Optimal Methodology for Designing and Testing Multicopter Arm Made of Composite Materials

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The modern unmanned aerial vehicle (UAV) industry relies heavily on structures made of composite materials. This study focuses on designing the structure of a military-grade multicopter. This type of UAV must meet rigorous standards to prevent risks of damage or even catastrophic failure during missions. One of the most challenging parts for design is the multicopter arm since it is exposed to high-magnitude forces during flight. Understanding these forces and how to withstand them is of crucial importance for good arm design. In this research, where the goal was to define the optimal methodology of arm design, it was necessary to conduct a static propulsion test to determine maximum force acting on the arm. Then, the arm design was validated using the finite element method (FEM) in combination with static experiments held on a specially created test stand. Finally, the production process, as one of the most demanding aspects of designing the arm, was carefully planned and defined, as it required not only selecting the appropriate materials but also mastering the technologies for high-quality arm manufacture.

Keywords: *Multicopter, Composite Materials, Experimental analysis, Finite Element Method*

1. INTRODUCTION

An unmanned aerial vehicle (UAV) is an aircraft that is remotely controlled by an operator. The operator can either control the UAV directly or set it to fly according to a predefined mission. The UAV industry is currently one of the fastest-growing sectors worldwide. While many view this industry as relatively new, the origins of UAVs can be traced back to the First World War. Although the technology was in its infancy at the time, the use of UAVs was restricted to a few countries. Today, however, it has become a global industry. Like many modern technological advancements, UAV deve–lopment was initially driven by military needs. Over the course of its more than 100-year history, the UAV has evolved from simple, modified combat planes to highly sophisticated flying machines.Early UAVs were pri–marily constructed from metals and wood, with alumi–num and balsa wood being the most used materials. These materials were favored for their low density, strong mechanical properties, and ease of processing with the technology available at the time. Although these materials were suitable to produce UAVs in the early days, they resulted in structures that were roughly twice as heavy as those of contemporary UAVs. With the advent of composite materials, UAV construction has significantly advanced, leading to lighter, more efficient designs that characterize modern UAVs. Com–posite materials constitute most of the structure in modern drones. The primary advantage of this tech–nology is its ability to precisely design each material parameter, enabling a high degree of structural optimi–zation. However, other materials are still utilized in certain components due to the complexity of manufac–turing these parts from composite materials.

2. LITERATURE REVIEW

In recent years, the need for the use of unmanned aerial vehicles has been increasing, and given that these are high-tech devices, it was necessary to provide scientific support for researches related to both civilian and military requirements. The number of scientific papers related to unmanned aerial vehicles is growing year by year, but it seems that there are still wide and unexp–lored fields in this area. This paper aims to contribute to the design and structural analysis of drones, as well as to the optimization and efficiency of drone production.

Important solutions and investigations carried out by other researchers were analyzed before the presented research to help the team of researchers choose the best strategy and approach in solving particular problems. It is the belief of the authors that some of the solutions implemented and presented in this paper were original but based on ideas obtained while studying the work of other teams. Some of the papers were more important than the others and hence will be mentioned here briefly.

The demand for structural testing of lightweight composite components in electric multicopter UAVs is addressed in [1], along with the development of a speci–alized static load test stand for evaluating carbon fiber arms during prototyping and production. Papers [2], [4], and [5] explore composite materials in aerospace appli–cations: [2] presents optimization of carbon/epoxy lami–nates for mechanical and aeroelastic performance using

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FEM and regression algorithms, [3] presents optimi–zation of composite engine mount which is designed for VTOL UAV, while [4] offers a broad overview of FEM modeling for composites, including material properties and failure criteria. In [5], the review of advanced methodologies for modeling stiffness degradation and failure in laminated composites under complex loading, with an emphasis on continuum damage mechanics and multiscale analysis, is presented. Paper [6] introduces an efficient method for estimating stress intensity factors in 3D elastic bodies with multiple surface cracks, validated through finite element analysis. Authors in [7] inves–tigate manufacturing techniques to reduce defects in carbon fiber-reinforced polymers used in a monocoque solar vehicle structure, highlighting pre-treatment met–hods to achieve defect-free parts. Paper [8] explores the parametric optimization of lightweight hexacopter drone frames, enhancing flight time and payload capacity while maintaining structural integrity, using finite element simulations. In [9], the buckling and post-buckling behavior of composite panels under axial compression is analyzed through geometric nonlinear FEA and validated by experimental results. Papers [10] and [11] examine different aspects of UAV operation: [10] sum–marizes NASA's DELIVER research on noise impact from small UAVs, while [11] investigates the flow field and sensor interactions induced by multirotor drones. An interesting overview is presented in [12]: the authors trace the historical development of drones, focusing on military applications, while [13] reviews FEA for UAV airframe structural analysis, emphasizing reliability, rigidity, and stability. Finally, [14] analyzes the structural and vibration response of a hexacopter carbon fiber arm, with both experimental and numerical methods identifying low-vibration zones to optimize performance.

3. IKA-M-AB94 MULTICOPTER

A multicopter is a type of UAV that achieves flight using two or more thrusters. The number of thrusters typically depends on the specific application of the aircraft and is often an even number for balance and stability. The classification of a multicopter is generally based on the number of thrusters or arms it possesses.

The IKA-M-AB94 is a multicopter, with a rotary-wingsthrusters (Figure 1). Featuring six propellers, it is classified as a hexacopter based on its configuration.It is fully electric multicopter.

The IKA-M-AB94 is designed and developed by the engineers at PR-DC doo, a Serbian drone manufacturer based in Šimanovci. The primary purpose of this aircraft is to engage in combat alongside enemy forces, providing support to infantry units. Additionally, it can be used for reconnaissance, offering valuable support to other branches of the military.

The aircraft's basic combat equipment includes two payload launchers. The total mass of the loaded system is 20 kilograms, which also represents the aircraft's optimal carrying capacity.The drone itself can also be equipped with a system for dropping and transporting various types of cargo.

Equipped with surveillance cameras, the aircraft is capable of reconnaissance under any weather conditions and at any time of day. These cameras also facilitate targeting for precision strikes on selected targets.

Figure 1. IKA-M-AB94 in flight, equipped with an aircraft payload carrier

4. TYPES OF MULTICOPTER ARM

The multicopter arm is a fundamental component of the overall structure. Its primary function is to establish a physical connection between the fuselage and the propulsion system. Various types of arms exist, categorized based on their design, material properties, and functional requirements.

Multicopter arms are commonly constructed from materials such as aluminum, composite materials, and plastic polymers. In certain instances, a combination of these three materials may be used to optimize per–formance. The simplest design configuration typically involves an integrated arm, directly combined with the fuselage (Figure 2).

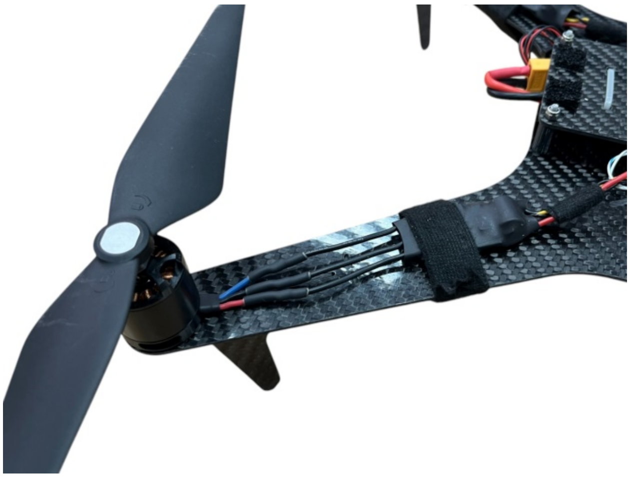

Figure 2. Integrated type of arm

This type of arm is fabricated from plate semi-finished products. The manufacturing process typically involves conventional cutting techniques, such as laser cutting or milling, depending on the material used.

One type of integrated multicopter arm features a design where the arm is permanently attached to the fuse–lage using an inseparable screw connection (Figure 3). This type of connection is designed to be disassembled only when repair of the arm is required due to damage.

Figure 3.Integrated arm with screw connection

These designsare most found in hobby grade multi–copters. In industrial grade multicopters, arms with a circular cross-section are commonly used. These semi-finished products are widely available on the market, making them the most frequently employed choice. The variety of parameters, such as pipe diameter and wall thickness, enables a high degree of optimization to meet specific performance requirements. Due to the demand for easy disassembly of drones for more convenient trans–portation, this manufacturing method allows for the complete or partial detachment of the arm from the rest of the structural components.

Partial disassembly of the arm refers to a design where the arm cannot be completely detached from the rest of the structure (Figure 4). Instead, the arm is positioned in a more transport-friendly orientation using a rotational axis.

Figure 4. Partially disassembled arm

Fully disassembling the arm means that it can be physically detached from the rest of the structure (Figure 5). Additionally, the signal and power cables can be separated, allowing for complete disconnection.

Figure 5. Fully disassembled arm

5. INITIAL DESIGN OF IKA-M-AB94 MULTICOPTER ARM

In the case of modern advanced multicopters such as IKA-M-AB94, integrated arms made of plate although tubular cross-section arms, often does not meet the required performance characteristics. To achieve an optimal multicopter arm design, it is essential to deve–lop a complex arm shape. Composite materials enable the creation of complex structural forms, offering significant design flexibility without major restrictions. The initial design of the arm was modelled in 3D using the *FreeCAD* software package.

FreeCAD is a free, open-source parametric 3D modelling software widely used for designing and prototyping objects in engineering, architecture, and product development.The software also includes an FEM module. Unlike commercial, closed-source software that can be costly and sometimes inaccessible, *FreeCAD* is developed by the entire community, making it easy to modify and tailor to specific needs. It is particularly popular among hobbyists and professionals due to its flexibility and compatibility with multiple platforms.

The most suitable modules for designing a multi–copter arm are the Part and Sketcher modules within the *FreeCAD* software package. There are also modules specialized in designing aerospace structures, but they are currently under development and sometimes have limitations that prevent the creation of the desired design.

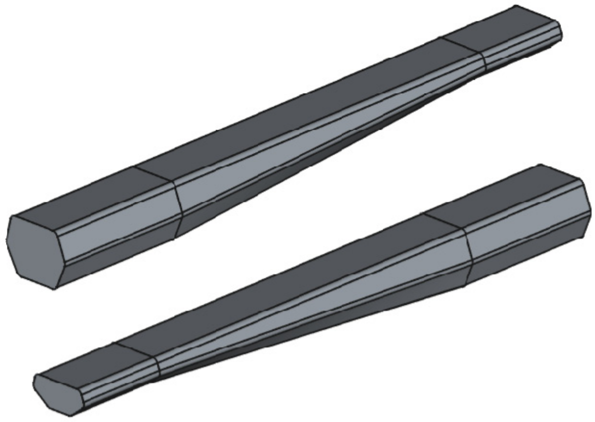

Figure 6. Initial design of arm

At both the base and the end of the arm, the cross-sectional shape is a hexagon with rounded edges (Figure 6). This shape was chosen for its ease of mounting the arm onto the central part of the aircraft structure. It ensures alignment between the surface where the thruster is installed and the plane where the arms are positioned. The arm tapers along its span, maintaining a constant cross-section at both the root and the end. I-beams are integrated into the root and end sections of the arm to help transfer loads. Additionally, the arm features several openings of varying sizes, which facilitate mounting on the central structure and the installation of propulsion components (Figure 7).

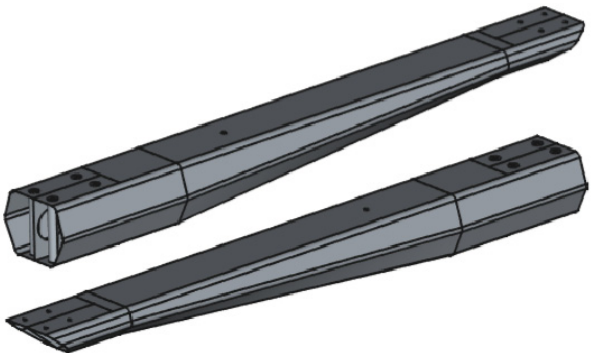

Figure 7. Structural parts of the arm

The arm's structure is thin-walled, as its wall thick–ness is significantly smaller than the other two dimensions. Thin-walled structures are known for their excellent mechanical properties relative to their mass. To enable finite element analysis in software as a thin-walled design, the arm and all its structural elements are modelled using surfaces.

6. COMPOSITE MATERIALS USED IN ARM DESIGN

Composite materials are created by combining two or more materials with different physical and chemical properties to produce a material with improved charac–teristics. By working together, these components create a material that is stronger, lighter, or more durable than the individual components on their own. Typically, a composite consists of a matrix and reinforcing fibers. Reinforced concrete is a prime example of a composite material, where the concrete acts as the matrix and the reinforcement (such as steel bars) serves as the fiber. Composite materials, with the ability to design desired mechanical properties in specific directions, offer a good strength-to-weight ratio, making them ideal for the aerospace industry, particularly in the production of unmanned aerial vehicles. In aerospace industry, mat–rices commonly include epoxy, polyester, vinylester, and phenolic resins, while carbon, glass, and aramid fibers are the most frequently used reinforcements. To enable their use in industry, fibers are woven into fab–rics with different densities and weaving patterns (Figure 8).

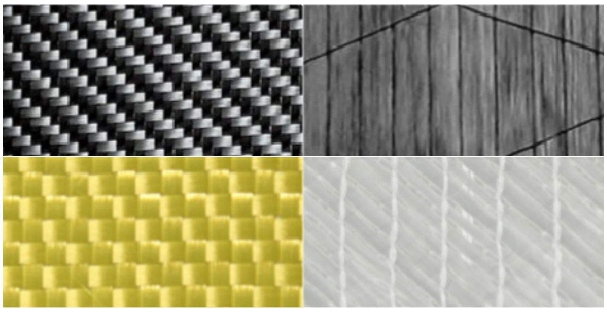

Figure 8. Different types of fabrics

Resins used in the industry as matrices are in a liquid state. Depending on the impregnation process, the resin's density may vary. The resin is mixed with a hardener to initiate curing. To achieve the maximum mechanical properties of composite parts, the curing process must be carried out according to a specific procedure.

For the purpose of creating the multicopter arm prototype, the composite material XPREG XC110 210g/m² from *EasyComposites*, a manufacturer in the UK, was used. This type of composite material is called prepreg, meaning it is a composite material in which carbon fibers are already impregnated with epoxy resin. This material offers ease of use and is an excellent choice for manufacturing prototype parts made from composite materials.

Before the strength calculation of the multicopter arm, mechanical property testing of used material was conducted on a tensile testmachine. The shape of the composite material test sample (Figure 10) is in accor–dance with the D638 standard of the American Society for Testing and Materials (ASTM International).

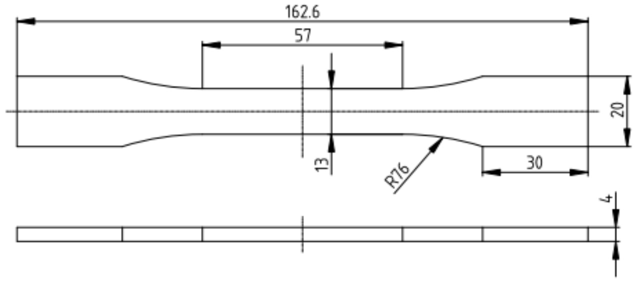

Figure 9. Shape of test sample

The first step in preparing test sample is to form a 4mm thick plate from the desired composite material. Then, the test sample is cut using a CNC router. After cutting and edge finishing, the test sample is ready for testing (Figure 10).

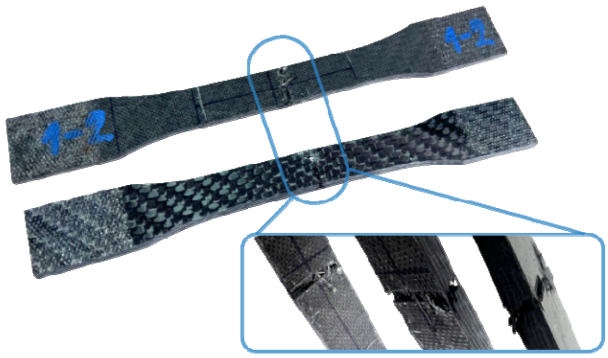

Figure 10. Test sample failure

The test results of conductedtest are presented in Table 1 and on the stress-strain graph (Figure 11).

Table 1. Characteristics of composite

XPREG XC110 210g/m²		
Property	Result	Unit
Tensile modulus	55.1	GPa
Tensile strength	521	MPa
Compressive strength	483	MPa
Shear modulus	2.78	GPa
Interlaminar shear strength	64.7	MPa
Deformation at failure	1.07	%

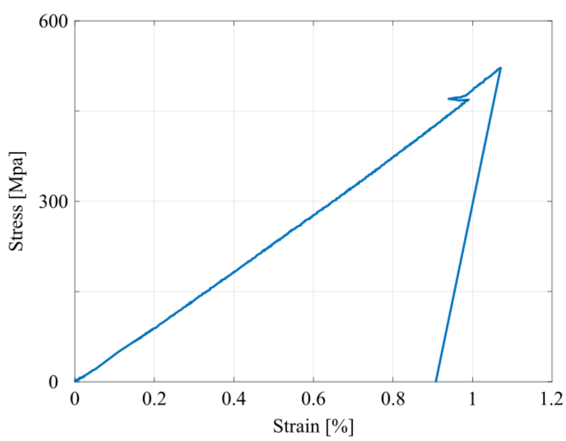

Figure 11. Stress-Strain diagram

7. PROPULSION TEST

To properly dimension a multicopter arm, it is essential to understand the loads acting on it during flight. The analysis has determined that during flight, the only force acting on the multicopter arm is the force generated by the propulsor. The IKA-M-AB94 multicopter propulsor is an electric propulsion system consisting of a battery, an ESC, an electric motor and a carbon fiber propeller (Figure 12).

Figure 12. Propulsion set

To verify the parameters of the propulsor in this specific combination of components, as stated by the manufacturer in the specifications, a propulsion test must be conducted. For this purpose, a specialized test stand has been designed (Figure 13).

Figure 13. Test stand – isometric view

The test standwas developed by our team and has a robust design to ensure safety and prevent tipping due to the motor's force. The frame of the test stand is made of stainless steel. The thrust force is measured using four load cells. Additionally, the teststand measures the propulsor's torque using two additional load cells. Furthermore, in order to monitor the electrical energy consumption for powering the propulsor, the test rig is equipped with specialized electronics. That monitoring system measures the current, battery voltage, and electric motor power. Data acquisition is performed using specially designed software for this purpose. The software allows not only simple motor thrust changes, but also the input of a thrust profile corresponding to the multicopter's flight, making it possible to estimate energy consumption.The thrust measurement results are shown in the following diagram (Figure 14).

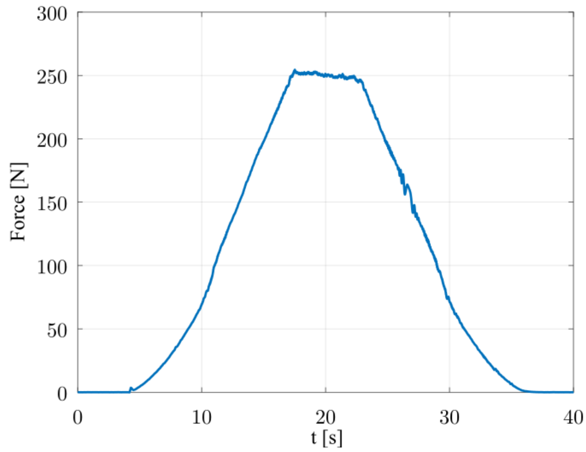

Figure 14. Force-Time diagram

8. FINITE ELEMENT ANALYSIS OF ARM

The finite element analysis was performed in the soft–ware package *Femap*. *Femap* is a sophisticated engi–neering analysis tool that allows users to model struc–tures and simulates their responses under various conditions using the finite element method.

The very first step in FEM analysis is importing geometry made in *FreeCAD*. The most suitable format for the further actions is *.stp*.

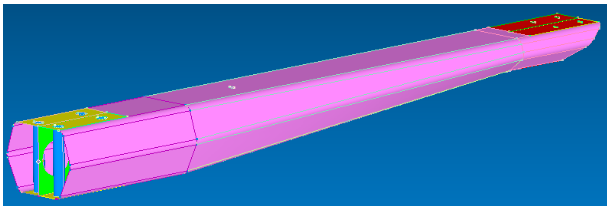

Figure 15. Geometry in Interface

In order to understand difference between properties of structure, surfaces are coloured in different colours (Figure 15).

Once the strength test results are known, it is possible to define the material characteristics within the software. To define the properties of the used composite material, the Material tab was used (Figure 17).

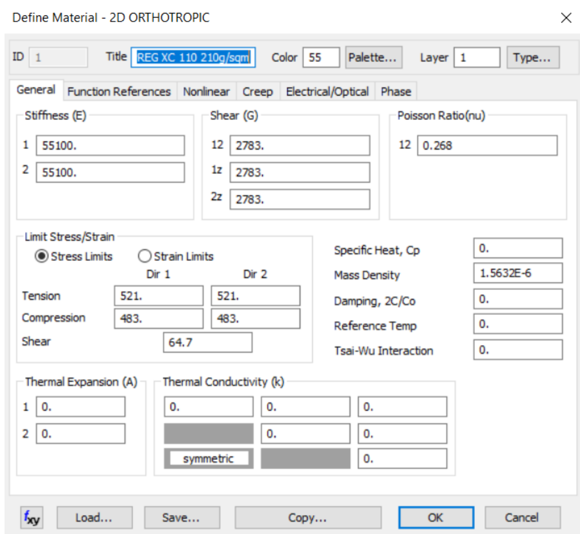

Figure 16. Material properties of composite

The assumption of the thickness of structural parts depends on multiple factors. These factors are most often related to the material thickness itself and, in some cases, limitations in manufacturing technology.

To ensure that the structure does not exceed the mass estimated at the beginning of the design process and based on experience with previously constructed designs of this type, the following thicknesses are assumed (Table 2).

Table 2. Arm structure thicknesses

Arm structure thicknesses (in mm)	
Property	Result
I profile wall	2
I profile flange	2
Spacer tubes	1
Arm shell	0.6

The density of the finite element mesh is a key factor for a quality of the analysis (Figure 17). Sometimes, the limitations of the computer cannot allow sufficient mesh density. Additionally, it is not necessary to create a uniform mesh density across the entire model, but rather focus on areas where critical stresses are likely to occur. It is also necessary to ensure the same number of finite elements along the edges of the joint between adjacent elements to guarantee the integrity of the structure.

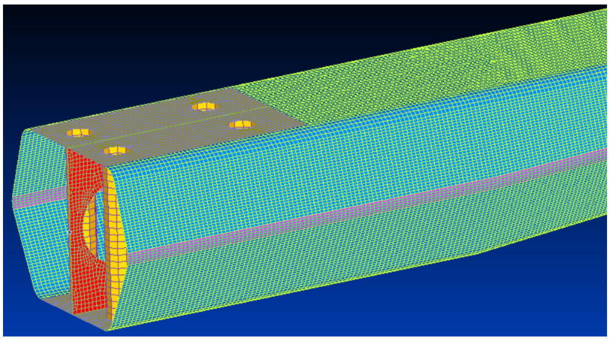

Figure 17. Finite element mesh

The boundary conditions must be set in such a way that they correspond to those applied to the actual structure (Figure 18). The arm itself is an integral type and its root part is bolted between two body plates of the UAV. Therefore, the constraint must be applied to the entire contact surface between the body and the arm.At the other end of the arm, the arm's propulsor is also mounted using bolts, so the force obtained from the test is applied to the entire contact surface between the arm and the propulsor.

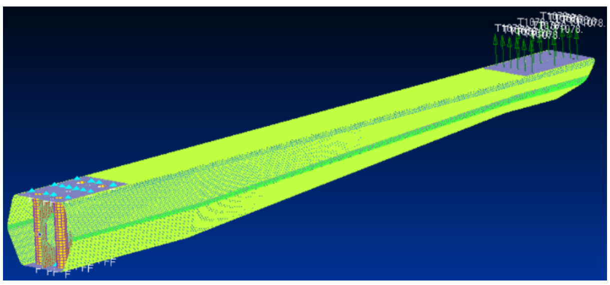

Figure 18. Constraints and forces

Once all the previous steps are satisfied, it is pos– sible to run the analysis.Figure19 shows one of the results of the analysis and relates to the displacement of the arm in the vertical plane. The display is not equivalent to the actual displacement but is exaggerated for easier understanding.

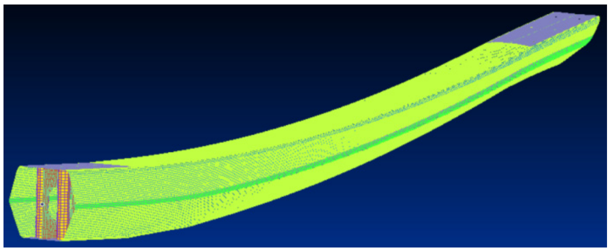

Figure 19. Displace1ment in vertical plane

8.1 Composite Lamina Failure Criteria

The first failure criterion of a composite lamina is the maximum stress criterion [15]. Based on the maximum stress criterion, failure of the lamina occurs when at least one stress component exceeds the allowable stress in that direction. This is defined by the following conditions that must be satisfied:

$$S_{\sigma_1} > 1 \wedge S_{\sigma_2} > 1 \wedge S_{\tau_6} > 1 \tag{1}$$

$$\nu_{21} = \frac{E_2}{E_1 * \nu_{12}} \tag{2}$$

$$S_{\sigma_2} = \begin{cases} \sigma_2 > 0, \dfrac{F_{2T}}{\sigma_1} \\ \sigma_2 > 0, \dfrac{F_{2C}}{|\sigma_1|} \end{cases} \tag{3}$$

$$S_{\tau_6} = \frac{F_6}{|\tau_6|} \tag{4}$$

The second criterion is the maximum strain criterion [16]. Based on the maximum strain criterion, failure of the lamina occurs when at least one strain component exceeds the allowable strain in that direction. This is defined by the following conditions that must be satisfied:

$$S_{\varepsilon_1} > 1 \wedge S_{\varepsilon_2} > 1 \tag{5}$$

$$S_{\varepsilon_1} = \begin{cases} \varepsilon_1 > 0, \dfrac{F_{1T}}{|\sigma_1 - \nu_{12}\sigma_2|} \\ \varepsilon_1 > 0, \dfrac{F_{1C}}{|\sigma_1 - \nu_{12}\sigma_2|} \end{cases} \tag{6}$$

$$S_{\varepsilon_2} = \begin{cases} \varepsilon_2 > 0, \dfrac{F_{2T}}{|\sigma_2 - \nu_{12}\sigma_2|} \\ \varepsilon_2 > 0, \dfrac{F_{1C}}{|\sigma_2 - \nu_{12}\sigma_2|} \end{cases} \tag{7}$$

The third criterion is the Tsai-Hill criterion [17]. The Tsai-Hill criterion is defined by the following relation:

$$S_{TH} = \left(\frac{\sigma_1}{F_1}\right)^2 + \left(\frac{\sigma_2}{F_2}\right)^2 + \left(\frac{\tau_6}{F_6}\right)^2 - \frac{\sigma_1\sigma_2}{F_1^2} < 1 \tag{8}$$

$$F_1 = \begin{cases} \sigma_1 > 0, F_{1T} \\ \sigma_1 < 0, F_{1C} \end{cases} \quad (9)$$

$$F_2 = \begin{cases} \sigma_2 > 0, F_{2T} \\ \sigma_2 < 0, F_{2C} \end{cases} \quad (10)$$

The fourth criterion is the Tsai-Wu criterion [18,19]. The Tsai-Wu criterion is defined by the following relation:

$$S_{TW} = f_1\sigma_1 + f_2\sigma_2 + f_{11}\sigma_1^2 + f_{22}\sigma_2^2 + \ldots$$
$$\ldots + 2f_{12}\sigma_1\sigma_2 + \left(\frac{\tau_6}{F_6}\right)^2 < 1 \quad (11)$$

$$f_1 = \frac{1}{F_{1T}} - \frac{1}{F_{1C}} \quad (12)$$

$$f_{11} = \frac{1}{F_{1T}F_{1C}} \quad (13)$$

$$f_2 = \frac{1}{F_{1T}} - \frac{1}{F_{1C}} \quad (14)$$

$$f_{22} = \frac{1}{F_{2T}F_{2C}} \quad (15)$$

$$f_{12} = -\frac{1}{2}\sqrt{f_{11}f_{22}} \quad (16)$$

8.2 Data Analysis

The analysis of the results is performed by our team using a specially created program written in the *MATLAB* software package (Figure 20). After reading the results after *Femap* analysis, the program checks the strength of the arm based on four composite material strength criteria. After the check, the program outputs the safety factor values for each criterion, as well as the envelope for the conservative approach. According to this approach, it is necessary for all criteria to be satisfied simultaneously in order for the laminate to be considered free of failure.

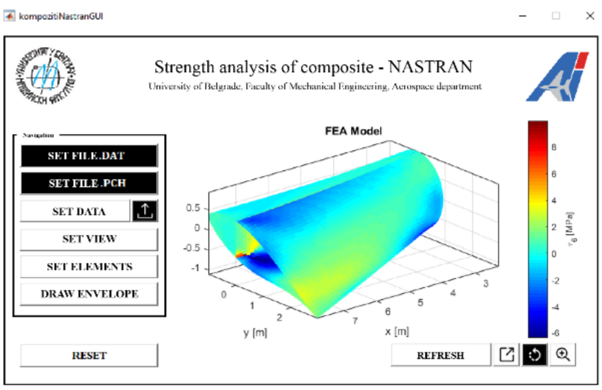

Figure 20. Program interface

Figure 21 shows the envelope of the conservative approach. Considering the fact that all the criteria have satisfied the desired values, it can be concluded that no failure of the composite will occur.

The following Table 3 shows the safety factors according to all the criteria.

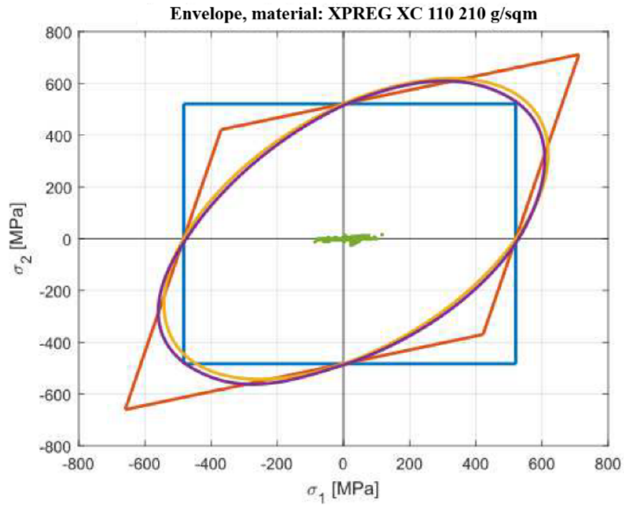

Figure 21. Envelope of conservative approach

Table 3. Values of safety factors

Safety factors	
The criterion for stress along the fibers	4.48>1
The criterion for stress in the direction normal to the fibers	19>1
The criterion for shear stress in the plane of the fibers	2.96>1
The criterion for deformation along the fibers	4.65>1
The criterion for deformation in the direction normal to the fibers	15.38>1
Tsai-Hill criterion	0.12<1
Tsai-Wu criterion	0.11<1

Additionally, the displacement value of the arm is satisfactory, meaning it does not interfere with either the aerodynamic or other conditions that must be met (Table 4).

Table 4. Displacement of the arm

Displacement in mm	4.81

The final step in the analysis is determining the force at which the structure will fail. It is also necessary to determine the displacement under the action of the maximum force.

The following Table 5 shows maximum values of force and displacement.

Table 5. Maximum values of force and displacement

	Result	Unit
Force	107.5	N
Displacement	21.6	mm

9. MULTICOPTER ARM MANUFACTURE

Considering that a composite prepreg material has been chosen for the production of the arm prototype, it is necessary to define the basics of manufacturing parts with such a material.

In order to activate the material, it is necessary to thermally treat it. The matrix itself requires exposure to temperature for hardening.

Figure 22. Aluminum mold for arm

Based on this fact, the material used for manu–facturing the mold for the part is chosen. Considering that the process reaches temperatures as high as 130 degrees Celsius, the optimal choice for mold production is aluminium.The mold was made on a CNC milling machine for metal processing. Its two-part design allows for the smooth removal of the arm from it (Figure 22).

The first step in the production of the part is cutting the pieces according to the templates from the chosen material and arranging them in the mold in the same way as done in the FEM analysis.Once the workpieces are arranged, the two halves of the tool are assembled and packed in vacuum bags with high-temperature resistance.The entire curing process is carried out under vacuum to ensure that the arranged workpieces are positioned as precisely as possible on the mold walls. After curing, the part is removed from the mold and cleaned of any auxiliary materials.

In the same way as the arm shell, the I profiles at the root and tip of the arm are also made, while the spacer tubes are purchased as they are readily available on the market.

Assembling the parts of the arm into a single unit is done with epoxy adhesive.After the adhesive has cured, the arm must undergo further processing. Cutting to size and drilling holes are done manually and with a CNC router. The final shape of the arm is shown in Figure 23.

Figure 23.The final shape of the arm

10. EXPERIMENTAL SETUP FOR STATIC TEST

The static experiment of the multicopter arm was conducted on a specially designed test stand. This test stand is unique and is a result of one month's work of our team of researchers (Figure 24).

The test stand structure itself was made of steel to ensure minimal deformation during the experiment. The actuator used for applying the load is a hydraulic cylinder powered by a hydraulic pump. The hydraulic pump is driven by an electric motor, with its *rpm* regulated via a frequency controller. By controlling the motor's *rpm*, the force variation characteristics during the experiment are managed. To ensure precise force variation, specialized electronics and software were developed for this purpose. The displacement of the arm's end is measured using a linear displacement sensor, while the applied force is measured by a load cell positioned between the actuator and the arm.

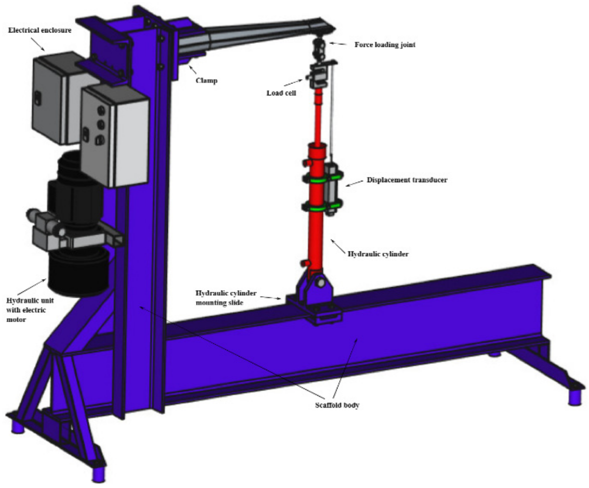

Figure 24. Static test stand

The value of the applied force was taken from the propulsion test. The force is gradually applied until the maximum force generated by the propulsion system is reached.

The diagram in Figure 25 shows the change in force over time while the next diagram in Figure 26 shows the change in displacement over time for the applied force.

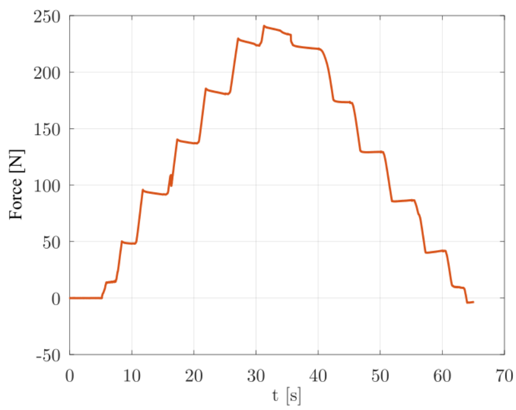

Figure 25. Force-Time diagram

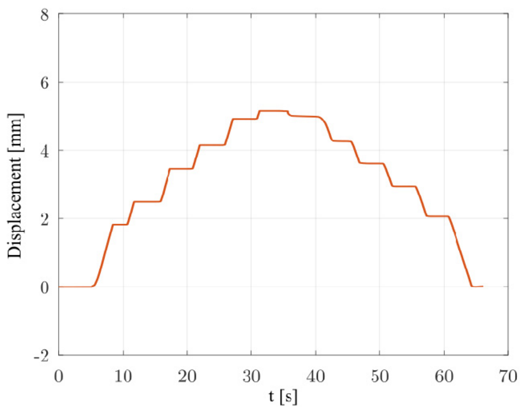

Figure 26. Displacement-Time diagram

It is also necessary to check the force value at which the arm breaks. Therefore, on the testing rig, the force was gradually increased until the arm failed. Three identical prototypes were prepared for the test. All three arms initially showed undulation on the upper surface, followed by breakage. The damage occurred in the same zone on all three arms. The differences in the forces required for failure in each individual arm are less than 3%.

The diagram in Figure 27shows a comparative display of the breakage force for all three arms.

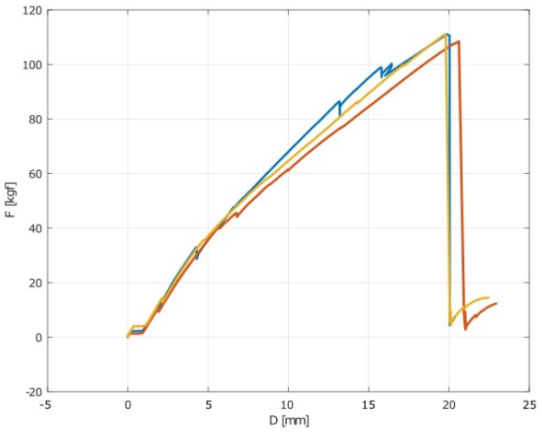

Figure 27. Failure force-Displacement diagram

Figure 28 shows a comparative view of the stress concentration areas in the FEM analysis and the point of failure on the arm that was tested on the test stand. Application of the critical force identified in the FEM analysis results in fiber failure under compression.

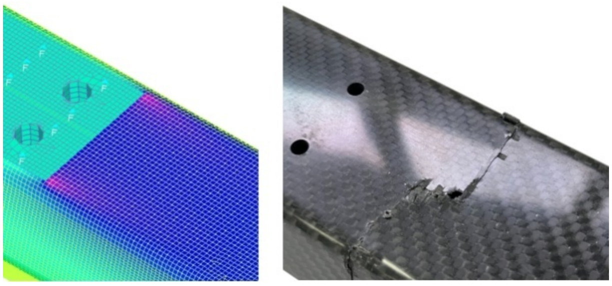

Figure 28. Failure force-Displacement diagram

11. DISCUSSION

At the very beginning of the multicopter design process, it is necessary to be familiar with the standards that must be met for an aircraft to be certified by the specialized institutions. The choice of arm design, as described in this paper, plays a significant role in this process. Selecting an integral arm type with a complex shape has ensured ease of manufacturing and a minimal number of individual components. Additionally, this type of arm is attached to the fuselage with a set of screws, which allows for easy replacement in the event of damage. The limited availability of materials on the market in the Republic of Serbia restricted the extent of optimization; however, excellent results were still achieved with the materials used. The material testing contributed to confirming the characteristics provided by the manufacturer. Additionally, the testing enabled the determination of unknown values that are essential for further work. The propulsion test provided a safe method for determining the characteristics of all propul–sion components, as well as the loading values acting on the multicopter arm.

We have fully verified the manufacturing process, leading to the production of an exceptional quality part. The production process requires, above all, carefully designed tools, followed by the optimization of proce–ssing parameters for the selected materials.

Through a comparative analysis of the FEM results and the results obtained from the test stand, it is concluded that the differences are reduced to less than 10%. This means that carried-out FEM analysis is relevant and accurately reflects the actual conditions. After the entire process of design, production, and testing, it becomes evident that the product has genuine practical value, and it meets all the predefined input parameters.

12. CONCLUSION

The research fills a practical and methodological gap in UAV structural design by quantifying the maximum forces acting on multicopter arms through dedicated static propulsion tests and validating designs with FEM coupled to controlled experiments. Integrating these va–lidation steps with detailed production planning addresses the frequently overlooked translation from prototype to manufacturable, high-quality composite parts. The resulting methodology improves the relia–bility and safety of military-grade UAVs and supplies a rigorous process other researchers and engineers can adopt or extend. Ultimately, this work strengthens the evidence base for design rules and testing protocols in composite UAV structures.

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NOMENCLATURE

σ_1	normal stress in the fiber direction
σ_2	normal stress perpendicular to the fiber direction
τ_6	shear stress
F_{1T}	tensile strength in the fiber direction
F_{1C}	compressive strength in the fiber direction
F_{2T}	tensile strength perpendicular to the fiber direction
F_{2C}	compressive strength perpendicular to the fiber direction
F_6	shear strength
ε_1	deformation in the fiber direction
ε_2	deformation perpendicular to the fiber direction
ν_{12}	shear modulus
E_1	Young's modulus in the fiber direction
E_2	Young's modulus perpendicular to the fiber direction

МЕТОДОЛОГИЈА ЗА ПРОЈЕКТОВАЊЕ И ТЕСТИРАЊЕ РУКЕ МУЛТИКОПТЕРА ИЗРАЂЕНЕ ОД КОМПОЗИТНИХ МАТЕРИЈАЛА

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Савремена индустрија беспилотних летелица (UAV) у великој мери се ослања на делове израђене од композитних материјала. Ово истраживање је усме–рено на пројектовање структуре војног мултикоп–тера. Овакви системи морају испуњавати строге ста–ндарде како би се смањио ризик од оштећења или чак отказа. Један од најсложенијих делова структуре је рука мултикоптера. Разумевање силе која делују на руку представља кључни корак у процесу пројек–товања. Како би се те сила одредила, спроведено је статичко тестирање пропулзора. Истраживање је затим верификовано комбинацијом прорачуна мето–дом коначних елемената (FEM) и статичких испити–вања изведених на наменски израђеној испитној скели. Производни процес представља једну од нај–захтевнијих фаза у развоју саме руке јер подра–зумева не само избор одговарајућих материјала, већ и примену сложених технологија израде.