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# DEVELOPMENT OF TAILORED FIBER PLACEMENT TEXTILE STRUCTURES FOR DRONE FRAME COMPOSITE REINFORCEMENT

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**ABSTRACT**

In recent years, the growing demand for lightweight and high-strength materials in unmanned aerial vehicles (UAVs) across various sectors has driven the need for innovative drone frames that balance performance, weight, waste minimization, and sustainability. Composite materials, known for their excellent strength-to-weight ratios, have emerged as the material of choice for UAV frames. Nowadays, drone frames made from inorganic fiber-reinforced composites, particularly glass and carbon fibers, dominate the market due to their exceptional strength-to-weight ratios and durability. However, these materials pose environmental challenges, as many drones, especially in military applications, are designed for single-use operations, generating non-biodegradable waste. To address this, sustainable alternatives like flax fiber-reinforced composites have gained interest due to their low environmental impact, renewability, and biodegradability. However, ensuring mechanical performance comparable to inorganic fibers remains a challenge. This work explores Tailored Fiber Placement (TFP), which employs a technical embroidery machine for precise fiber placement along load paths, optimizing material distribution and maximizing performance. Integrating natural fibers with TFP reduces waste and enables lightweight, high-performance, environmentally friendly drone frames. In this work, bio-based epoxy resin was also used as a matrix in drone frame production using resin-infusion technology. The mechanical properties of the flax fiber-reinforced composite showed that combining TFP and flax fibers for drone frame preparation has a promising effect both in mitigating the environmental impact of drone technology and reducing costs.

**KEYWORDS**: Composite; Drone; Embroidery; Flax; Sustainability; Tailored Fiber Placement.

**INTRODUCTION**

The world is currently facing the risk of a climate catastrophe driven by the ever-increasing waste generated across industries. As global economies turn toward sustainable development, minimizing production waste has become a critical goal for manufacturers. A significant aspect of this sustainable approach is the “reduce–reuse–recycle” principle, which aims to limit production and waste, extend the life cycle of goods, and recycle materials that are no longer usable. In this context, the need for innovative manufacturing solutions that align with sustainability principles is more urgent than ever.

Technical embroidery technology, particularly Tailored Fiber Placement, aligns well with these goals. TFP is a process that allows for the precise and customized placement of fibers to create composite materials with optimized mechanical properties while minimizing waste. By enabling complete control over the medium direction on a flat textile substrate, TFP offers significant advantages in terms of material efficiency. The automation of the embroidery process ensures that fibers are placed exactly where needed, reducing material consumption and waste. Unlike traditional methods that may require cutting out material, TFP only generates minimal waste, such as interlining or backing. This contributes to a highly efficient and sustainable manufacturing process.

In this study, TFP is used in combination with natural flax fibers to reinforce composites for drone frame applications. Flax fibers, known for their renewability, biodegradability, and low environmental impact, offer an eco-friendly alternative to conventional glass and carbon fibers used in UAVs. However, the challenge remains that natural fibers do not offer mechanical properties that are comparable to those of conventional materials. TFP provides a solution that allows precise control over fiber placement and optimizes the material distribution along load paths to enhance the composite’s mechanical performance.

Additionally, bio-based epoxy resin is utilized as the matrix material, further supporting the sustainable approach. The combination of flax fibers, TFP, and bio-based resins results in lightweight, high-performance drone frames that reduce environmental impact, production costs, and material waste. The use of flax fibers, a renewable and lower-cost alternative to carbon fiber, significantly lowers material costs. TFP’s precision in fiber placement further minimizes material usage, contributing to a reduction in overall manufacturing expenses. Furthermore, integrating sustainable materials in drone production not only reduces costs but also positions the industry to align with the growing emphasis on eco-friendly practices in manufacturing.

This research highlights the potential of using TFP with flax fibers for drone frame production, demonstrating how advanced manufacturing techniques can reduce costs while mitigating the environmental footprint of drone technology, all while promoting a circular, sustainable economy.

**LITERATURE REVIEW**

Over the past decade, the number of countries around the world that own unmanned aerial vehicles has increased significantly. This surge has sparked considerable interest within the research community, prompting extensive exploration into new technologies that can enhance UAV performance. Researchers are also investigating materials and production processes that are not only efficient and cost-effective but also environmentally sustainable, minimizing any potential ecological impact. Among these emerging solutions, a few researchers have begun exploring the potential of natural fiber-reinforced composites (NFRCs) for use in drone technology (Harika et al., 2024; Khalid et al., 2021; Maiti et al., 2022; Rajoo et al., 2024; Ramesh et al., 2021). These materials offer a promising alternative to traditional composites, as they are lightweight, renewable, and biodegradable while maintaining the necessary strength and durability for UAV applications. The integration of NFRCs into UAV design could represent a significant step toward more sustainable and eco-friendly aviation technologies.These scholars utilized conventional composite preform manufacturing techniques for composite reinforcement.

Additionally, these articles focused on the viability of using natural fibers in UAV applications as a replacement for inorganic fiber-based composite materials. However, the authors highlighted several challenges associated with the use of natural fiber-reinforced composites (NFRCs) in such applications. One of the primary concerns raised was the unsatisfactory mechanical properties of NFRCs, which may limit their effectiveness in UAV structures.

In other cases, several researchers have begun exploring the potential of the Tailored Fiber Placement technique for manufacturing composite preforms. This approach aims to optimize material usage, minimize production costs, and enhance the mechanical properties of composite materials. By precisely controlling fiber orientation and distribution, TFP enables the creation of highly efficient and structurally optimized components while significantly reducing material waste. As a result, this innovative technique is gaining attention as a sustainable and cost-effective solution for the production of advanced composite structures. (Coppola et al., 2023; Khodunov et al., 2021; Poniecka et al., 2022b, 2022a; Spickenheuer et al., 2008). However, to the best of our knowledge, no existing research or article has explored the combination of the Tailored Fiber Placement technique for composite preform preparation with the concept of natural fiber-reinforced composites (NFRCs) for UAV applications. Therefore, this study investigates the feasibility of utilizing the TFP technique to manufacture natural fiber-based preforms for producing NFRCs designed explicitly for drone frames.

**MATERIALS AND METHODOLOGY**

This section provides a detailed description of the materials, equipment, and methodologies used in this study to ensure its clarity and reproducibility.

**Materials**

The composite material used for the drone frame was fabricated using low-twist flax roving and a bio-based epoxy resin system. Flax roving with a linear density of 400 tex was sourced from Safilin company, a well-established supplier known for high-quality natural fibers. Flax was selected due to its favorable mechanical properties, sustainability, and lightweight characteristics, making it an ideal reinforcement for bio-composites in UAV applications. For the matrix, a low-viscosity bio-epoxy resin SR 8100, supplied by Sicomin Epoxy Systems, was used in combination with its SD 477x hardener. This resin system was chosen for its superior mechanical performance, good fiber impregnation capability, and reduced environmental impact compared to conventional petroleum-based epoxies. The bio-based content in SR 8100 enhances the sustainability of the composite while maintaining structural integrity and durability.

**Drone Frame Design**

The design of the drone frame followed a structured process to ensure optimal performance and manufacturability. CAD and SolidWorks software were used for 3D modeling, taking into account both mechanical and manufacturing considerations shown in Figure 1. 

*Figure SEQ Figure \\* ARABIC 1.Drone Frame Design.*

The 3D model of the drone frame was transferred to the embroidery software GiS BasePack version 10 (GiS, Lenningen, Germany) for further refinement and preparation for production, as shown in Figure 2. In the embroidery software, the shape of the frame was outlined, and key parameters, such as fiber orientation and spacing, were defined. 

**Figure 2.** Drone frame design in Embroidery software interface.

The software enabled the precise placement of fibers along load paths, optimizing material distribution and maximizing performance. The reinforcement with six layers was arranged from bottom to top in the following sequence: 45°, -45°, 0°, 90°, -45°, and 45°, to withstand multidirectional stresses on the frame.

Once the design was finalized using embroidery software, it was prepared for production. The final design file was then exported and transferred to the embroidery machine, where the drone frame reinforcement was produced with high precision.

The composite preform was produced using a computerized ZSK embroidery machine, model JCZA 0109-550, Figure 3. This machine features a W-type head, which enables precise placement of the flax roving onto a textile backing along the x- and y-axis. The material was secured to the backing using a zigzag stitch with fastening yarn.

Three variants of stitching length, 2mm, 4mm, and 8mm were used to analyze the effect of the stitching length on the tensile properties of the composites.

**Figure 3.** Composite preform preparation using a technical Embroidery machine.

**Composite Preparation**

The composite preform produced using the embroidery machine was prepared using resin infusion technology, as shown in Figure 4. The resin infusion process began by arranging the preform layers in the desired orientation on a glass plate.

A peel ply and flow mesh were placed over the preform stack to aid resin flow, and the setup was sealed with a vacuum bag. After leak testing, a vacuum pump created a pressure differential to draw the resin, pre-mixed with hardener and degassed, through an inlet port and into the fiber layers. Once infused, the composite was cured under vacuum at room temperature for 24 hours. The final composite was inspected for uniformity and structural integrity before being subjected to experimental investigations. A flat composite plate was also produced for experimental investigation, in addition to the drone frames.

**Experimental Investigations**

The tensile strength of the composite samples prepared was also investigated to determine the mechanical properties of the drone frames produced. The tensile strength test was carried out according to ISO 527-4. The experimental test was performed using a 10 kN load cell universal INSTRON testing machine.

**RESULTS AND DISCUSSION**

The results of tensile strength and Young’s modulus of the composite made from three variants of the embroidered preforms were analyzed and discussed in this section.

Figure 4. (a) Composite preparation stage, (b) Drone frames prepared form flax roving

The composite with a 4 mm stitch length exhibited the highest tensile strength in the 0⁰ (fiber) direction, 10% stronger than the 8 mm variant and 15% stronger than the 2 mm variant as shown in Figure 5. This suggests that using too many needle stitches (2 mm variant) negatively affects the composite’s strength, likely due to needle punctures damaging the sample’s structure. Similarly, a stitch length of 8 mm does not enhance the composite’s strength either, as fewer monofilaments hold the roving in place, resulting in less material being engaged in the stretching process and weakening the sample. When the tensile strength was measured in the 90⁰direction to the fiber alignment, the strength was significantly lower. This is because the fibers are primarily aligned to resist forces along the fiber direction, so there is less reinforcement when the force is applied perpendicular to the fibers.

Additionally, the stitching pattern is less effective in this orientation, further reducing the composite’s strength in the 90-degree direction.



Figure 5. Tensile strength of composite samples produced from embroider fabrics with different stitch length

These properties are particularly beneficial for drone frames, where high strength and lightweight materials are crucial. The 4 mm stitch length offers the optimal balance of tensile strength and durability, making it well-suited for withstanding the stresses experienced by drone frames during flight. The composite’s ability to maintain strength along the fiber direction ensures resilience to the forces that occur during takeoff, landing, and maneuvering, while its lower strength in the 90-degree direction is less critical, as the primary loads are carried along the fibers.

The study also showed that composites reinforced with 2 mm, 4 mm, and 8 mm stitch variants exhibited a noticeably higher Young’s modulus both in 0⁰and 90⁰ to fiber arrangement compared to the standard glass-epoxy composite, which typically has a modulus of ~30 and ~15 GPa in the 0⁰ and 90⁰ to fiber arrangement, respectively (Poniecka et al., 2022a). These findings suggest that the stitching pattern significantly influences stiffness of the composite material.

This increase in Young’s modulus is particularly important for drone frame applications, where stiffness plays a key role in structural integrity and performance. A higher modulus means the frame resists deformation underload, reducing vibrations and improving stability, control responsiveness, and aerodynamic efficiency. Excessive flexing in drone structures can lead to poor maneuverability and inaccurate sensor readings, particularly in high-speed or precision operations.



**Figure 6.** Young’s modulus of composite samples produced from embroidered fabrics with different stitch lengths.

By enhancing stiffness, the stitched composites offer a promising balance of rigidity and lightweight performance, making embroidered fabric-reinforced composites strong candidates for drone applications that demand durability, vibration damping, and optimal flight performance.

**CONCLUSION**

In this work, we focused on the viability of using an embroidery machine to produce drone frames from flax rovings and achieving good mechanical properties in the composites through Tailored Fiber Placement (TFP). We also investigated the impact of stitch length on the production of composite preforms using embroidery machines and its influence on the tensile strength and Young’s modulus of the composite. Overall, the use of a technical embroidery machine has significant advantages in terms of reducing material wastage, as it allows the production of the exact shape of the object with the desired properties by offering various options for fiber arrangement. Reducing waste provides several benefits, such as minimizing production costs and promoting environmental sustainability.

Additionally, this study assessed the feasibility of using flax fiber-based composites with the TFP technique for entry-level drones from a cost perspective. The results showed that, on average, using flax fiber composites can reduce drone production costs by approximately 41% compared to carbon fiber. Furthermore, flax fiber is a renewable resource with a low environmental impact, and the manufacturing process for flax fiber composites is less complex and energy intensive. This makes flax fiber composites easier and more cost-effective to produce and recycle than carbon fiber.

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