Silesian University of Technology
Faculty of Mechanical Engineering
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Doctoral Dissertation

Optimization method for ultralight aerial composite structures

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Content

1. Introduction

Composite materials are characterized as substances comprising two or more macroscopically distinct phases. This differs from materials like alloy steel, wherein the alloying components are integrated at the microscopic scale, yielding a material that exhibits macroscopic homogeneity. The preeminent exemplar of a composite material is concrete, wherein particles of sand and gravel are amalgamated with a blend of cement and water, resulting in the composite material [1]. Within this investigation, the term "composite materials" refers specifically to fiber-reinforced polymers (FRPs), which encompass resilient and rigid fibers, including glass, carbon, Kevlar, and other types. These fibers are integrated into a flexible and lightweight matrix, such as epoxy, ensuring that the resulting composite materials demonstrate a harmonious blend of properties. The orientation of the constituent fibers has a significant impact on the mechanical properties of these composite materials [2]. Composite materials have been extensively utilized in aerospace applications to attain elevated levels of strength and stiffness while concurrently reducing weight in comparison to corresponding metallic components. Laminates are manufactured by stacking and curing a few plies Fig.1 illustrates a Bio composite structure manufactured strategy.

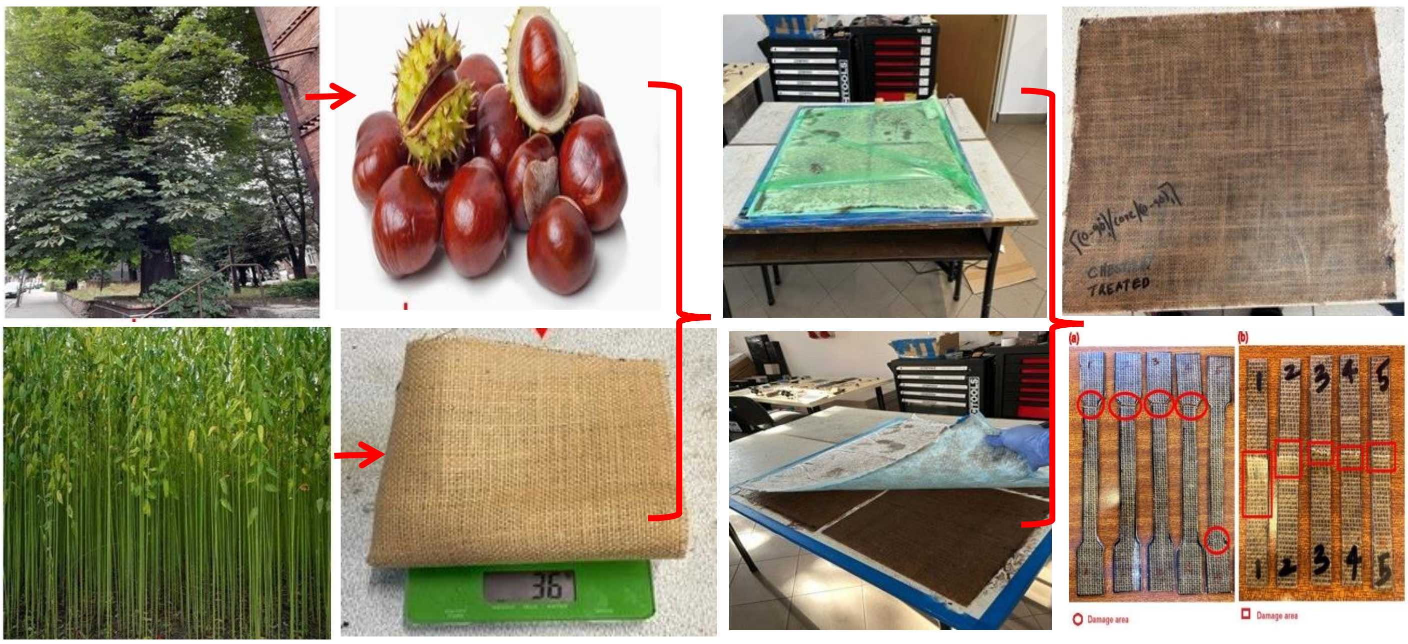

Figure 1. Bio-Composite sandwich structure fabrication strategy for TS17 UAV wing

To achieve the required thickness and stiffness, multiple reinforced plies are layered to create composite laminates. Each of these layers is made up of a sheet with many fibers embedded in a matrix material, which could be a polymer or a metal. Usually, the same matrix material that is present in a single sheet is used to connect the layers. Comprising of multiple sheets oriented in distinct directions, the bidirectional fiber-reinforced sheets are what give composite laminate its name. This arrangement of various orientations is referred to as the lamination scheme or stacking sequence. The stacking sequence, along with the material properties of each individual sheet, grants designers additional flexibility to customize the stiffness and strength of the laminate. I employ classical laminated plate theory to explain the mechanical behaviour of a typical composite laminate [3]. The mechanical characteristics of a laminate result from various factors, such as the material properties of each individual layer, the quantity of layers, the thickness of each layer, and the orientation of the layers. Utilizing laminated composite materials provides significant design flexibility and allows for a high level of customization in the composite structure. By carefully designing and strategically positioning fibers, one can achieve effective structures that possess stiffness meticulously tailored to meet specific operational requirements [4]. Composite materials are frequently employed in high-performance structures because of their superior stiffness and strength-to-weight ratio in comparison to their metallic counterparts [5]. The elevated specific properties facilitate additional weight reduction, leading to decreased fuel consumption in applications such as civilian air transport. Fig.2 illustrates typical uses of laminated composite reinforcements.

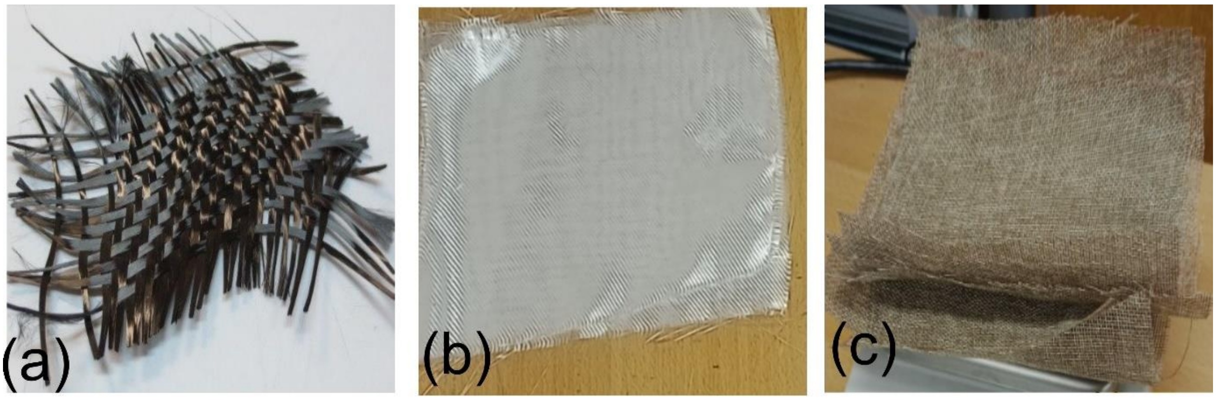

Figure 2. Composite reinforcements, (a) carbon, (b) E-glass and (c) Jute fiber respectively

It is a prevalent characteristic of these structures that their mass significantly impacts their performance, contributing to increased fuel consumption and greater forces transmitted through the structure [6]. The major goal is to use optimization approaches based on classical laminate theory to discover the most effective stacking sequence, resulting in higher performance metrics while drastically reducing the overall weight of the composite structure. This weight reduction is critical for increasing UAV endurance and fuel efficiency, as lighter structures use less energy during flight. The doctoral dissertation includes two case studies: T-joint structural analysis and sandwich core optimization approaches. During work related to the doctoral thesis, the optimization method was applied for developing a sandwich structure at various shaped was analysed and four distinctive T-joint geometrical models were developed and analysed with different material, thickness, and shape, which were included in the doctoral dissertation as one of the case studies. The study involved the fabrication and optimization of a prototype bio-composite material with a focus on environmental sustainability.

2. Objective and thesis of the work

- Review of methods for forming load-bearing composite structures
- Numerical analysis and verification tests of thin-layer sandwich structures
- Development of principles for forming thin-layer composite structures
- Development of a method for optimizing thin layer structures

The thesis investigates an optimization methodology designed for ultra-lightweight composite constructions. This method requires rigorous control of ply orientation, stacking sequence, and individual lamina thickness. The goal of implementing an optimization technique is to determine the most effective stacking sequence while adhering to classical laminate theory concepts. The outcome of this effort yields highly refined performance measures, resulting in a significant reduction in the overall weight of the composite structure, thereby improving its lightweight features. Such advances have significant consequences for aircraft endurance and fuel efficiency since reduced weight equates to lower energy consumption during flight operations. Furthermore, the use of a prototype bio-composite material demonstrates a dedication to environmental sustainability. This eco-friendly material not only adds to the composite's structural integrity, but it also aligns with larger programs focused on decreasing the environmental impact of aerospace engineering techniques.

3. Discussion of the presented research

3.1 Ply based optimization

In this study, diverse materials with varying strengths and ply sequences were investigated, accounting for thickness variations. Through Ansys simulations, maximum stress, strain, deformation, and shear stress were analyzed for different ply configurations. Particularly, natural reinforced fiber composite (Jute) laminates were scrutinized, revealing that mechanical properties, especially maximum stress, peaked in the longitudinal direction with varying fiber orientations. The study showcased the superiority of hybrid natural-fiber-reinforced composites over natural fibers, particularly at specific configurations, offering promising prospects for UAV wing construction. The combination of jute and glass fiber with epoxy resin composite, especially at a 45° ply orientation and 3 mm thickness, demonstrated notable mechanical properties. Despite the linear elastic behavior of natural fibers, a substantial increase in material yield strength was observed when natural fibers were combined with synthetic ones. Laboratory testing is imperative to validate these simulation findings. Nevertheless, based on the results, it was concluded that natural hybrid composites hold promise for prototype UAV structure fabrication. Recommendations for future work include fabricating test specimens according to ASTM standards and conducting further analyses based on laboratory tests. If corroborated through testing, this material could revolutionize UAV manufacturing applications. The design methodology is depicted in Figure 3.

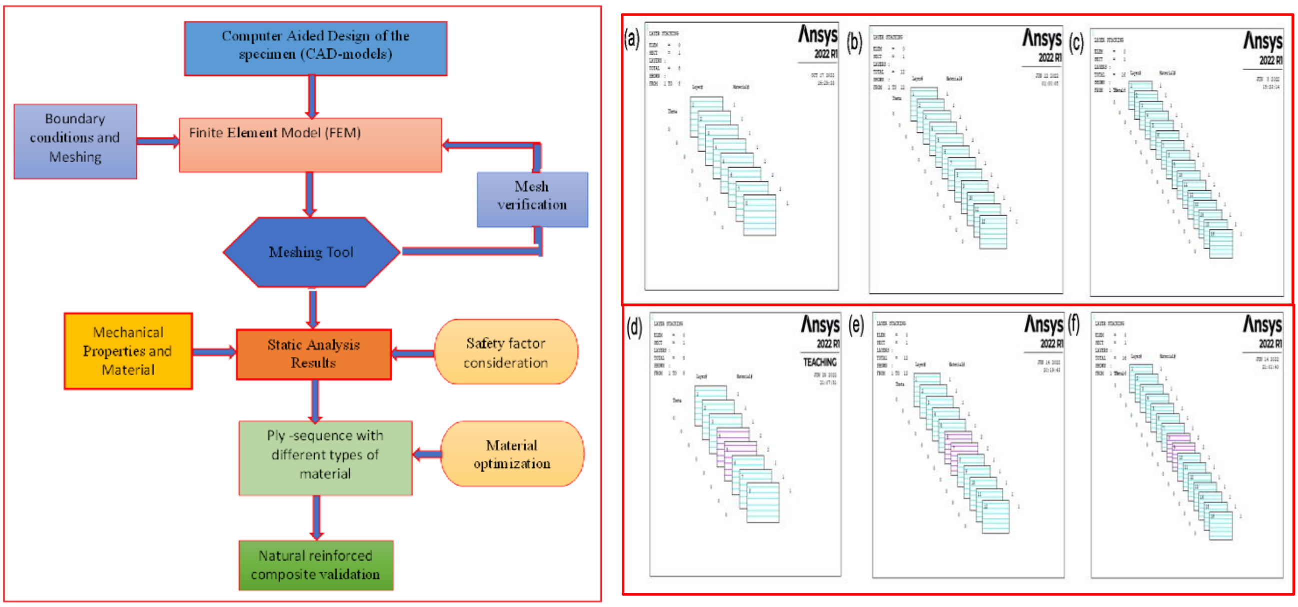

Figure 3. NFRC optimization layout.

3.2 Multi-objective optimization methodology by GA

The second optimization approach for composite structures, focusing on the utilization of genetic algorithms. The research work included the optimizing stacking sequences in lightweight composite structures that employs multi-objective evolutionary algorithms. In the optimization framework, were successfully incorporated engineering design standards applicable to stacking sequence design as constraints or supplementary targets. Additionally, were created a new initiation technique based on the real applications to improve the optimization process. The optimization procedure is illustrated in Fig.4

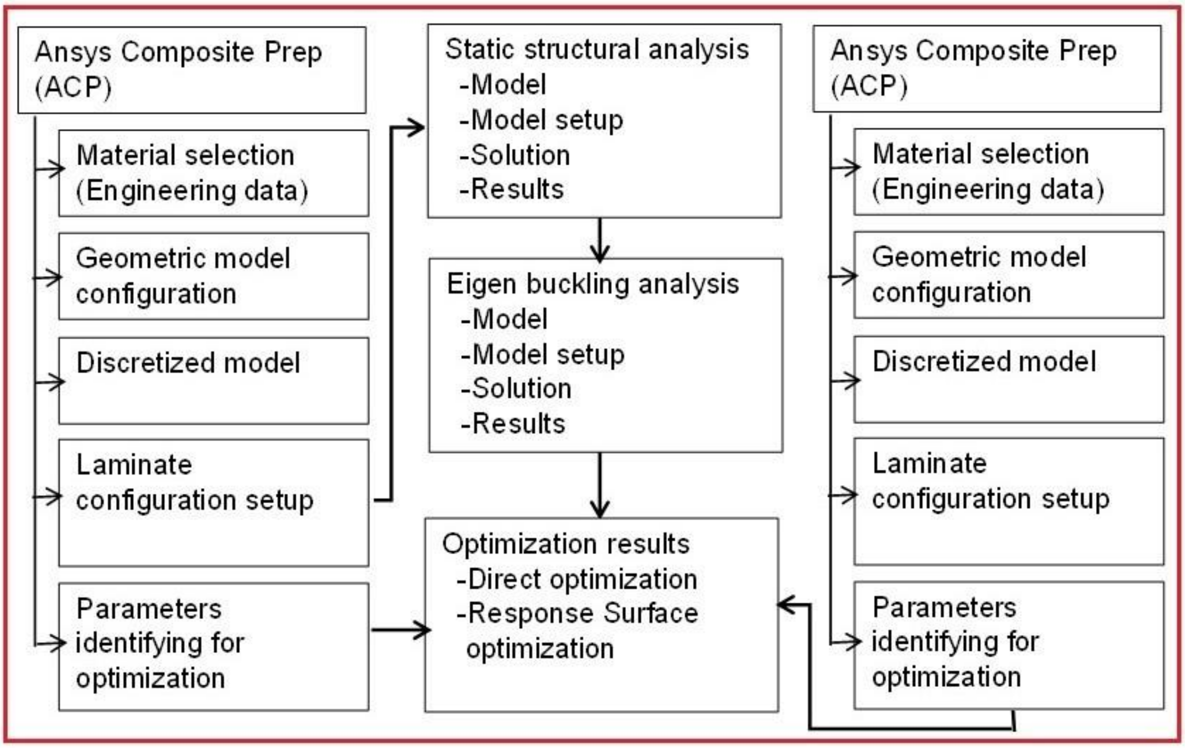

Figure 4. Multi- objective optimization strategy

3.3 Sandwich structure design and analysis

This study aims to design and analyze composite sandwich structures with the goal of optimizing material weight while enhancing material strength to reduce aerodynamic loads. The research involves analyzing material stability and mechanical properties to develop thin-walled composite materials. Since material failure modes occur during operational loads, including debonding at core-facing interfaces, indentation failure under concentrated loads, core material failures, compression wrinkling above the core face, and global buckling, it is crucial to address these issues. To do so, core materials are analyzed alongside skin materials using scale models, followed by the creation of CAD models with various geometric parameters analyzed in ANSYS. Simulation results are compared with results from multiple models and mechanical properties to determine the most effective approach for ensuring material stability. A novel corrugated material is proposed as the core material, with layers formed by Epoxy Carbon fibers UD and glass-epoxy fibers planned for the skin. This combination of materials in different proportions aims to resolve the aforementioned issues and achieve lightweight, high-strength material preparation. Noval sandwich structure is presented in Fig.5.

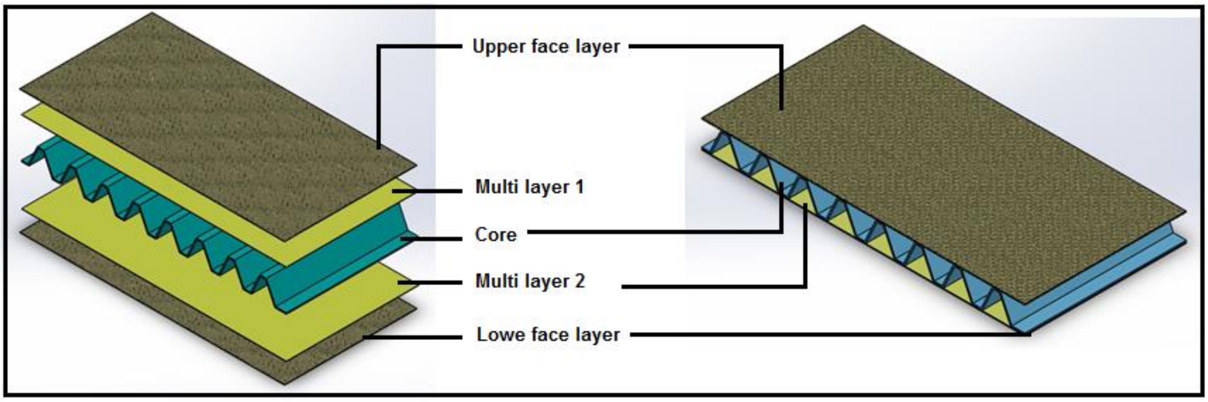

Figure 5. Novel sandwich structure schematic diagram.

3.4 Design and optimization of composite sandwich T-joint

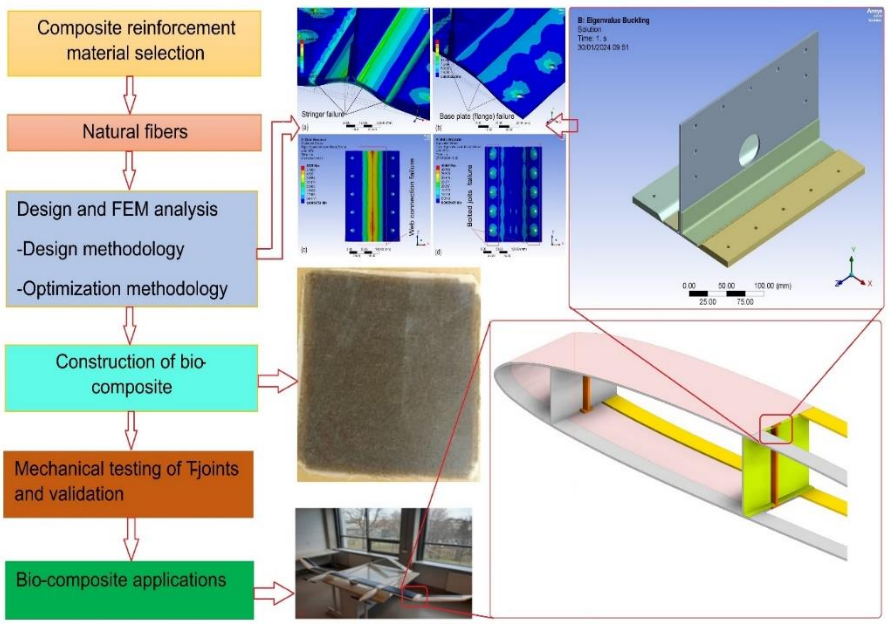

Figure 6. Process flow layout for Sandwich T-joint.

Airframe structures consist of fundamental components that are interconnected to form a channel for the transmission of loads. The joints serve as potential areas of vulnerability and play a pivotal role in determining the overall efficiency of the composite structure. The importance of T-joints in aircraft wings made of composite materials resides in their complex geometry and their crucial function in sustaining the overall structural integrity. These joints repeatedly fail because of transverse normal and shear stresses. This is mostly due to the absence of any reinforced fibers that are perpendicular to the plane of the laminate. The process layout illustrated in Fig.6

Therefore, resin predominates, resulting in diminished interlaminar strength qualities. Therefore, the strength of the individual laminates greatly restricts the strength of T-joints in the out-of-plane direction. When a force is applied in a direction perpendicular to the plane, it results in many types of stresses, including interlaminar normal stress (σz), interlaminar shear stresses (τyz and τxz), and in-plane stress (σy). All these factors contribute to the failure of T-joints.

3.5 Optimization of composite sandwich structure for TS-17 UAV

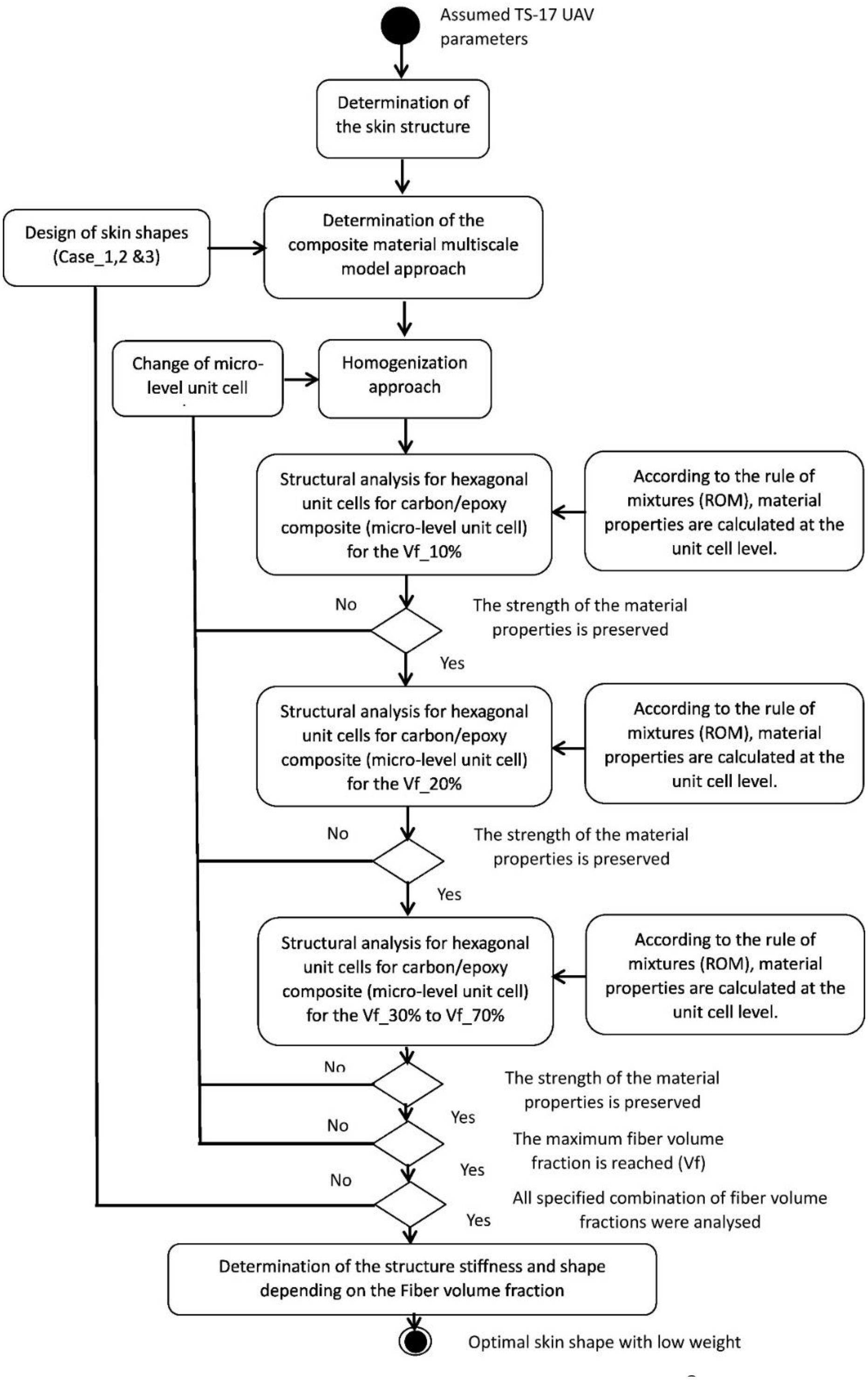

Figure 7. T17 UAVs wing skin optimization layout

In smaller companies that develop and produce single series of modern ultra-light unmanned aerial vehicles (UAVs), the design process typically starts with hand calculations. Although these calculations are supported by standards and guidelines, often the aircraft being designed do not conform to these specifications. Additionally, the unpredictable aerodynamic forces acting on the wings and the use of sandwich-structured composites that deform nonlinearly complicate the design process. This makes the introduction of the Finite Element Method combined with an optimization scheme particularly beneficial. This is especially crucial for ultra-light structures like the High-Altitude Long Endurance Unmanned Aerial Vehicle Twin Stratos (HALE UAV TS) family, which includes the TS12 and TS17, developed by a scientific and technical consortium. The optimization mythology was presented in Fig. 7.

Table.1 Case_1,2 and 3 Compression test FEM analysis result

		Thickness	IRF	Deformation	Stress	Strain	Compressive stress_X	Compressive stress_Y	Compressive stress_Z	Weight
Case_1	Compression load	0.4	0.058	0.054	11.709	0	-4.41E-08	-9.414	0	6.89E-03
Case_2_ Results		1	0.156	0.0452	18.854	0.175	11.757	0.446	11.757	1.40E-02
		2	0.263	0.06	41.287	0.0874	17.633	1.119	20.481	1.42E-02
		3	0.27	0.068	41.318	0.057	16.768	1.642	20.876	1.45E-02
Case_3_ Results		0	0.462	0.144	79.479	0.053	35.312	20.921	62.967	2.02E-02
		1	0.495	0.125	59.391	0.044	32.938	22.216	53.515	2.03E-02
		2	0.653	0.1	59.902	0.046	30.941	20.563	57.009	2.06E-02
		3	0.729	0.084	72.339	0.046	29.437	28.914	62.653	2.09E-02

Comparison in between Sandwich structure vs Sandwich structure with hat shaped stiffeners the several factors.

- **Structural behaviour**: Case 2 (Sandwich Structure) generally exhibits more predictable and consistent mechanical responses with increasing thickness under both compression and shear loads.
- **Stress distribution**: Case 3 (Sandwich Core with Hat-Shaped Stiffener) shows more varied stress distributions with thickness, likely due to the presence of stiffeners affecting load distribution.

Table.2 Case_1,2 and 3 Shear test FEM analysis result

		Thickness	IRF	Deformation	Stress	Strain	Shear_XY	Shear_XZ	Shear_YZ	Weight
Case_1_ Results	Shear load	0.4	0.423	0.081	98.53	0.005	20.969	4.91E-26	1.85E-15	6.89E-03
Case_2_ Results		1	0.83	0.307	296.16	0.236	8.678	134.67	4.538	1.40E-02
		2	0.621	0.119	215.75	0.132	5.176	97.917	2.572	1.42E-02
		3	0.655	0.116	200.35	0.1	3.805	90.958	1.899	1.45E-02
Case_3_ Results		0	0.838	0.243	289.29	0.01	0.365	130.88	29.565	2.02E-02
		1	3.368	0.543	756.62	0.103	3.87	131.61	343.84	2.03E-02
		2	2.668	0.462	694.75	0.087	2.793	121.14	314.53	2.06E-02
		3	2.285	0.324	639.35	0.087	2.408	110.45	289.52	2.09E-02

3.6 Manufacturing of bio-composite and validation

The current research focuses on conducting various tests to assess the mechanical properties of bio-composite and hybrid composites. The study involves fabricating different configurations of composite laminates and sandwich structures. The process of fabricating composite laminates begins by using a 600x600x10 mm square wood plate as a mould. In this research, the vacuum bagging technique was utilized for the fabrication of composite structures. Vacuum bagging techniques are widely employed in the fabrication of composite structures due to their ability to enhance mechanical properties and prevent structural defects. Initially, the mould is cleaned, and a layer of wax is applied as a mould release agent. After the application of wax, the mould is left for 30 minutes to allow the wet surface to dry. The reinforcements are trimmed according to ASTM standards, and a thin layer of resin, mixed with 100:27% hardener (bio-resin), is applied to the mould using a flat brush. The weight of the bio-resin is determined based on the weight of the fibers, which is measured using a calibrated digital scale. Next, the successive layers of reinforcement are impregnated with the bio-resin using a brush with a roller. This process helps compact the layers and remove any air bubbles. Once the plies are laid based on the stacking sequence and ply orientation, a peel ply is applied to the combined laminate surfaces. A thin layer of release film is then placed to ensure the uniform flow of bio-resin throughout the reinforcement. A breather cloth is applied as the next layer, followed by sealing the vacuum bagging film with vacuum bagging sealant. The mould is then connected to a vacuum pump, which runs for approximately 8 hours to cure the laminates. Finally, after a post-curing period of 24 hours, the laminate is demoulded.

Table 3. Description of the current research design methodology for laminate

Types of tests	Types of laminate	Number of plies	Stacking sequence	Designation
Compression test	Bio-composite	6	[0-90°/0-90°/±45/±45/0-90°/0-90°]S	J/J/J/J/J/J
	Hybrid (Jute-75%)	8	[0-90°/0-90°/0-90°/±45/±45/0-90°/0-90°/0-90°]S	G/J/J/J/J/J/J/G
	Hybrid (Jute-25%)	8	[0-90°/0-90°/0-90°/±45/±45/0-90°/0-90°/0-90°]S	G/G/G/J/J/G/G/G
	Synthatic composite	10	[0-90°/0-90°/0-90°/±45/±45/±45/±45/0-90°/0-90°/0-90°]S	G/ G/ G/ G/ G/ G/ G/ G/ G/ G
Tensile test	Bio-composite	6	[0-90°/0-90°/±45/±45/0-90°/0-90°]S	J/J/J/J/J/J
	Hybrid (Jute-75%)	8	[0-90°/0-90°/0-90°/±45/±45/0-90°/0-90°/0-90°]S	G/J/J/J/J/J/J/G
	Hybrid (Jute-25%)	8	[0-90°/0-90°/0-90°/±45/±45/0-90°/0-90°/0-90°]S	G/G/G/J/J/G/G/G
	Synthatic composite	10	[0-90°/0-90°/0-90°/±45/±45/±45/±45/0-90°/0-90°/0-90°]S	G/ G/ G/ G/ G/ G/ G/ G/ G/ G
Flexural test	Bio-composite	8	[0-90°/0-90°/±45±45/±45/±45/0-90°/0-90°]S	J/J/J/J/J/J/J/J
	Hybrid (Jute-75%)	10	[0-90°/0-90°/0-90°/±45/±45/±45/±45/0-90°/0-90°/0-90°]S	G/J/J/J/J/J/J/J/J/G
	Hybrid (Jute-25%)	18	[0-90°/0-90°/0-90°/0-90°/0-90°/±45/±45/±45/±45/±45/±45/±45/±45/0-90°/0-90°/0-90°/0-90°/0-90°]S	G/G/G/G/G/G/G/J/J/J/G/G/G/G/G/G/G/G
	Synthatic composite	14	[0-90°/0-90°/0-90°/0-90°/±45/±45/±45/±45/±45/±45/0-90°/0-90°/0-90°/0-90°/]S	G/ G/ G/ G/ G/ G/ G/ G/ G/ G/G/G/G/G

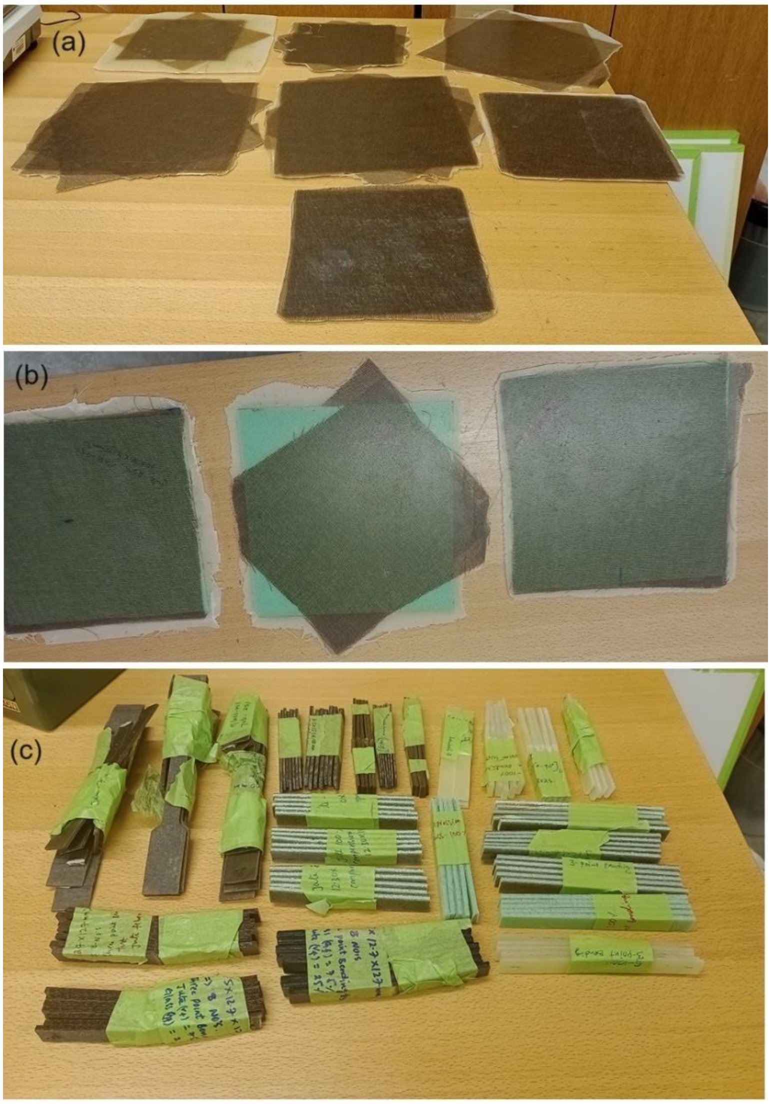

Figure 8. Bio-composites (a) Laminates, (b) Sandwich structures with different configurations and (c) Tested specimens as ASTM standards.

4. Conclusion

- The findings presented in this doctoral dissertation confirm the hypothesis proposed in this research. The suitability of the optimized ultra-lightweight structure for creating lightweight UAVs has been validated, highlighting its eco-friendly and biodegradable qualities. During this PhD research, results were methodically derived, covering optimization approaches, Ansys analysis, manufacturing processes, and laboratory testing procedures.

- **Case study _1:** This study's findings can be compared to prior research, and it is recommended to explore alterations in geometric shapes, fiber orientations, and ply stacking sequences to mitigate structural failures in T-joints, particularly at the interfaces of the stringer, base plate, and web.
- **Case study _2 (Approach_1):** The findings have significant ramifications for the development and enhancement of natural composite materials in engineering applications. The findings of this study indicate that the sandwich structure experiences a shear stress of 28.889 MPa and von Mises stresses of 57.754 MPa, which are higher than those observed in design cases 1 and 2. Furthermore, design case 3 is deemed suitable for aerospace applications. Further inquiry and testing may be necessary to authenticate and improve the findings of this study
- **Case study _2_(Approach_3):** The structural static tests were conducted using Ansys, and four laminates with different configurations were analyzed in this research. The highest stress was observed in laminate_1, while the minimum deformation was noted in laminate_4. Laminate_2 demonstrated the best results when compared to all evaluated laminates. These simulation results hold promise for future applications in UAV wing design.
- **Case study_3:** Comparison in between Sandwich structure vs Sandwich structure with hat shaped stiffeners the several factors.
- **Structural behaviour**: Case 2 (Sandwich Structure) generally exhibits more predictable and consistent mechanical responses with increasing thickness under both compression and shear loads.
- **Stress distribution**: Case 3 (Sandwich Core with Hat-Shaped Stiffener) shows more varied stress distributions with thickness, likely due to the presence of stiffeners affecting load distribution.
- From a future perspective, the optimized methodology holds promise for fabricating UAV structures. Specifically, hybrid composites can be utilized in wing construction, while bio-composites are suitable for fuselage components. However, in this research, bio-composites were explored for use throughout the UAV's parts. This study has the potential to catalyze significant advancements in both the automobile and aerospace industries. Further research is necessary to transition this work into real-world applications, including fabrication and flight testing.

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