties

are exhibited by the technical PETG Carbon filament [25], reinforced with 10% carbon fibers. For example, the manufacturer Spectrum reports that this material offers increased stiffness, enhanced abrasion resistance, and good mechanical performance while maintaining ease of printing and a density of 1.32 g/cm³.

The use of 3D printing represents an attractive option, particularly for racing drones or UAVs operating in hazardous environments, where structural durability is not the primary concern. In such applications, significant emphasis is placed on the rapid restoration of airframe airworthiness at the lowest possible repair cost, including not only the low cost of replacement parts but also the logistical support costs associated with the repair process. The study aimed to preliminarily determine selected mechanical properties of two materials potentially applicable in the manufacture of drone frames: a conventional carbon-fiber composite and a material produced by 3D printing using PETG Carbon filament. The performance of UAVs equipped with a composite frame and a frame manufactured using 3D printing technology was also compared during the study. The study aimed at assessing the feasibility of the practical application of a low-cost drone load-bearing structure manufactured using 3D printing technology for specialized applications, as well as comparing the mechanical properties of the two tested materials.

METHODOLOGY

To perform a comparative analysis of the mechanical properties of materials selected for the UAV frame structure, a CFRP was manufactured using the infusion method, whereas a PETG Carbon filament composite was produced using 3D printing technology.

The laminate plate was manufactured as a material reinforced with seven layers of carbon-fiber roving fabric, weighing 220 g/m². The matrix material consisted of an epoxy system manufactured by MGS, comprising L285 resin and H287 hardener mixed at a ratio of 100:40. After the mold was sealed, the composite was left under vacuum conditions for 24 hours. A composite with a thickness of 1.7 mm and a density of 1.39 g/cm³ was obtained and subsequently cut into test specimens for mechanical testing using the waterjet method.

The printed specimens were manufactured using 3D printing technology on a Prusa i3 MK3 printer. PETG Carbon filament reinforced with a 10% addition of short carbon fibers was used for the printing process. All specimens were printed with 100% infill. The test specimens were printed in the XY plane (flat orientation) with 100% linear infill applied alternately at $+45^\circ$ and -45° between successive 0.2 mm layers. The nozzle temperature during the printing process was maintained at 255°C , while the build plate temperature was set to 85°C . The initial layer height was configured to 0.2 mm, and a 4 mm brim was applied to enhance adhesion to the build plate. The number of perimeters was set to 5, while the number of top and bottom layers was specified as 6. The printing process was carried out at a printing speed of 40 mm/s, using a 0.45 mm extrusion width and a 0.4 mm nozzle. The retraction was set to 0.6 mm with a retraction speed of 35 mm/s. The specimens were printed on a textured PEI (Polyetherimide) build plate.

RESULTS

Two mechanical strength tests were performed on the prepared materials:

- tensile test;
- impact strength test.

A total of twenty five specimens of each material were prepared for the tests (Figure 1). For impact strength tests, 20 printed specimens were prepared from PETG Carbon filament with dimensions of $80 \times 10 \times 2$ mm, as well as 20 specimens made of CFRP with dimensions of $80 \times 10 \times 1.7$ mm. For the tensile test, five printed specimens ($150 \times 20 \times 2$ mm) and five composite specimens ($150 \times 20 \times 1.7$ mm) were prepared.

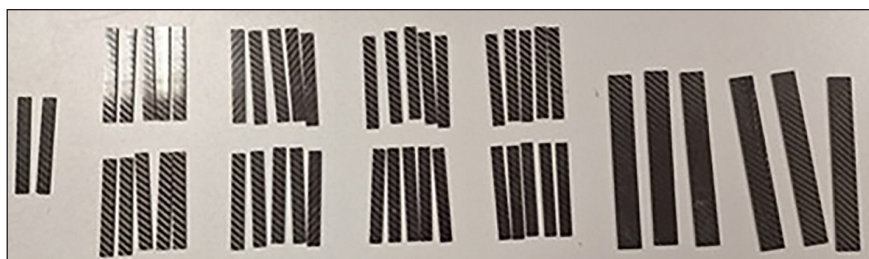


Figure 1. Composite specimens for mechanical strength testing

Tensile test

The tensile test was conducted using an Instron 5982 testing machine (Figure 2) in accordance with the ISO 527-5 standard. The sample size for each material series was 5. The tensile tests were conducted at a testing speed of 2 mm/min.

The failure mechanisms of the samples varied. In the case of CFRP, all samples failed by tearing the reinforcing fibers from the matrix and then breaking them. Matrix defects were visible in the area where the reinforcing fibers broke. In the case of PETG Carbon, the failure occurred between the layers. The results of the tensile test are presented in Figure 3 and Figure 4.

The CFRP had more than 16 times higher tensile strength and a 10-fold higher Young's modulus compared with PETG Carbon (Figure 2 and Figure 3). For the PETG Carbon material, the average tensile strength was 46.0 ± 0.5 MPa,



Figure 2. Instron 5982 testing machine

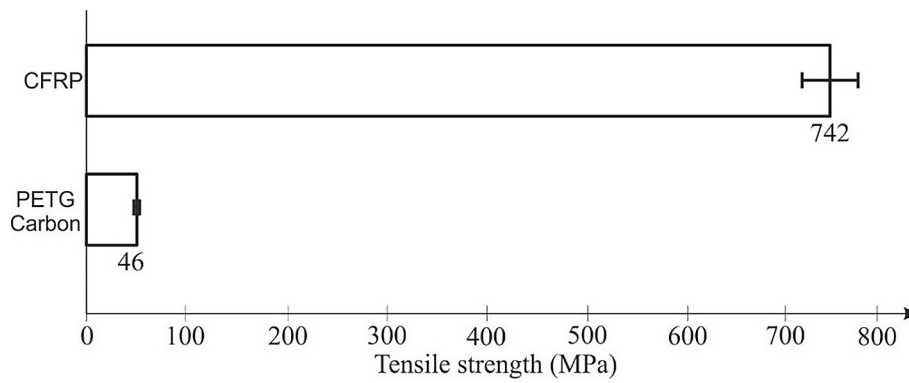


Figure 3. Tensile strength of the tested specimens

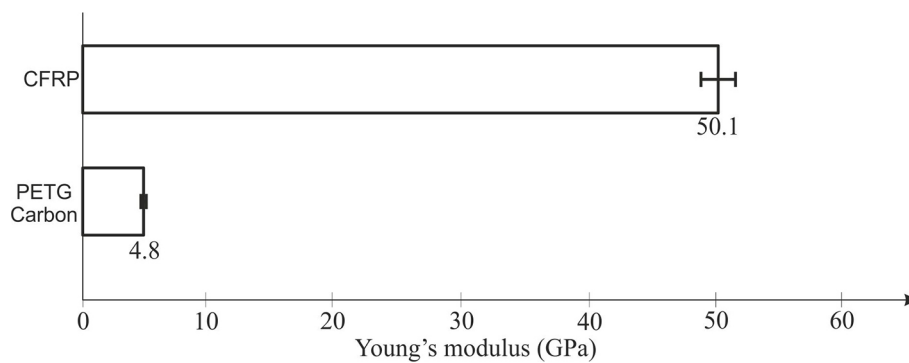


Figure 4. Young's modulus of the tested specimens

while the Young's modulus (E) reached an average value of 4.8 ± 0.2 GPa. The average tensile strength of the carbon fiber-reinforced composite specimens was 742 ± 32 MPa, while the average Young's modulus (E) reached 50.1 ± 1.6 GPa. The scatter of results for PETG Carbon was low, indicating stable mechanical properties of this material. In the case of the CFRP, the standard deviations were greater, which may result from structural non-uniformity of the composite or differences in the quality of fiber impregnation with the liquid matrix.

The specific strength of CFRP is 534 kNm/kg, while for PETG Carbon it is 35 kNm/kg, indicating a load-bearing capacity of composite elements that is over 15 times higher, providing them with greater strength and durability. This parameter is relevant for UAV frame design, particularly when comparing materials of similar density.

Impact strength

The impact strength test was performed using the Charpy method on 20 specimens from each material: 10 surface-tested and 10 tested edgewise. The tests were conducted using an SW-5 impact

hammer equipped with a 50 J pendulum (Figure 5). The test results are presented in Figure 6.

In the Charpy impact test, CFRP exhibited 72% higher surface impact strength and 121% higher edge impact strength compared to PETG Carbon (Figure 6). The average impact strength of the PETG Carbon printed specimens was 74.89 ± 5.62 kJ/m² under surface loading and 73.16 ± 3.53 kJ/m² under edge loading. For specimens made of the carbon composite, the values were significantly higher: 128.95 ± 15.13 kJ/m² (surface) and 161.52 ± 12.71 kJ/m² (edge). The standard deviation of results for PETG Carbon (similarly to the tensile strength test) was found to be low, indicating good repeatability and a homogeneous material structure resulting from the uniform distribution of short fibers within the polymer matrix.

Such a large difference in impact strength, despite the small difference in density between the two materials, results primarily from differences in their manufacturing technologies and, to a lesser extent, from the type of used reinforcement (continuous fibers in the laminate and chopped fibers in the printed material). The results of all mechanical property tests with standard deviations are presented in Table 1.



Figure 5. SW-5 impact hammer

UAV structure

The drone frame was manufactured using 3D printing from carbon fiber-reinforced filament. The UAV employed a “QUAD X” configuration, characterized by the arrangement of four motors on arms positioned in an “X” layout. This configuration enables the maintenance of a centralized center of gravity and ensures adequate flight stability. It also enables optimal placement of onboard components. The quadcopter was equipped with an analog FPV vision system, enabling the pilot to receive the transmitted video feed through goggles with an integrated receiver and monitor the flight from a first-person perspective. Drone control was ensured by an electronic motor control system consisting of a flight controller, an electronic speed controller, and a signal receiver that receives signals transmitted by the controller transmitter.

The propulsion system consisted of four YSIDO brushless electric motors. The project utilized a “Mamba F405 MK2 V2” flight controller equipped with an integrated STM32F405 microcontroller, gyroscope, 16 MB of onboard memory, “Betaflight” firmware, and support for 4–6S LiPo batteries. The quadcopter design utilized a YSIDO electronic speed controller (ESC) and a BETA FPV SuperD Diversity Receiver RC receiver equipped with two receiving circuits, enabling simultaneous reception from two antennas and selection of the stronger signal. The UAV video

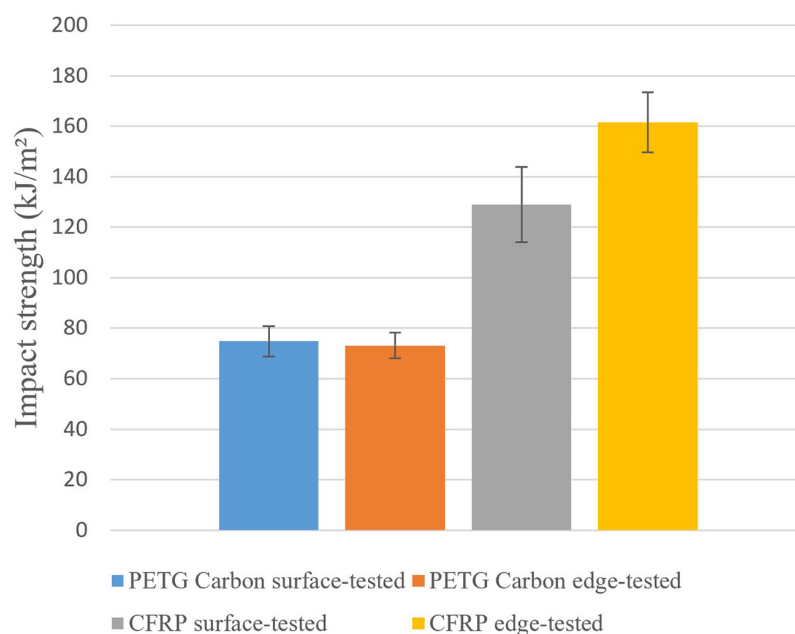


Figure 6. Impact strength of examined samples

Table 1. The results of all mechanical property tests

Material	Tensile strength (MPa)	Young's modulus (GPa)	Impact strength	
			Surface loading (kJ/m ²)	Edge loading (kJ/m ²)
CFRP	742 ± 32	50.1 ± 1.6	128.95 ± 15.13	161.52 ± 12.71
PETG Carbon	46.0 ± 0.5	0.48 ± 0.02	74.89 ± 5.62	73.16 ± 3.53

transmitter responsible for real-time transmission of the quadcopter camera feed was a T-Motor FT800. A 4-cell OVONIC lithium-polymer battery with a capacity of 1,550 mAh was used to power the quadcopter. Three-blade polycarbonate propellers with a diameter of 129.5 mm and a pitch of 73.6 mm were used. The camera mounted on the quadcopter records video feed that is observed by the pilot in real time during a flight, enabling precise flight control. The MS-519 camera operating in an analog vision system was selected for the drone design. Although this technology is relatively outdated, it is still used in drones performing high-speed flights close to obstacles due to its low transmission latency, which is particularly important for the pilot. The quadcopter utilized the M10Q Micro GPS module manufactured by NewBeeDrone. A Diatone 5.8 GHz Mamba Ultra antenna was used for video transmission, while two BetaFPV Dipole T antennas were employed for receiving control signals. The quadcopter frame was designed using SolidWorks software. The assembly consisted of thirteen separately designed components (Figure 7).

Based on the frame volume calculated by the software, equal to 64.64 cm³, and the PETG Carbon material density provided by the

manufacturer, equal to 1.32 g/cm³, the calculated frame mass was 85 g.

The quadcopter frame parts (Figure 8) were manufactured using 3D printing technology on a Prusa i3 MK3 printer, employing the same settings as those used for the specimens in the mechanical property tests.

After all components had been printed, the structure was assembled. Figure 9 shows the assembled structure with all installed components, excluding the propellers and battery, which are frequently removable elements.

The quadcopter flight controller was equipped with “Betaflight” control firmware, which enables configuration of the parameters displayed on the on-screen display (OSD) (Figure 10). Parameters such as speed, altitude, flight time, and others were configured to provide the pilot with valuable information regarding the flight status and the condition of the quadcopter during operation [6].

Flight testing of the quadcopter

Several flight tests of the quadcopter were conducted, with a takeoff mass of 550 g without payload. The tests consisted of twelve flights, including three flights for each loading configuration:

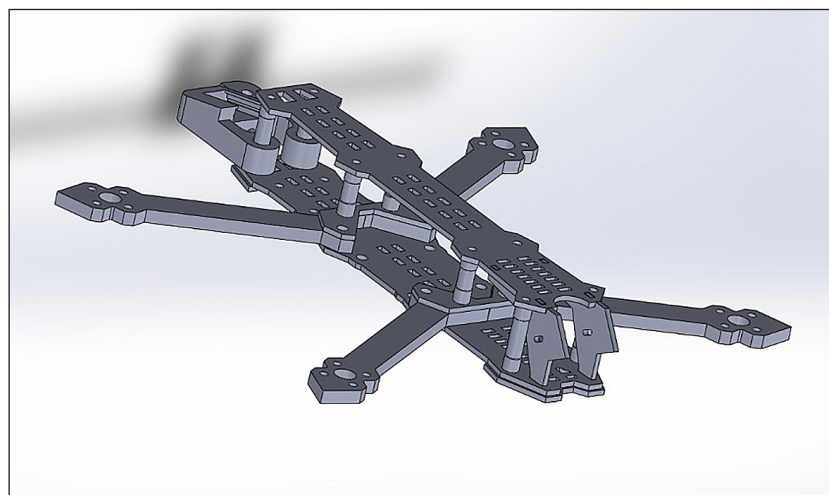


Figure 7. Quadcopter CAD design

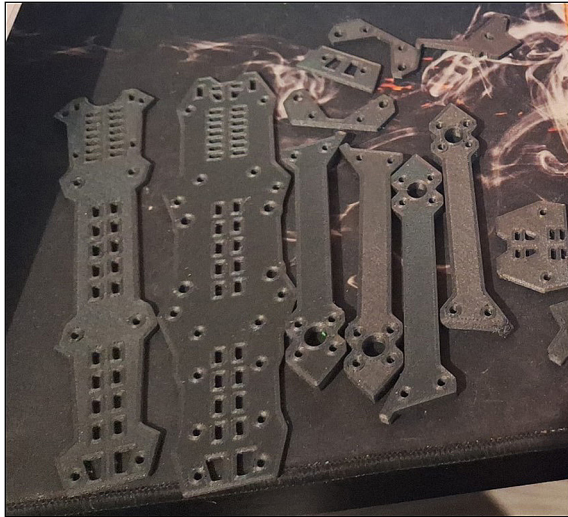


Figure 8. 3D-printed quadcopter frame components



Figure 9. Assembled quadcopter structure

without payload and with attached payloads of 550 g, 1.100 g, and 1.650 g. The results are presented in Table 2. The obtained average flight time of the quadcopter without payload was 11 min 29 s. The maximum level-flight speed was also measured with the throttle set to full opening and without an attached payload. The recorded speed based on GPS parameter readings was 110 km/h (Figure 11).

The quadcopter design was also tested using a frame made of CFRP. The design featured a similar configuration with comparable components, and its takeoff weight was 567 g (excluding the GPS module and its mounting bracket, whose combined weight was approximately 13 g). The average flight time reached 11 min 8 s $\pm$ 55 s (approx. 11.1 min).

For comparison, the drone with a frame printed from PETG Carbon achieved an average flight time of 11 min 29 s with a takeoff mass of 550 g. It can, therefore, be observed that the flight times of both configurations were very similar, indicating that the frame's own weight did not have a decisive influence on performance in the absence of additional payload and on this basis it is difficult to clearly assess the impact of the frame material itself on the quadcopter's performance. The differences result primarily from the material characteristics and the frame manufacturing technology. CFRP is characterized by significantly higher stiffness and strength (as confirmed by the mechanical tests),



Figure 10. Example OSD configuration

Table 2. Measurement results from flight tests

Test number	Payload mass (g)	Thrust for level flight (%)	Battery voltage for takeoff (V)	Battery voltage for landing (V)	Battery voltage after motors shutdown (V)	Flight time (min:s)
1	0	28	17	14	14.8	11:21
2		29	17	14	14.7	11:32
3		28	17	14	14.8	11:36
4	550	51	17	14	14.8	07:31
5		53	17	14	14.7	07:43
6		52	17	14	14.7	07:36
7	1.100	71	17	14	14.7	04:35
8		74	17	14	14.8	04:42
9		72	17	14	14.8	04:39
10	1.650	91	17	14	14.8	02:12
11		88	17	14	14.7	02:24
12		90	17	14	14.8	02:18


Figure 11. FPV camera view during maximum speed flight

making it possible to achieve a comparable total mass while maintaining high structural durability and safety. Although PETG Carbon enables rapid and low-cost fabrication of the frame using 3D printing, it exhibits significantly lower mechanical resistance, which limits its potential under higher loads. In the context of unmanned aerial vehicles, it should be emphasized that different application segments are characterized by distinct structural and operational requirements. While systems intended for industrial, military, or inspection purposes prioritize structural strength and long-term resistance to dynamic

loads, FPV racing applications place particular emphasis on reducing the overall mass. Even a seemingly minor reduction in mass, on the order of several to several dozen grams, can lead to a noticeable increase in acceleration, shorter response time to operator inputs, and improved maneuverability of the platform in space. An important advantage of 3D printing technology using composite materials such as PETG Carbon is the relatively low cost of frame fabrication. The manufacturing cost of a complete structure produced using this technology is approximately several tens of PLN, whereas frames made of

carbon fiber-reinforced laminate typically cost between 200 and 500 PLN. This indicates that, in the case of prototyping and amateur sports applications, where rapid testing of new solutions and cost minimization are of primary importance, 3D printing constitutes a fully justified alternative. At the same time, the lower mechanical strength of 3D-printed frames does not constitute a significant limitation in this application, since, in FPV racing, the decisive factors are primarily low weight and ease of component replacement following collisions.

CONCLUSIONS

The research results indicate that CFRP remains a significantly superior material in terms of stiffness and strength, while PETG Carbon (for the selected print configuration) can be useful in low-cost prototypes, amateur designs, and FPV, where low cost, rapid production, and easy replacement of damaged components are essential. The presented results do not fully confirm the suitability of such a frame for applications requiring high durability, fatigue resistance, or high reliability. The differences in strength between the investigated materials result primarily from differences in their internal structure and reinforcement characteristics. PETG Carbon is a polymer filament containing short carbon fiber additives (approximately 10%), which improve stiffness and strength compared to pure PETG, however, they do not form a continuous and homogeneous load-bearing structure. Short fibers operate primarily on a local scale and despite their homogeneous (in assumptions – not confirmed by research) distribution, they do not enable the production of an isotropic material, which results from the manufacturing technology. Therefore, the material behaves as a typical thermoplastic with limited tensile resistance. In contrast, CFRP manufactured using the infusion method and reinforced with seven layers of carbon fabric exhibits a completely different behavior, as long and continuous carbon fibers constitute the dominant load-bearing phase responsible for transferring the primary mechanical loads. Such a layered structure enables highly efficient stress distribution and significantly increases both tensile strength and the modulus of elasticity. It should be noted, however, that the mechanical properties of 3D

printed components are strongly dependent on the printer's settings. Parameters such as nozzle temperature, bed temperature, layer height, print speed, infill ratio, model orientation, and material path routing significantly impact the print's internal structure, interlayer adhesion, and final component strength. As a result, it is not the material density itself, but rather the reinforcement architecture, the nature of the reinforcement, and the manufacturing quality that determine the substantial strength advantage of the carbon composite over PETG Carbon. Appropriate optimization of 3D printing process parameters can significantly improve the mechanical properties of polymer elements, but it does not allow for complete replacement of continuous carbon fiber reinforcement used in classic composite laminates.

Flight tests demonstrated that the quadcopter was capable of sustained level flight for approximately 11 minutes and 29 seconds with the frame manufactured using 3D-printing technology, and 11 minutes and 8 seconds with the CFRP frame. However, the differences in flight time appear to be minor, making it difficult to definitively assess the impact of the frame material alone on the quadcopter's performance.

The completed project demonstrates the potential application of 3D printing technology in the construction of certain types of drones. The developed design and prototype may serve as a basis for further structural modifications, replacement of components, or testing of alternative engineering materials.

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