

Design, Structural Analysis and Optimization of a Composite Cargo Compartment of a UAV

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*"There may be people that have more talent than you, but there's no excuse
for anyone to work harder than you do."*

-Derek Jeter

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Abstract

This thesis is developed in collaboration with Tekever, a Portuguese company dedicated to Unmanned Aerial Vehicles, within the scope of the development of its latest project, the ARX, and this work focuses on the design, structural analysis, and optimization of a composite cargo compartment for this aircraft. The aim is to create a compartment capable of deploying a swarm of drones mid-flight, integrating it seamlessly into the existing aircraft structure, and starting from a basic CAD model, the compartment and its mechanisms, including trapdoors and actuators, were developed. Various analyses, including structural and functional assessments were conducted to ensure the compartment's performance under critical flight conditions.

A significant part of the study involved the validation and improvement of an existing optimization algorithm, that aims to minimize weight while maintaining structural integrity by optimizing the number of layers and the fiber orientation of the composite material for each critical section of the cargo compartment. The tool, based on a genetic algorithm, explores the search space with constraints based on different failure criteria, particularly Hashin's damage initiation criteria. A surrogate model was created to integrate Abaqus with Python using a Latin Hypercube sampling technique to generate the training set and develop the regression model using the Gaussian process. The improvements made to the tool enhanced computational efficiency, allowing for the analysis of 1,200 samples, which led to a significant weight reduction of approximately 54% from the initial design.

The study also included a detailed conceptual analysis of different methods for connecting the cargo compartment to the fuselage, ensuring ease of extraction for loading and maintenance. The preferred solution for the extraction mechanism was a lateral opening with a sliding rail system, offering a smooth and controlled movement for loading and unloading, and for the trapdoor opening, linear actuators were identified as the most suitable actuation mechanism due to their combination of precision, high force output, and reliability. An electric strike lock mechanism was recommended for securing the trapdoors, providing fail-safe operation and moderate cost.

The final optimized design was subjected to comprehensive structural analysis using ABAQUS, validating its ability to withstand operational loads and conditions, and this optimization process demonstrated substantial weight savings and improved structural performance, highlighting the effectiveness of the optimization tool and the benefits of using advanced algorithms and FEA in aeronautical engineering. The results provide valuable insights and methodologies for future UAV structural designs, hoping to contribute to the advancement of lightweight, high-performance aeronautical structures.

Keywords: Cargo compartment, Composite Materials, Finite Element Analysis, Genetic Algorithms, Optimization Tool, Structural Analysis, Structural Optimization, Unmanned Aerial Vehicle, Weight Reduction.

Resumo

Esta tese foi desenvolvida em colaboração com a Tekever, uma empresa portuguesa dedicada a Veículos Aéreos Não Tripulados, no âmbito do desenvolvimento do seu mais recente projeto, o ARX, e este trabalho foca-se no design, análise estrutural e otimização de um compartimento de carga compósito para esta aeronave. O objetivo é criar um compartimento capaz de lançar um grupo de drones em pleno voo, integrando-o na estrutura existente da aeronave. A partir de um modelo CAD básico, foram desenvolvidos o compartimento e os seus mecanismos, incluindo portas e atuadores. Foram realizadas várias análises, incluindo avaliações estruturais e funcionais, para garantir o desempenho do compartimento em condições críticas de voo.

Uma parte significativa do estudo envolveu a validação e melhoria de um algoritmo de otimização existente, que visa minimizar o peso enquanto mantém a integridade estrutural, otimizando o número de camadas e a orientação das fibras do material compósito para cada secção crítica do compartimento de carga. A ferramenta, baseada num algoritmo genético, explora o espaço de busca com restrições baseadas em diferentes critérios de falha, particularmente o critério de Hashin. Foi criado um "Surrogate Model" para integrar o Abaqus com o Python, utilizando uma "Latin Hypercube sampling technique" para gerar o conjunto de treino e desenvolver o modelo de regressão usando o processo Gaussiano. As melhorias feitas na ferramenta aumentaram a eficiência computacional, permitindo a análise de 1.200 amostras, o que levou a uma redução significativa de peso de aproximadamente 54% em relação ao design inicial.

O estudo também incluiu uma análise conceptual detalhada de diferentes métodos para conectar o compartimento de carga à fuselagem, garantindo facilidade de extração para carregamento e manutenção. A solução preferida para o mecanismo de extração foi uma abertura lateral com um sistema de trilhos deslizantes, oferecendo um movimento suave e controlado para o carregamento e descarregamento, e para a abertura das portas, atuadores lineares foram identificados como o mecanismo de atuação mais adequado devido à sua combinação de precisão, alta distribuição de força e fiabilidade. Um mecanismo de fecho elétrico foi recomendado para garantir a segurança das portas, proporcionando operação à prova de falhas e custo moderado.

O design otimizado final foi submetido a uma análise estrutural abrangente usando o Abaqus, validando a sua capacidade de resistir a cargas e condições operacionais, e este processo de otimização demonstrou reduções substanciais de peso e melhoria do desempenho estrutural, destacando a eficácia da ferramenta de otimização e os benefícios do uso de algoritmos avançados e FEA na engenharia aeronáutica. Os resultados fornecem insights e metodologias valiosas para futuros designs estruturais de UAV's, esperando contribuir para o avanço de estruturas aeronáuticas leves e de alto desempenho.

Palavras-chave: Algoritmos Genéticos, Análise de Elementos Finitos, Análise Estrutural, Compartimento de carga, Ferramenta de Otimização, Materiais Compósitos, Otimização Estrutural, Redução de Peso, Veículo Aéreo Não Tripulado.

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Nomenclature

AI	Artificial Intelligence
ASTM	American Society for Testing and Materials
CAD	Computer Aided Design
CFRP	Carbon Fiber Reinforced Polymer
CFR	Code of Federal Regulations
CS	Certification Specifications
DOE	Design of Experiments
EASA	European Union Aviation Safety Agency
EU	European Union
FAA	Federal Aviation Administration
FEA	Finite Element Analysis
FPF	First Ply Failure
FRP	Fiberglass Reinforced Polymer
ICAO	International Civil Aviation Organization
LARC	Lamina Analysis and Research Composite
LPF	Last Ply Failure
MAME	Medium Altitude Medium Endurance
NASA	National Aeronautics and Space Administration
NAS	National Airspace System
NDT	Non-Destructive Techniques
SAR	Synthetic Aperture Radar
SORA	Specific Operations Risk Assessment
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
VTOL	Vertical Take-Off and Landing
XWB	Extra Wide Body

Chapter 1

Introduction

1.1 Problem Statement and Objectives

In the scope of the development of the ARX drone by Tekever, the possibility of creating a cargo compartment capable of deploying a swarm of drones mid-flight was suggested, and this thesis addresses the design, analysis, and optimization of such a compartment. Starting from a simple CAD model of the UAV provided by the company, the cargo compartment and its respective trapdoors and opening mechanisms were developed and, consequently, various analyses became necessary, ranging from the opening mechanism to the structural analysis of the compartment when subjected to flight limit conditions, as well as the optimization of the developed structure.

A significant part of the thesis is also dedicated to the improvement and application of an optimization algorithm aimed at minimizing the weight of composite structures, developed by Eng. Douglas Rodriguez [1] and Eng. Dilki Dias [2], and this optimization focuses on determining the optimal number of layers and the orientation of the fibers of the composite material, with the goal of maximizing weight reduction while adhering to a predefined failure criterion.

The primary objectives of the thesis are to conduct a literature review on UAV's, composite materials, and their failure mechanisms, as well as the incorporation of trapdoors into this type of aircraft and, following this, the development and application of an optimization algorithm to a composite structure, specifically the cargo compartment, will be explored. Additionally, different methods of connecting the compartment to the global structure and various approaches to extracting the cargo compartment will be examined, as well as the study of actuation and locking mechanisms of the trapdoors to ensure a fail-safe operation. Moreover, a structural analysis of the cargo compartment will be performed, calculating the loads acting on the structure and evaluating different geometries, materials, and structural configurations based on parameters such as stress, deflection, and composite failure criteria. Ultimately, the developed optimization tool will be applied to the structure to determine the optimal number of layers and fiber orientations for the composite material, thus obtaining a structure capable of sustaining the acting loads with the least weight possible.

1.2. Thesis Layout

1.2 Thesis Layout

In alignment with the previously described objectives, the chapters of this work follow the logical order of presenting the complete development of the cargo compartment and trapdoors, starting from the provided initial CAD model to the complete analysis and optimization of the created structure.

The 2nd chapter of this work presents the literature review regarding Unmanned Aerial Vehicles (UAV's), composite materials and their failure mechanisms, materials certification on this type of aircraft, the use of trapdoors and its application on cargo compartments, optimization algorithms and its application in composite structures.

The 3rd chapter involves the design and modeling of the cargo compartment structure, starting with its connection to the fuselage, to the study of different possible methods of extracting it for loading, unloading, or maintenance of the structure, followed by the definition of the best type of hinges suited to open the trapdoors and the ideal actuation mechanism that should be used to actuate the trapdoors of the cargo compartment. Finally, the study of different locking mechanisms is performed, in order to have a fail-safe structure as required.

The 4th chapter encompasses the structural analysis performed on the cargo compartment, starting from the most realistic boundary conditions to apply, followed by the determination of the total loads acting on the structure and the appropriate materials to use on the structure. Then, several different geometries and structures with different materials from the available ones are created and analyzed through a FEA in ABAQUS, thus providing the optimal structure from the created ones to insert in the cargo compartment, where stresses, deflections and the composite's failure criteria are the main areas of investigation.

The 5th chapter refer to the development and improvement of the optimization tool, as well as the study of the different parameters of the genetic algorithm that are crucial to the correct functioning of the tool, as well as the validation of the improved algorithm for different failure criteria (Tsai-Hill, Hashin and Larc05) using simple classical cases, such as a plate with an applied tensile load and with an applied shear load.

Finally, in the 6th chapter, the developed optimization tool is explained, and all of the improvements performed to the code are detailed, as well as a description, or a guide, on how the code works from the introduction of the geometry to the genetic algorithm and the final results. Then, it is applied to the modeled structure, and the obtained results on the optimal number of layers and the direction of the fibers in each ply are obtained, analyzed and discussed, finalizing with a study on how the weight of the structure evolved from the initial geometry to the final optimized one.

The final discussion, conclusions on the performed work and potential future works are presented in the 7th and final chapter.

Chapter 2

Literature review

2.1 Unmanned Aerial Vehicles (UAV's)

Unmanned Aerial Vehicles (UAV's), commonly referred to as drones, have emerged as versatile tools with applications spanning various industries including military, commercial, scientific research, and even recreational pursuits. These aerial vehicles, which do not require onboard human operators, offer a range of capabilities from surveillance and reconnaissance to payload delivery and remote sensing, and with advancements in technology, UAV's have evolved significantly in terms of design, functionality, and autonomy, making them indispensable assets in modern aviation. Their compact size, maneuverability, and ability to access remote or hazardous environments with minimal risk to human operators have led to widespread adoption across diverse sectors [3]. Furthermore, the integration of sophisticated sensors, high-resolution cameras, and data processing algorithms has enhanced their utility for tasks such as mapping, monitoring agricultural fields, inspecting infrastructure, and conducting search and rescue operations [4].

In addition, they are extensively used for mapping and surveying applications due to their ability to capture high-resolution imagery and generate accurate three-dimensional models of terrain. Thus, they enable efficient aerial surveys of large areas with rapid data acquisition, making them invaluable tools for cartography, urban planning, environmental monitoring, and disaster management [5]. Regarding search and rescue operations, UAV's can be equipped with thermal imaging cameras and autonomous navigation capabilities, to swiftly survey large areas, locate missing people, and deliver essential supplies or communication equipment to remote locations. Their rapid deployment, aerial perspective, and real-time data transmission capabilities improve response times and increase the chances of successful rescue missions, thereby saving lives in critical situations [6].

On the other hand, the use of Unmanned Aerial Vehicles presents significant challenges and concerns, particularly in the areas of safety and privacy, and instances of drones interfering with commercial aircraft have raised concerns about potential accidents and disruptions to air traffic, highlighting the need for stringent safety regulations and measures [7]. Furthermore, the ease of access to drones and their relatively low cost have raised concerns about their potential misuse by individuals or groups with malicious intent. There have been instances of drones being used for activities such as smuggling contraband into correctional facilities or conducting unauthorized surveillance of sensitive locations. Moreover, having into account the exponential growth of artificial intelligence (AI) and its autonomous operation, new dimensions of privacy risks have to be

2.1. Unmanned Aerial Vehicles (UAV's)

accounted for. With the ability to autonomously identify and track individuals or objects, drones equipped with AI-powered algorithms can potentially infringe upon personal privacy rights by indiscriminately collecting data without proper oversight or consent mechanisms in place [8].

2.1.1 Vertical Take-Off and Landing

There is a wide range of possibilities regarding UAV's design and configuration, and Vertical Takeoff and Landing (VTOL) drones represent a significant advancement in unmanned aerial vehicle technology, offering unique capabilities that make them well-suited for a wide range of applications. VTOL drones have the ability to take off and land vertically, eliminating the need for a traditional runway, making them particularly valuable for operations in urban environments, remote areas, or locations where access to conventional runways is limited or impractical. One of the primary advantages of VTOL drones is their ability to hover in place, providing robust stability and maneuverability during operations such as aerial surveillance, mapping, or reconnaissance, allowing them to maintain a fixed position or conduct detailed inspections with precision, making them invaluable tools for tasks that require close proximity to the target area. On the other hand, they have typically shorter flight endurance and lower speed compared to fixed-wing drones, which may restrict their utility for certain long-range or high-speed missions [9].

Due to their unique capabilities, VTOL drones are employed across various industries for a multitude of applications, and some examples include emergency response, including search and rescue missions, disaster assessment, and firefighting support. In fact, companies like Parrot, with their Anafi USA drone (Figure 2.1), provide VTOL solutions equipped with thermal imaging and zoom capabilities, enabling first responders to quickly locate and assess critical situations from the air [10].



Figure 2.1: Anafi USA drone [11].

It is also relevant to approach this type of UAV's importance in the transportation and logistics industry, where companies in this sector explore the use of VTOL drones for last-mile delivery and cargo transport. In fact, Wing, a subsidiary of Alphabet Inc. (Google's parent company), operates a commercial drone delivery service in select regions, utilizing these types of drones to deliver goods directly to customers' doorsteps, like the one seen in Figure 2.2 [12].



Figure 2.2: Alphabet's Wing drone for transportation and logistics [13].

Regarding Tekever, the AR3 VTOL is a versatile small UAS designed for both land and maritime operations, and one of its standout features is the hot-swappable VTOL capability, which allows the vertical lift components to be easily removed, converting the drone into a fully functional fixed-wing system (Figure 2.3). This adaptability extends the AR3's flight endurance from 8 to 16 hours, making it suitable for missions requiring longer duration, and the modular design enhances its transportability and minimizes the logistics footprint, which is crucial for operations in remote or challenging environments.

What truly sets the AR3 apart from its competitors is its advanced VTOL properties, as the ability to take off and land vertically eliminates the need for runways or large open spaces, providing significant flexibility in deployment, and this is especially beneficial for maritime operations, as the drone can be launched from the deck of a ship. The AR3 also features a high-performance, dual-side-looking Synthetic Aperture Radar (SAR), making it the smallest UAV on the market with such advanced sensor capabilities, enabling it to capture detailed imagery and data in various conditions, including adverse weather, thus enhancing its utility for a wide range of demanding missions while maintaining low operational costs [14].



Figure 2.3: Tekever AR3 UAV [14].

2.1. Unmanned Aerial Vehicles (UAV's)

2.1.2 Fixed Wing UAV's

Fixed-wing drones represent a different approach to UAV design compared to VTOL systems, as these drones are characterized by their airplane-like structure, which includes a fixed set of wings that provide lift as the drone moves forward. Unlike VTOL drones, fixed-wing UAV's require a runway or a catapult launch system for takeoff and landing, which can limit their deployment in certain environments. However, the trade-off is a significant advantage in flight endurance and speed, as fixed-wing drones are capable of covering large distances and staying airborne for extended periods, making them ideal for long-range missions such as environmental monitoring, border patrol, and agricultural surveying [15].

Due to their efficient aerodynamics, fixed-wing drones can achieve higher speeds and longer flight times than their VTOL counterparts, which is particularly beneficial for applications that require extensive area coverage or quick response times. Its ability to cover large fields efficiently makes it an invaluable tool for precision agriculture, and in the defense sector, fixed-wing drones provide critical reconnaissance and surveillance capabilities, offering a higher operational range and endurance necessary for military applications. Additionally, these UAV's often carry sophisticated payloads, including high-resolution cameras and advanced sensors, enhancing their utility across various industries.

The AR5, designed by Tekever, is an advanced medium-altitude, medium-endurance (MAME) fixed-wing unmanned aerial vehicle, with a cruise speed of about 100 km/h, an endurance of 20 h, a payload capacity of 50 kg, and the ability to take off and land in an unprepared airstrip. The primary missions performed by this UAV include surveillance and reconnaissance, border and maritime patrol, and environmental monitoring, and can be seen in Figure 2.4 [16].



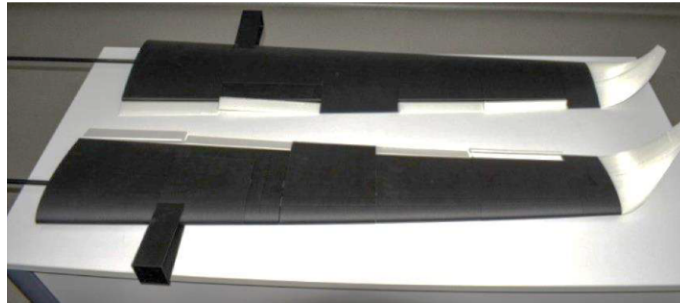
Figure 2.4: Tekever AR5 UAV [16].

2.2 Composite Materials

Composite materials have revolutionized the field of aeronautics, offering unparalleled strength-to-weight ratios, durability, and versatility compared to traditional metallic materials, and they consist of two or more distinct materials combined to create a superior material with enhanced properties. In the aeronautical field, composite materials are extensively utilized in the construction of aircraft structures, components, and systems, and these advanced materials play a critical role in reducing weight, improving fuel efficiency, and enhancing performance, thereby contributing to the development of more efficient and environmentally sustainable aircraft designs [17].

2.2.1 Composite Materials in UAV's

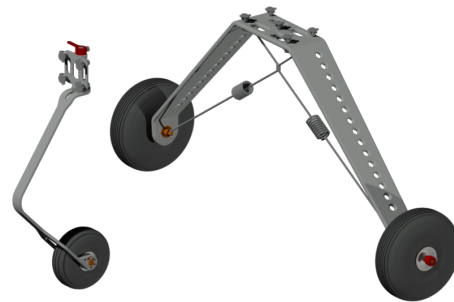
Composite materials find widespread use in various components of unmanned aerial vehicles (UAV's), offering several advantages over traditional materials such as metals or alloys. It is then relevant to detail key parts of UAV's where composites are commonly used and the benefits they provide. In Figure 2.5, we can see different applications of composite materials in UAV's.



(a) Left half-plane and right half-plane of an UAV wing [18].



(b) Composite Rotor in a UAV [19].



(c) CAD model of a UAV landing gear system [20].

Figure 2.5: Possible applications of composite materials in an unmanned aerial vehicle.

- **Airframe:** Composites are extensively used in the construction of UAV airframes, including fuselages, wings, and empennages, and by using composite materials such as carbon fiber reinforced polymers (CFRP) or fiberglass, manufacturers can achieve significant weight savings while maintaining structural integrity and stiffness. This reduction in weight translates to improved fuel efficiency, extended endurance, and enhanced maneuverability, making composite airframes ideal for long-range and endurance missions [21].

2.2. Composite Materials

- **Propellers and Rotors:** Composite materials are also employed in the manufacturing of UAV propellers and rotors, as they offer advantages such as higher strength-to-weight ratios, improved fatigue resistance, and reduced noise compared to traditional metal propellers. Additionally, composite rotors can be designed with complex aerodynamic shapes and profiles to optimize performance and efficiency, resulting in smoother operation and increased thrust generation [22].
- **Structural Components:** Composites are employed in various structural components of UAV's, including ribs, spars, and fairings, and by using composite materials in these critical components, manufacturers can achieve optimal strength-to-weight ratios, corrosion resistance, and fatigue performance. This results in aircraft that are more resilient to harsh environmental conditions and capable of enduring prolonged operational lifetimes with minimal maintenance requirements [23][24].

Carbon Fiber Reinforced Polymers (CFRP's) have emerged as a primary material for UAV structures, offering exceptional strength-to-weight ratios and structural performance, however, the integration of hybrid composite structures, which combine CFRP's with other reinforcing materials such as glass fibers or Kevlar, presents significant advancements in UAV design, addressing specific performance requirements and overcoming limitations associated with CFRP's alone.

These hybrid composite structures display an enhanced impact resistance and vibration damping by integrating materials with superior impact resistance properties, such as glass fibers or Kevlar, therefore they better absorb and dissipate energy during impacts; they also enable cost-effective solutions by strategically incorporating less expensive reinforcing materials in areas where high strength is not the primary requirement, while still maintaining structural integrity and performance; hybrid composites also allow for the customization and optimization of properties for different regions of the UAV, and this flexibility enables designers to tailor UAV structures for weight reduction, performance, and reliability in specific areas [25]. On the other hand, they present some challenges, as ensuring proper bonding and compatibility between different materials can be complex, requiring careful consideration of manufacturing processes and material compatibility to prevent delamination or structural weaknesses; advanced modelling and analysis techniques are required to optimize hybrid structures and to determine the most effective combination of materials and their distribution within the UAV structure, needing sophisticated simulation tools and expertise in composite materials engineering; these materials may also present challenges in repairability, particularly when addressing damage to CFRP components, as these are highly sensitive to impact damage, and repairing damaged parts may require specialized techniques and materials [26].

Despite these challenges, ongoing research and advancements in hybrid composites hold great potential for enhancing the capabilities and applications of UAV's in various industries, and while CFRP's offer exceptional performance characteristics, they also have limitations such as heterogeneity and difficulty in predicting behavior. Additionally, repairing damaged CFRP components can be challenging, necessitating regular inspection and maintenance procedures. To address these challenges and improve sustainability, there is a growing focus on developing recyclable and reusable composite materials, including CFRP's, and researchers are exploring innovative methods for recycling composite materials, such as solvent-based processes to dissolve resins and recover carbon fibers [27][28].

The integration of composite materials in Airbus aircraft represents a significant trend in aeronautical manufacturing, exemplified by models like the Airbus A350 XWB, where Airbus has strategically utilized carbon fiber reinforced polymers (CFRP's) in key structural components of

aircraft such as the fuselage and wings, resulting in substantial weight savings and improved fuel efficiency. In Figure 2.6 it is possible to observe the growing tendency in the use of this material and, in fact, more than half of the percentage of the weight of the aircraft is already obtained from composite materials.

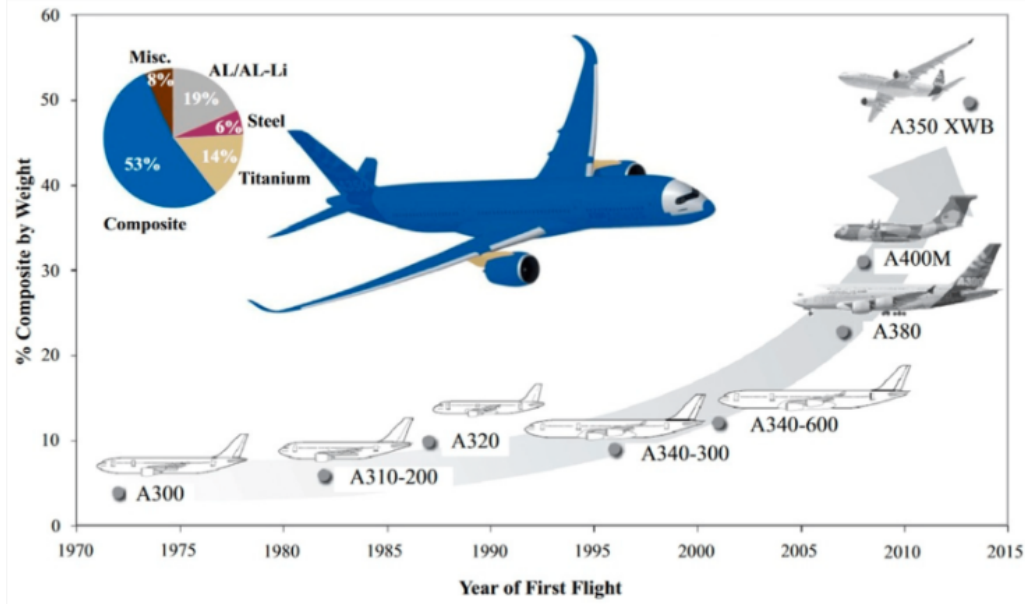


Figure 2.6: Evolution of the use of composite materials in Airbus aircraft. [29]

2.3 Composite Materials Failure Mechanisms and Analysis

Composite materials are known and used due to their exceptional strength-to-weight ratio, making them suitable for everything from aircraft components to cutting-edge sporting equipment. However, beneath their many advantages, a complex reality appears, as unlike their homogeneous counterparts (metals), composites are intricate materials constituted from fibers and matrices, each with distinct properties and interfaces. This very synergy that grants them remarkable strength also introduces a unique challenge: understanding how and why they fail, as the interplay of its constituent materials and their interfaces can lead to various failure modes [30].

Laminated materials usually experience a variety of discrete damage events, or localized failures at smaller magnitudes, before coming apart. These occurrences include matrix cracking, fiber/matrix debonding, and fiber breakage, pullout, or kinking/buckling. Furthermore, delamination may occur in between the plies as well, and these damages gradually grow worse as the load increases. The failure of composite structures may be analyzed from two approaches: the First Ply Failure (FPF), where there is an initial breakdown within a specific ply, usually the one experiencing the highest stress concentration. This initial failure doesn't necessarily mean complete structural failure, as it depends on the material properties and loading conditions, and the remaining plies can still carry some load, offering a degree of redundancy [31]. This approach is usually characterized by matrix-dominated mechanisms, whereas in Last Ply Failure (LPF), fibre-dominated mechanisms are in order. In this approach, the composite endures progressively accumulating damage across multiple plies until the last remaining ply can no longer withstand the load and fails. While FPF offers valuable insights into initial weaknesses, LPF provides information about the overall load-bearing capability of the entire structure, and this is particularly important for applications

2.3. Composite Materials Failure Mechanisms and Analysis

where complete structural integrity is paramount, such as in aircraft components [32][33].

It is possible to divide the different types of failure mechanisms (Figure 2.7) into two categories: interlaminar and intralaminar damage. Interlaminar failure refers to failure that occurs between adjacent plies of a composite material, and these interfaces are typically weaker than the individual layers themselves due to factors such as inadequate bonding between layers, voids, defects introduced during manufacturing, and differences in material properties between layers, and we can include delamination in this category. Intralaminar failure, on the other hand, occurs within individual layers or plies of the composite material and is influenced by factors such as fiber-matrix bonding, fiber orientation, and the mechanical properties of the constituent materials. In this category, we can include fiber breakage and matrix cracking [34].

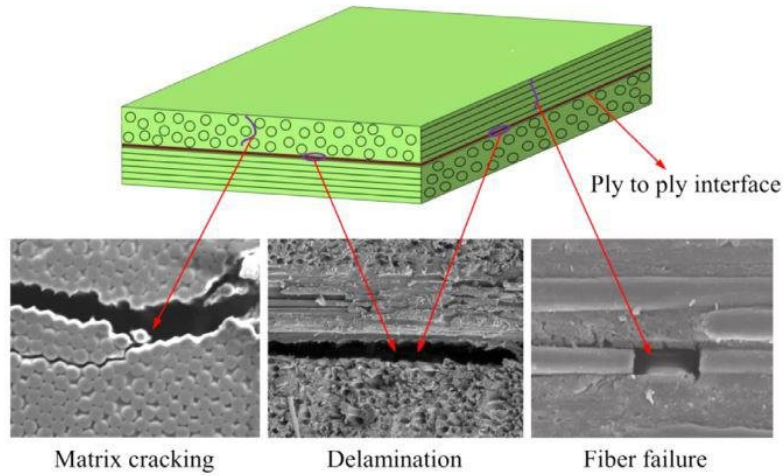


Figure 2.7: Major failure mechanisms in carbon fiber-reinforced composite laminates [35].

It is now relevant to study the existing failure criteria usually used in optimization problems, and the ones existing in the ABAQUS software, as different failure criteria are employed to predict and analyze different failure modes in composite materials, including both interlaminar and intralaminar failures.

The Maximum Stress/Strength Criterion and the Maximum Strain/Energy Criterion are two commonly used approaches in predicting failure in materials, and the first one is a straightforward method that predicts failure based on the maximum stress or strength of the material. It is easy to apply but may not always accurately represent the failure behavior of composites, especially under complex loading conditions [36]. On the other hand, the Maximum Strain/Energy Criterion considers failure to occur when a critical strain or energy limit is reached, and it provides a more accurate representation of failure under multiaxial loading compared to the maximum stress criterion [37].

- **Tsai Hill and Tsai Wu:** The Tsai Hill failure criterion is widely used in composite materials, particularly for analyzing intralaminar failure modes, as it takes into account both material strengths and interaction terms to predict composite failure under multi-axial loading conditions. It is based on the concept of linearized stress-strain relationships and assumes that failure occurs when a certain combination of stresses exceeds a critical value, making it valuable in situations where different stress components act simultaneously, as it allows for a more accurate prediction of failure under complex loading conditions.

This failure criterion is mathematically expressed as:

$$\left(\frac{\sigma_{11}}{X}\right)^2 + \left(\frac{\sigma_{22}}{Y}\right)^2 - \left(\frac{\sigma_{11}}{X}\right)\left(\frac{\sigma_{22}}{Y}\right) + \left(\frac{\tau_{12}}{S}\right)^2 = 1 \quad (2.1)$$

where σ_{11} , σ_{22} and τ_{12} are, respectively, the applied normal stress, the applied transverse stress and the applied shear stress. X stands for the Limit normal stress (Compression or tensile), Y for the Limit transverse stress (Compression or tensile), and S for the Limit shear stress (Compression or tensile) [2].

The Tsai-Wu failure criteria for composite materials is also based on linearized stress-strain relationships but employs a quadratic equation to capture the interaction between different stress components, and it considers the ratio of stress components to their corresponding strengths and interaction terms involving ratios of stress components. The criterion is expressed as an inequality where the sum of normalized stress terms and interaction terms is compared to a constant value, usually 1 [2][1]. The failure envelope can be calculated as,

$$F_1\sigma_{11} + F_2\sigma_{22} + F_{11}\sigma_{11}^2 + F_{22}\sigma_{22}^2 + 2F_{12}\sigma_{11}\sigma_{22} + F_{66}\tau_{12}^2 = 1 \quad (2.2)$$

where,

$$\begin{aligned} F_1 &= \frac{1}{X_T} + \frac{1}{X_C}, & F_2 &= \frac{1}{Y_T} + \frac{1}{Y_C}, & F_{11} &= -\frac{1}{X_T X_C}, \\ F_{22} &= -\frac{1}{Y_T Y_C}, & F_{66} &= \frac{1}{S_{12}^2}, & F_{12} &= -\frac{1}{2} \sqrt{\frac{1}{X_T X_C} \frac{1}{Y_T Y_C}} \end{aligned} \quad (2.3)$$

being:

X_T - Limit tensile normal stress

X_C - Limit compressive normal stress

Y_T - Limit tensile transverse stress

Y_C - Limit compressive transverse stress

S_{12} - Limit shear stress

While both criteria aim to capture the complex failure behavior of composites, they differ in their formulations and approaches. The Tsai-Hill criterion incorporates interaction terms between stress components to assess failure, and it is particularly suited for analyzing intralaminar failure modes and is relatively simpler to implement compared to the Tsai-Wu criterion. In contrast, the Tsai-Wu criterion employs a quadratic equation to account for stress interactions, providing a more comprehensive representation of failure behavior under complex loading conditions. It offers a more general approach to failure prediction and can be applied to both intralaminar and interlaminar failure modes, however, its complexity may require more computational effort, so the choice between the two depends on factors such as the specific failure behavior being studied, the loading conditions, and the balance between accuracy and computational effort [38].

2.3. Composite Materials Failure Mechanisms and Analysis

- **Hashin Criterion:** Developed by Tsu-Wei Chou and Edward M. Arruda, the Hashin Criterion is a widely used failure criterion for predicting intralaminar failure modes in composite materials, and it considers various failure mechanisms such as fiber fracture, matrix failure, and fiber-matrix debonding.

This criterion consists of four separate modes of failure, each represented by specific equations, as shown below in Equations 6 to 9, that address different failure mechanisms within composite materials, including fiber rupture in tension, fiber buckling in compression, matrix cracking under transverse tension and shearing, and matrix crushing under transverse compression and shearing [39].

Fiber tension ($\sigma_{11} \geq 0$) :

$$F_f^t = \left(\frac{\sigma_{11}}{X^T} \right)^2 + \alpha \left(\frac{\tau_{12}}{S^L} \right)^2 = 1; 0 \leq \alpha \leq 1 \quad (6)$$

Fiber compression ($\sigma_{11} \geq 0$) :

$$F_f^c = \left(\frac{\sigma_{11}}{X^c} \right)^2 = 1 \quad (7)$$

Matrix tension ($\sigma_{22} \geq 0$) :

$$F_m^t = \left(\frac{\sigma_{22}}{Y^T} \right)^2 + \alpha \left(\frac{\tau_{12}}{S^L} \right)^2 = 1 \quad (8)$$

Matrix compression ($\sigma_{22} \geq 0$) :

$$F_m^c = \left(\frac{\sigma_{22}}{2S^T} \right)^2 + \left[\left(\frac{Y^c}{2S^T} \right)^2 - 1 \right] \frac{\sigma_{22}}{Y^c} + \left(\frac{\tau_{12}}{S^L} \right)^2 = 1 \quad (9)$$

where σ_{11} , σ_{22} , and τ_{12} are the components of the effective stress tensors, X^T and X^c denote longitudinal tensile and compressive strength, Y^T , Y^c denote the transverse tensile and compression fiber strength, and S^T , S^C denote longitudinal and transverse shear strength, respectively [39].

In each case, failure is indicated when the corresponding failure criterion equation equals 1, and this indicates that the applied stresses have reached or exceeded the critical levels, leading to failure in the respective mode. One significant advantage lies in its comprehensive consideration of various failure modes, enabling to capture a broader spectrum of failure mechanisms, leading to more accurate predictions of structural integrity under diverse loading conditions. Additionally, the Hashin criterion's simplicity and empirical validation through extensive experimental testing and numerical simulations contribute to its reliability and ease of implementation [40].

- **LARC05:** The LARC05 (Lamina Analysis and Research Composite 2005) failure criterion is a composite material failure model developed by NASA, and it is specifically designed to predict the initiation and progression of delamination in composite structures, making it particularly valuable for interlaminar failure analysis. This criterion integrates several failure mechanisms, including matrix cracking, fiber fracture, and delamination into a unified framework, and it considers factors such as material properties, loading conditions, and geometric parameters to assess the propensity for delamination initiation and growth.

One of the distinguishing features of the LARC05 criterion is its consideration of stress-based and energy-based failure modes, as it accounts for the energy release rate associated with delamination propagation. Furthermore, the LARC05 criterion has been extensively validated and calibrated through experimental testing and finite element analysis, ensuring its accuracy and reliability across a wide range of composite materials and configurations.

Included in the advantages of the LARC05 criterion is its specific focus on predicting delamination initiation and growth. Unlike some other failure criteria that primarily address intralaminar failure modes, the LARC05 model is tailored to assess interlaminar failure mechanisms, which are critical in laminated composite structures, and this specialization makes it particularly valuable for applications where delamination is a primary concern, such as aircraft components. This criterion is also more recent and modernized compared to some other failure criteria, and its development incorporates advancements in composite materials science and computational methods, ensuring that it reflects the latest understanding of interlaminar failure mechanisms [41].

2.4 Materials Certification in Aircraft

Materials certification is a crucial process in ensuring the safety and reliability of aircraft within the aviation industry, and this process involves a thorough evaluation of various materials used in aircraft construction, with a particular emphasis on metals and composites. The Federal Aviation Administration (FAA) in the United States and the European Union Aviation Safety Agency (EASA) play pivotal roles in materials certification, overseeing and regulating the adherence to rigorous standards throughout the certification process. Type certificates, issued by these regulatory bodies, attest that an aircraft or its component meets the prescribed airworthiness standards, including those related to materials usage [42].

The certification process typically involves demonstrating the repeatability of the production process and the consistency of the quality of fabricated components, and it is important to note that the FAA introduced a 'slow growth' approach to the certification of composites, emphasizing the need for a comprehensive methodology for determining design allowables, particularly in the context of delamination fatigue growth in polymer-matrix fiber composites. This process is defined by the Federal Aviation Regulations, EASA regulations, and the FAA policy statements, orders, advisory circulars, technical standard orders, and FAA airworthiness directives, and the certification of large commercial aircraft is covered by the EASA CS-25 (Certification Specifications) or FAR-25 documents, which outline the specific requirements for crash protection and crash worthiness of aerospace composite components [43][44].

Metals, traditional components in aircraft construction, undergo meticulous scrutiny during certification, and the evaluation encompasses assessments of material composition, mechanical properties, and manufacturing processes to ensure compliance with stringent safety requirements. Concepts such as fail-safe design, which ensures that the structure can withstand the failure of a critical component, and safe-life design, which establishes a predetermined lifespan for components, are integral to the certification process for metallic structures [45]. The certification process for metallic structures is governed by various regulations and standards, including those related to airworthiness and safety considerations [46], and it involves demonstrating the reliability and integrity of the materials and components used in aircraft construction, with a focus on ensuring that they meet the prescribed safety standards. Additionally, the certification process for metallic structures involves considerations of redundancy and control reconfiguration to ensure fault tolerance and system reliability. Furthermore, the evaluation of metallic structures for certification

2.4. Materials Certification in Aircraft

involves simulating impact scenarios and assessing damage tolerance to ensure structural integrity under various operational conditions. This includes the assessment of accidental impact scenarios and the establishment of energy probabilistic distributions to evaluate the impact resistance of metallic components [47].

The certification of composites, which are increasingly prevalent in modern aircraft due to their lightweight and durable properties, involves addressing unique challenges, and material characteristics such as damage tolerance and crack growth behavior are thoroughly analyzed to ensure structural integrity over the aircraft's lifespan. Issues like weak bonds and delamination, which can compromise the structural integrity of composite components, are meticulously examined to mitigate the risk of failure [48]. The evaluation of delamination in composite materials is a critical aspect of certification, as it can significantly impact the structural integrity of composites, and studies have focused on assessing delamination in composite materials during drilling processes, impact scenarios, and under various loading conditions [49].

Additionally, the detection and analysis of delamination in composite materials using advanced techniques such as acoustic emission waveform analysis and finite element modeling have been explored to understand and mitigate the effects of delamination on composite structures. Furthermore, the assessment of weak bonds and interfacial bonding in composite materials has been a subject of research, with a focus on understanding the impact of surface treatments, adhesives, and bonding materials on the strength and integrity of composite structures. The influence of interfacial stiffness on the effective properties of composite materials has also been investigated to enhance the understanding of the mechanical behavior of composites [50]. In addition, the development of comprehensive assessment factors and optimization approaches for the determination and minimization of displacement under tensile load in composite joints has been explored to improve the design and performance of composite structures [51], and studies have also focused on the impact damage, residual strength, and crashworthiness of composite structures to ensure their reliability and safety under various operational conditions [52].

2.4.1 Certification from a Design Approach

Airworthiness is a critical aspect of aviation safety, encompassing the design, construction, and maintenance standards necessary to ensure the structural integrity and mechanical reliability of an aircraft, as well as compliance with regulatory requirements. The maintenance of aircraft is a fundamental responsibility to ensure their safe and efficient operation, and neglecting it can lead to defects that have the potential to cause severe damage to the aircraft, resulting in accidents and fatalities [53]. To maintain airworthiness, aircraft manufacturers provide documents indicating required maintenance tasks and procedures to be carried out in view of keeping the aircraft to mandatory airworthiness standards set by respective national civil aviation authorities and the International Civil Aviation Organization [54]. Furthermore, the planning and management of aircraft maintenance is crucial, and mathematical models and optimization tools have been developed to facilitate this process. It is essential to consider factors such as human factors, type of inspection, type of aircraft, and operation location in aircraft inspection planning models to ensure effective maintenance [55].

The entire process from design and certification for aircraft components involves several key steps, starting from development tests to certification tests (Figures 2.8 and 2.9):

- **Design and Analysis:** The component undergoes rigorous design and analysis to ensure that it meets specified performance requirements and safety standards. This includes structural analysis, material selection, and testing to validate the component's integrity under various operating conditions.
- **Testing and Evaluation:** The component is subjected to a series of tests to verify its compliance with regulatory requirements. This may include static and dynamic testing, fatigue testing, environmental testing, and functional testing to assess performance and durability.
- **Documentation and Compliance:** Documentation detailing the component's design, testing, and manufacturing processes is compiled and submitted to regulatory authorities for review. Compliance with applicable regulations and standards is confirmed through thorough documentation and certification.

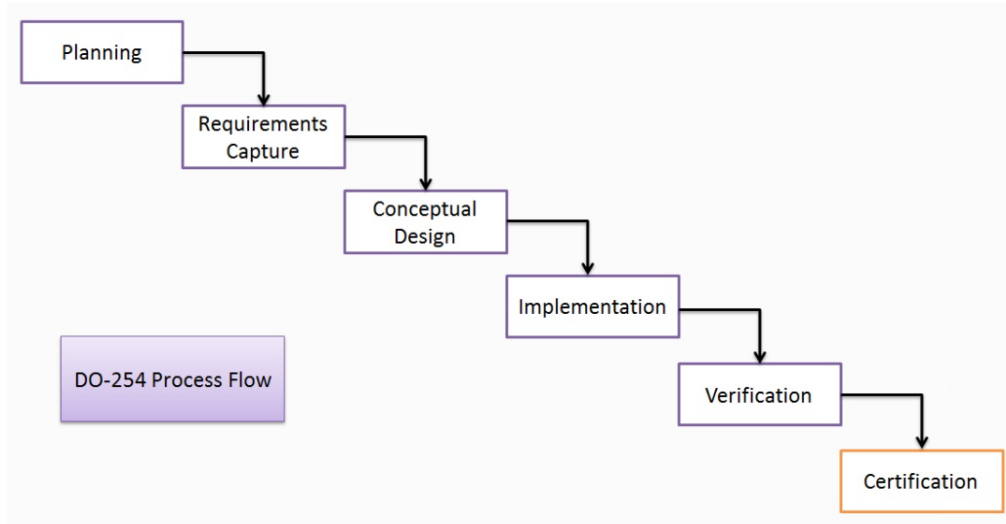


Figure 2.8: Certification Process for an aircraft component or structure [56].

Aircraft components are susceptible to failure due to various factors, including material fatigue, manufacturing defects, environmental conditions, and operational stress, and common failure modes encompass fatigue cracking, corrosion, wear, and structural deformation. Identifying and mitigating these failure modes is crucial to ensure the continued airworthiness of aircraft. For instance, the mechanical behavior of composite panels under debonding loads is also analyzed to improve the understanding of failure mechanisms and enhance structural integrity [57]. Furthermore, the development of airworthiness database systems with validation processes is essential for tracking and ensuring the compliance of design programs for general aviation aircraft, contributing to the prevention of potential failure modes [58].

2.4. Materials Certification in Aircraft

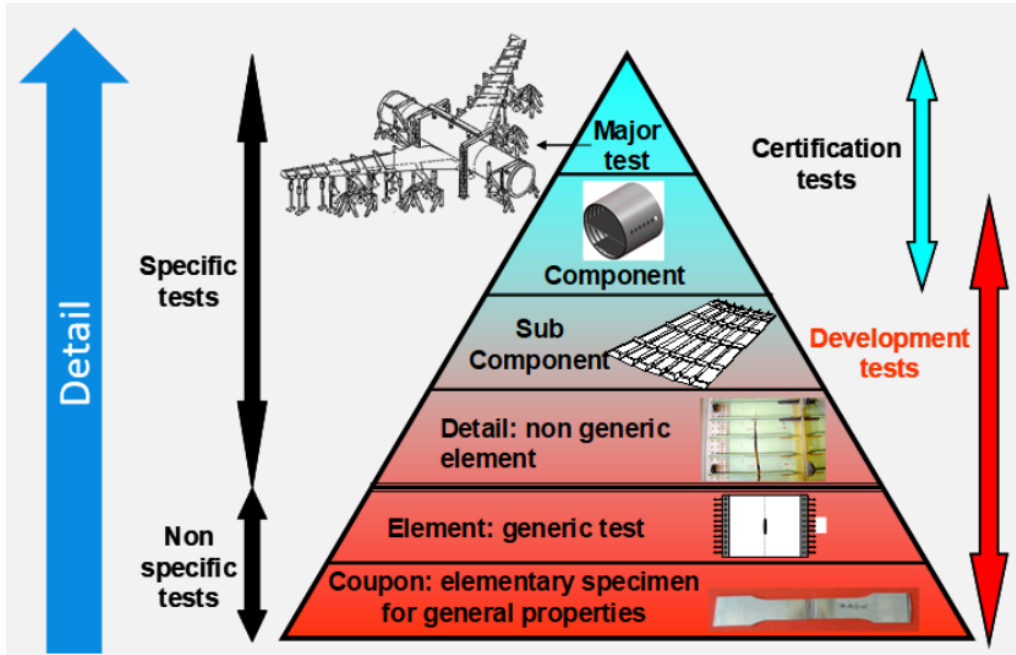


Figure 2.9: Building block approach to certify an aircraft component or structure [59].

The design philosophy of aircraft structures evolved to embrace what is known as Damage Tolerant Design, which revolves around the concept that a structure or its components can continue to operate safely even in the presence of damage. This methodology acknowledges that damage, such as fatigue or corrosion, may occur during service and allows for its growth up to a predetermined threshold without compromising safety [60]. It is relevant to note the differences in approach between civil and military aviation. Therefore, in civil aviation, components are meticulously designed to withstand anticipated loads and operating conditions while minimizing the risk of catastrophic failure [61]. On the other hand, military aviation may prioritize performance and mission capabilities over damage tolerance, often incorporating redundant systems, advanced materials, and protective measures to enhance survivability in combat environments [60]. In Figure 2.10, it is possible to see the different design philosophies depending on the case we are subjected to.

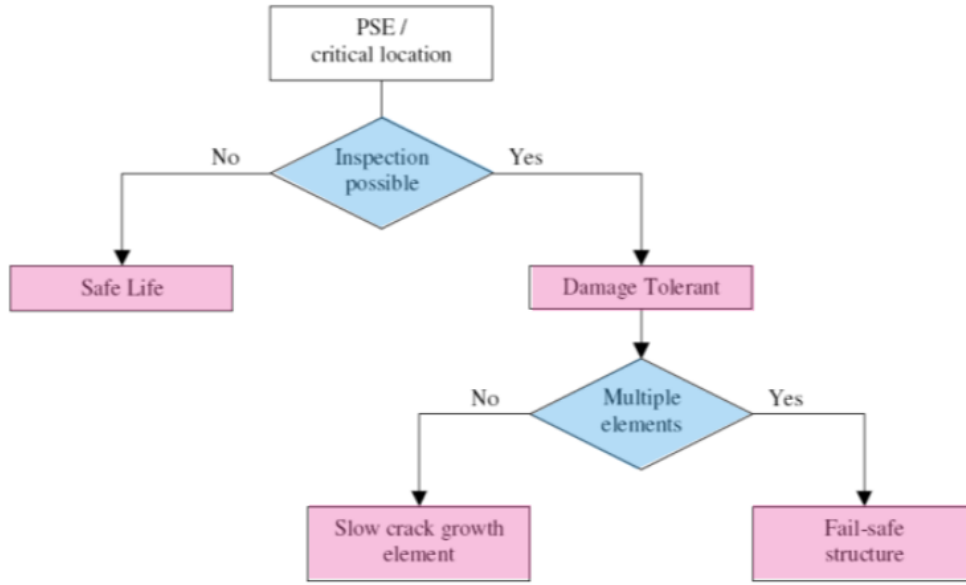


Figure 2.10: Fatigue Design Philosophies [59].

2.4.2 Regulations and Certification of UAV's

Regulations and certification for unmanned aerial vehicles have evolved significantly in response to the rapid proliferation of these aircraft across various industries. The regulatory framework for UAV's is governed by various authorities such as the Federal Aviation Administration (FAA) in the United States, the European Union Aviation Safety Agency (EASA) in Europe, and the International Civil Aviation Organization (ICAO) at the international level [62]. The FAA, under Title 14 of the Code of Federal Regulations (14 CFR) Part 107, outlines rules for operating small UAV's for commercial purposes, including requirements for remote pilot certification, operating limitations, and safety guidelines. Similarly, EASA has introduced regulations specific to unmanned aircraft, including the Specific Operations Risk Assessment (SORA) framework for assessing the risk of UAV operations and the Common European Rules for Drones (EU Regulation 2019/947) for standardizing unmanned aerial vehicles operations across EU member states. Furthermore, ICAO provides guidance and standards for UAV operations through Annex 2 (Rules of the Air) and Annex 8 (Airworthiness of Aircraft), which outline general principles and requirements for these aircraft operations and airworthiness certification, providing a framework for harmonizing regulations at the international level [63].

In addition to regulatory frameworks, there are also studies focusing on safety assessment and risk estimation for unmanned aerial vehicles operating in the National Airspace System (NAS). These studies propose effective approaches for modeling and assessing the risks associated with UAV's integrated into the national airspace system, contributing to the development of safety protocols and risk management strategies for UAV operations [64]. Moreover, the integration of these vehicles into various industries such as construction, agriculture, and civil engineering has led to the need for certification and safety evaluation methods for both manned transport aircraft and large UAV's in mixed airspace [65].

2.4. Materials Certification in Aircraft

Regarding the certification process, certain topics must be considered:

- **Airworthiness Certification:** UAV manufacturers may seek airworthiness certification for their aircraft to demonstrate compliance with regulatory standards for safety and reliability, and it involves testing and evaluation of the drone’s design, construction, and performance characteristics to ensure that it meets prescribed airworthiness requirements [66].
- **Type Certification:** Type certification is the process of certifying a specific type or model of unmanned aerial vehicle as meeting airworthiness standards. Type certification involves submitting detailed documentation, conducting testing and analysis, and obtaining approval from the regulatory authority to operate the UAV commercially [66].
- **Remote Pilot Certification:** Part 107 in the U.S. and similar regulations in other jurisdictions require remote pilots operating UAV’s for commercial purposes to obtain certification from the regulatory authority. Remote pilot certification involves passing a knowledge test, demonstrating proficiency in UAV operation, and adhering to safety regulations and operational limitations [67].

On the other hand, unmanned aerial vehicles operations are subject to various operational limitations and restrictions imposed by regulatory authorities to ensure safety and mitigate risks to airspace users and the public, such as restrictions on flight altitude, distance from populated areas, airspace restrictions, and operational requirements for specific types of UAV operations (e.g., beyond visual line of sight operations, night operations), and compliance with operational limitations and restrictions is essential for obtaining regulatory approval to conduct these vehicles operations and ensuring a safe and responsible use of these vehicles. As the regulatory landscape for UAV’s continues to evolve, with ongoing efforts to address emerging technologies, operational challenges, and safety concerns, regulatory authorities are working to harmonize regulations at the international level and develop standards for integrating UAV’s into airspace systems. Future developments may include advancements in the certification processes, updates to regulations to accommodate new technologies and operational concepts, and collaboration among regulatory authorities, industry stakeholders, and other relevant organizations to promote safe and efficient UAV operations [68].

2.5 Trapdoors and Cargo Compartments in UAV's

Trapdoors, fundamental components within aviation, serve as strategic access points integrated into aircraft structures to facilitate the deployment, retrieval, or integration of various payloads, cargo, and sensors, and these mechanisms are meticulously designed to ensure safe operations while maintaining aerodynamic efficiency and structural integrity. Trapdoors offer a versatile solution, enabling aircraft to adapt to diverse mission requirements across different aviation sectors, from cargo transport in large planes to specialized missions in unmanned aerial vehicles (UAV's) [69]. In Figure 2.11 it is possible to analyze different UAV's capable of transporting loads and sensors that connect to the fuselage.



(a) Chaparral C1 [70].



(b) Tekever AR5 [16].

Figure 2.11: Different UAV's with trapdoors capable of transporting loads and/or sensors.

Large cargo planes rely on trapdoors to streamline loading and unloading operations efficiently, and these aircraft feature robust trapdoor systems engineered to withstand the demands of heavy-duty cargo handling. Trapdoors in cargo planes are equipped with mechanisms allowing for swift and precise deployment of freight, ensuring optimal utilization of cargo space and minimal turnaround times. Operators can open trapdoors at strategic points during flight, such as during cruise speed or at specific altitudes, to facilitate cargo deployment with maximum efficiency. Additionally, trapdoors in cargo planes may include safety features and locking mechanisms to secure cargo during transit, ensuring safe and reliable transport of goods over long distances [71]. Therefore, it is relevant to analyze how trapdoors in cargo planes are designed in order to optimize the design of the trapdoor of a UAV and to identify the main types of failures of this mechanism and how to prevent and account for them. In Figure 2.12 we can observe an example of a trapdoor of a cargo aircraft.

2.5. Trapdoors and Cargo Compartments in UAV's



Figure 2.12: Military cargo plane back [72].

In the realm of unmanned aerial vehicles, trapdoors play a crucial role in enabling mission-specific functionality and adaptability, as these aircraft leverage trapdoors to integrate specialized payloads, sensors, or equipment necessary for a wide range of operational tasks, including surveillance, reconnaissance, delivery, and scientific research. Trapdoors in these vehicles are meticulously designed to minimize aerodynamic drag and maintain stability during flight, allowing for seamless integration of mission-critical components without compromising aircraft performance. Operators can deploy trapdoors at predetermined locations and angles, enabling precise deployment of payloads or sensors while optimizing UAV efficiency, and whether deploying sensors for environmental monitoring or releasing cargo for delivery missions, trapdoors provide these vehicles with the flexibility and versatility needed to excel in dynamic operational environments [73].

The connection of trapdoors to the fuselage in UAV design is a critical aspect that demands careful engineering and attention to detail, as these connections serve as the interface between the fuselage structure and the trapdoor, playing a crucial role in ensuring the overall integrity, functionality, and aerodynamic performance of the UAV. One key consideration in the connection design is structural integrity, and the connection mechanism must be able to withstand the dynamic forces experienced during flight, including aerodynamic loads, vibrations, and inertial forces. To achieve this, engineers often employ robust fastening methods such as bolts, hinges, or latches, and these fasteners are selected based on their strength, reliability, and compatibility with the materials used in both the trapdoor and the fuselage [74]. In Figure 2.13, it is possible to observe a riveted connection in an aircraft.

Aerodynamic efficiency is another important factor in connection design, as the connection mechanism should maintain a tight seal when the trapdoor is closed to minimize aerodynamic drag and maintain the overall efficiency of the drone. This way, engineers usually employ seals or gaskets to ensure a proper seal between the trapdoor and the fuselage, reducing airflow disruptions and improving the vehicles performance in flight. Ease of operation and maintenance are also key considerations in trapdoor connection design, as the connection mechanism should allow for easy opening and closing of the trapdoor, whether done manually by ground personnel or remotely by the operator. Additionally, the connection should be designed for ease of inspection, maintenance, and potential replacement of components as needed to ensure continued reliability and functionality over the UAV's operational lifespan [75].

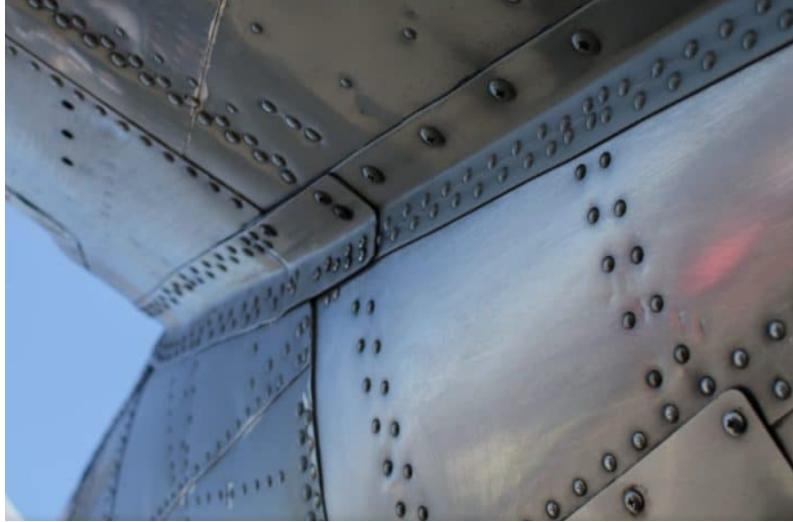


Figure 2.13: Riveted Aircraft connection [76].

When considering the connection between the trapdoor and the main fuselage of a UAV, especially when both components are made of composites, several precautions and considerations must be taken into account to ensure structural integrity and reliability.

- **Material Compatibility:** It is crucial to select materials for the connection components that are compatible with the composite materials used in both the trapdoor and the fuselage, so if the composite material is carbon fiber reinforced polymer (CFRP), it is essential to choose fasteners that will not cause galvanic corrosion or degradation of the composite material over time [77].
- **Fastener Selection:** Depending on the specific design requirements and load considerations, various fastening options can be considered for connecting the trapdoor to the fuselage. These may include rivets, bolts, screws, or adhesive bonding.
 - **Rivets:** If rivets are chosen, it is important to use rivets made of materials compatible with composites, such as aluminum or titanium, and special care must be taken during the riveting process to avoid delamination or damage to the composite layers.
 - **Bolts:** Bolts provide a more adjustable and removable connection compared to rivets, however, similar precautions must be taken to ensure that the bolts and accompanying nuts or washers are made of materials compatible with composites.
 - **Adhesive Bonding:** Adhesive bonding can be an effective method for connecting composites, providing a strong and lightweight bond, however, thorough surface preparation and proper adhesive selection are essential to ensure bonding integrity and durability. The certification of this type of connection is much more complex than the others, posing a big disadvantage compared to other types of connections.
- **Preventing Galvanic Corrosion:** When using metallic fasteners with composite materials, the potential for galvanic corrosion must be considered, and this can be mitigated by using isolation barriers, such as non-conductive washers or coatings, between the fastener and the composite material to prevent direct contact.
- **Structural Analysis:** Before finalizing the connection design, it is crucial to conduct structural analysis and testing to ensure that the chosen fastening method can withstand the

2.6. Optimization of Composite Structures

anticipated loads and operational conditions. Finite element analysis (FEA) and physical testing can help validate the design and identify any potential areas of weakness or failure.

- **Installation and Inspection:** Proper installation procedures must be followed to ensure that the connection is secure and meets design specifications, and regular inspection and maintenance are also necessary to detect any signs of degradation, wear, or damage to the connection components over time [78].

This way, by carefully considering these factors and selecting appropriate connection methods and materials, it is possible to design a robust and reliable connection between the trapdoor and the main fuselage of a UAV made of composites, and this contributes to the overall safety, performance, and longevity of the UAV. In summary, the use of composite materials in aircraft structures presents both opportunities and challenges, as it is essential to consider the stress concentration and fatigue breakdown associated with mechanical connections, the detection and repair of barely visible impact damage, and the use of NDT methods such as ultrasonic techniques for examining seal surface contact stress.

2.6 Optimization of Composite Structures

In the pursuit of enhancing the performance and efficiency of aeronautical systems, the integration of optimization techniques has become indispensable, as the quest for lighter, stronger, and more durable materials has led to the widespread adoption of composite structures in aerospace engineering, including the design and manufacturing of Unmanned Aerial Vehicles. These composite materials offer a unique set of properties that can be tailored to meet specific performance requirements, making them particularly well-suited for applications where weight reduction and structural integrity are essential. The optimization of composite structures involves the systematic exploration of design parameters to achieve desired performance objectives while adhering to various constraints. In the context of aeronautics and UAV's, this optimization process plays a crucial role in enhancing key characteristics such as structural strength, aerodynamic efficiency, and overall mission capability [79]. Composite materials, composed of a combination of fibers and matrices, offer a versatile platform for optimization, as by strategically orienting and layering these constituent materials, engineers can tailor the mechanical properties of composites to optimize specific performance metrics. This ability to customize material properties presents a significant advantage in the design and fabrication of lightweight yet structurally robust components for aerospace applications [80].

These vehicles, in particular, benefit greatly from optimization techniques applied to composite structures they demand lightweight yet durable components to maximize endurance, payload capacity, and maneuverability while ensuring operational safety and reliability. Optimization methodologies enable to strike a delicate balance between competing design requirements, ultimately leading to the development of UAV's that push the boundaries of performance and efficiency. As the demand for unmanned aerial vehicles technology continues to grow across various sectors, from surveillance and reconnaissance to infrastructure inspection and environmental monitoring, the importance of optimizing composite structures is notable.

In the context of selecting an optimization algorithm, it is crucial to consider the advantages and disadvantages of different methodologies, given the variables, constraints, and computational limitations inherent in such tools. Gradient-based algorithms, which utilize the gradient of the objective function to iteratively refine solutions, are efficient in optimizing smooth and continuous objective functions. However, they may face challenges when dealing with non-linear or

non-smooth objective functions, struggling to navigate local minima and discontinuities. While gradient-based methods offer computational efficiency, their effectiveness may diminish in scenarios with significant non-linearity or complexity [81]. Exhaustive search and pattern search are also two distinct optimization approaches with unique characteristics and applicability in solving optimization problems. Exhaustive search, a brute-force method, evaluates all feasible solutions within the solution space, making it suitable for small optimization problems with a limited number of variables, and despite being computationally expensive and time-consuming, exhaustive search is effective in scenarios where the search domain is manageable and the objective function is well-defined. On the other hand, pattern search algorithms systematically explore the solution space using a set of search directions. These algorithms offer versatility in handling non-linear and non-smooth objective functions, making them attractive for optimization problems with a modest number of variables. However, their efficacy may decrease in highly complex scenarios with numerous constraints and variables [82].

Genetic algorithms, inspired by biological evolution principles, offer a robust solution for optimizing complex problems with large solution spaces and multiple constraints, and particularly relevant in composite structure optimization, these algorithms excel in exploring diverse solution spaces efficiently, accommodating non-linearity, and integrating constraints seamlessly into the optimization process. Their stochastic nature enables them to escape local optima, a common pitfall of deterministic optimization methods, thereby enhancing their robustness and effectiveness. Therefore, and given the multifaceted nature of optimizing composite structures, the selection of genetic algorithms emerges as a prudent choice, as their ability to handle non-linearity, explore large solution spaces, incorporate constraints, and mitigate the risk of local optima aligns seamlessly with the challenges inherent in composite trapdoor design. In the following subsection, the process of creating a genetic algorithm and the main points to take into special care when developing it are stated [83].

2.6.1 Genetic Algorithm

“Why do some die and some live? The answer was clearly, that on the whole the best-fitted live. From the effects of disease, the most healthy escaped; from enemies, the strongest, swiftest, or the most cunning; from famine, the best hunters or those with the best digestion; and so on. Then it suddenly flashed upon me that this self-acting process would necessarily improve the race, because in every generation the inferior would inevitably be killed off and the superior would remain, that is, the fittest would survive.” - Alfred Russel Wallace [84].

Building upon the foundational principles of natural models developed by Charles Darwin, Alfred Russel Wallace, and later Gregor Mendel, computational and mathematical models emerged in the mid-20th century that adapted the concept of biological evolution for analysis and resolution of optimization problems. In 1975, John Holland proposed a genetic algorithm that, starting from a population of chromosomes, generates a population with fewer individuals but more capable and adept within their environment. The process of selecting individuals relies on operators inspired by genetic operations of crossover, mutation, and inversion [85].

The optimization process involves defining an appropriate fitness function that evaluates the performance of the trapdoor based on desired criteria such as structural strength, weight, and aerodynamic efficiency, and genetic algorithms iteratively evolve a population of potential solutions, utilizing mechanisms of crossover and mutation to generate new candidate designs while preserving advantageous traits from previous generations. Furthermore, genetic algorithms excel in incorporating constraints, such as limitations on material properties, manufacturing constraints,

2.6. Optimization of Composite Structures

and performance requirements, and by integrating these constraints into the optimization process through the fitness function, genetic algorithms ensure that the generated solutions adhere to practical considerations and design specifications.

2.6.2 General Aspects of a Genetic Algorithm

For a complete definition and proper creation of a genetic algorithm, we must take into account other details beyond those detailed in the section above, such as the population size, mutation and crossover probabilities, and the tournament selection size. These data are called "algorithm parameters," and they constitute the complete definition of the genetic algorithm in order to create an executable version.

There are two main ways to configure parameter values: parameter tuning and parameter control. The first approach involves finding good values for the parameters before executing the programmed code and then running the code with those values. This is a common practice for defining algorithms. This tuning is done by using different parameter values and selecting the ones that return better results to the problem being solved. On the other hand, parameter control involves creating an execution with the initial parameter values that are altered during execution. It is recognized that genetic algorithms require parameter adjustments depending on the problem at hand. Ideally, the algorithm should make the specific adjustments needed for each problem through parameter control in the evolutionary search [85].

- **Population Size:** The most important aspect of this point is the idea that we should always strive for a proper balance between the efficiency and computational cost of the algorithm. Thus, it is understood that there should be an optimal value for the population size. On one hand, a small population size does not provide enough space to effectively explore the search space, while a large population size significantly increases computational cost [85].

It is also relevant to note that a large population size can reduce not only the loss of alleles but also genetic drift. For large populations, fitness grows more slowly in initial phases but yields better overall results. It is therefore concluded that extreme population sizes are detrimental. With a small population, the number of generations required to reach the desired solution is too large, while for a large population, there are not enough generations generated to find an optimum.

- **Generation of Initial Population:** The first step of any genetic algorithm is the generation of an initial population. This population consists of a random set of chromosomes representing potential solutions to the problem being solved.

This random generation can be carried out using a pseudo-random method or through quasi-random number sequences. The former is the most common strategy for random generation. As it is not possible to generate truly independent random numbers, pseudo-random numbers are generated using classical generators such as the quadratic congruential Fibonacci. On the other hand, in quasi-random sequences, the objective of generation is related not only to the independence of successive values but also to their dispersion in order to cover the entire search space. In a quasi-random generation, the diversity of the population is generally better than in a pseudo-random generation.

- **Convergence and Stopping Criteria:** Stopping criteria are a fundamental aspect in the formulation of the algorithm and can be related to a maximum iteration limit, a maximum computational time limit, or even proximity to the solution or achievement of a certain level of merit for a part of the population. Thus, we have two variants of stopping criteria [85]:

The first is a stopping criterion based on genotype, which terminates when the population reaches certain levels of convergence regarding the chromosomes of the population, that is, the number of genes that have converged to an allele is checked, and when a certain portion of the population verifies this convergence, the genetic algorithm terminates. As for the phenotype-based stopping criterion, the progress made by the algorithm in the last n generations, defined by the designer, is measured. When this measure, usually the average merit value for the population, produces a value beyond a certain defined limit, it is said that the algorithm has converged, and the evolution is promptly interrupted [85].

The challenges often present in defining these criteria include the difficulty in defining appropriate values for the associated parameters and how to determine a reasonable value for, for example, a fixed number of generations.

2.6.3 Surrogate Models

Surrogate models, in the context of engineering applications, serve as efficient approximations or simplified representations of complex and computationally expensive systems or processes. These models provide a less computationally demanding way to explore the design space, which might be an alternative to time-consuming or expensive evaluations. Typically constructed through mathematical functions based on a limited number of evaluations, surrogate models capture the input-output relationship of the original system, and sampling the original system at various input configurations enables surrogate models to predict the system's response at unexplored points within the design space. In the case of weight optimization of structures, where detailed finite element analysis for each evaluation is computationally expensive, surrogate models offer a promising solution, as one can interact with the optimization algorithm more efficiently, facilitating the search for optimal design configurations, considering that the evaluation of failure constraints for each individual is performed by a finite element analysis, where the results are subjected to post-processing in each iteration [86].

A crucial component of experimental design is choosing the right sampling strategy, which has a significant impact on the reliability and precision of the gathered data, and the sampling strategy must always be taken into account as it directly affects the way the input space is examined and how the selection of data points is performed. In fact, an ineffective sampling strategy can provide biased or insufficient data, which can produce inaccurate models and unreliable predictions. The correct use of a sampling strategy is particularly significant when discussing the Design of Experiments (DOE), where the objective is to comprehend how the input variables relate to the corresponding system response [87].

The Design of Experiments (DOE) serves as a systematic approach to optimize processes and understand the effects of varying factors on a response variable, and its primary purpose is to methodically design experiments to manipulate independent variables while observing the resulting changes in a dependent variable. By controlling and adjusting these independent variables, the optimal settings that lead to the desired outcomes for the dependent variable are identified, and whether optimizing manufacturing processes, refining product designs, or enhancing chemical reactions, DOE provides a structured framework to systematically explore the parameter space and uncover insights into the underlying relationships between variables [88].

The concept of statistical inference is the basis of the Design of Experiments (DOE), a fundamental concept in the field of statistics, and it involves using sample data collected from experiments to make generalizations or predictions about a larger population. This process involves analyzing the collected data using statistical methods to quantify the relationship between inde-

2.6. Optimization of Composite Structures

pendent and dependent variables, identify significant factors, and assess the effects of these factors on the system's response. There are various methodologies for the Design of Experiments, each one tailored to different research objectives, experimental setups, and resource constraints, and by understanding the different types of DOEs, the most appropriate approach to achieve the most desired outcomes may be selected [89].

Chapter 3

Design and Modelling of the Structure

One of the main goals of this project is to design and model a cargo compartment tailored for Tekever's latest UAV project, the ARX, and the objective is to create a cargo compartment that enhances the ARX's capabilities in transporting payloads efficiently and safely, as well as the creation of a trapdoor mechanism to allow the cargo to be deployed while the vehicle is in the skies. This involves focusing on two key aspects: first, the focus is on the connection mechanisms that will safely attach the cargo compartment to other parts of the UAV, including hinges and locking mechanisms, using design techniques and complying with industry standards to ensure these connections are strong, reliable, and easy to work with during assembly and disassembly. Second, the study of mechanisms to safely open the trapdoor of the cargo compartment is necessary, as this feature is crucial for precise and dependable payload deployment mid-flight.

The initial model for the cargo compartment was provided by Tekever, and it is the starting point for the design and modeling of these parts. The cargo compartment is strategically designed to be housed internally within the fuselage of the ARX rather than being an external bay, and this internal integration not only optimizes aerodynamic performance but also enhances the UAV's overall sleekness and maneuverability. In Figures 3.1 and 3.2 it is possible to see this first prototype of the cargo compartment and its location on the overall structure.

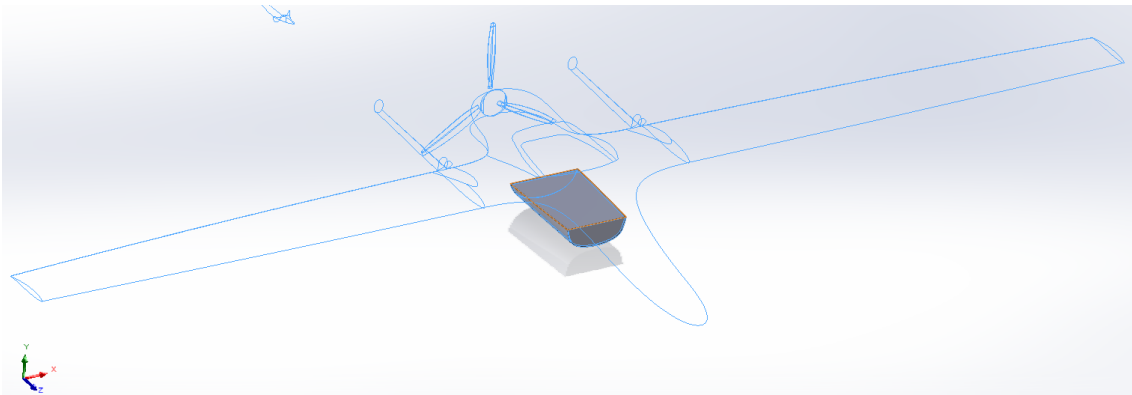


Figure 3.1: Relative position of the cargo compartment in the whole model.

3.1. Connection to the fuselage

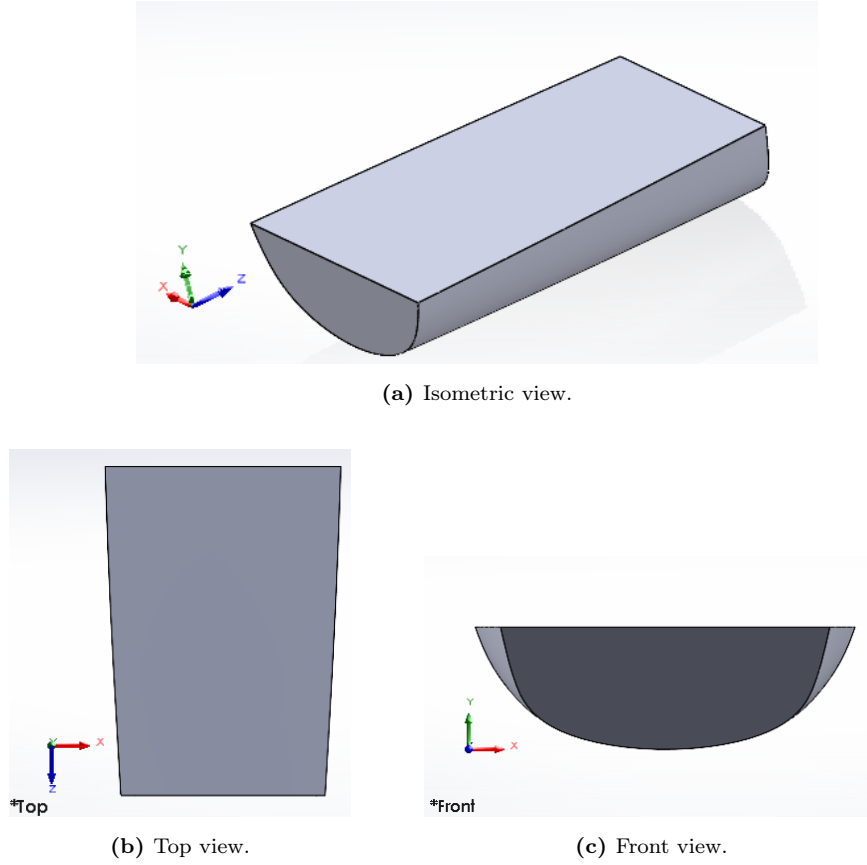


Figure 3.2: Different views of the cargo compartment first prototype.

Now that the initial model of the cargo compartment has been introduced, the subsequent step is to refine the design by modeling the necessary connections to securely connect it with the main structure of the UAV. Additionally, the focus will be on studying a robust mechanism for opening the trapdoor, with fail-safe methodology, enabling precise and reliable payload deployment during flight operations. Through this design process, the goal is to achieve a solution that not only meets the stringent requirements of industry standards but also spans good results in terms of operational efficiency and safety.

3.1 Connection to the fuselage

To seamlessly integrate the cargo compartment into the ARX drone, the selection and design of the connection mechanism play a crucial role, and in this subsection, multiple fitting connections are explored to carefully analyze and define what the best type of connection is. The primary objective of these connections is to establish a robust and reliable attachment between the cargo compartment and the main structure of the ARX UAV. To achieve this, careful consideration is given to the design of the joint geometry, ensuring optimal load distribution and structural integrity, and the utilization of L-shape joints offers versatility in design, allowing for variations such as the inclusion of triangular reinforcements to enhance structural resistance, for example. Following this process, the aim is to develop connections capable of withstanding the desired loads, including inertial forces and aerodynamic loads, ensuring the safety and stability of the cargo compartment during all phases of operation.

Furthermore, an emphasis is placed on ease of assembly and disassembly, acknowledging the practical necessity for swift reconfiguration and maintenance of the UAV and as such, the selected L-shape fitting joints must be engineered to facilitate straightforward installation and removal, minimizing downtime and facilitating operational procedures. This way, several variations of fitting connections offer distinct advantages and disadvantages, so each option must be studied carefully.

- Basic L-shape Connection:** This connection offers simplicity as its primary advantage, and its straightforward design facilitates ease of manufacturing and assembly, making it an attractive option for applications where simplicity is important. Additionally, its versatility allows it to be employed in a wide range of scenarios, accommodating various load requirements and operational conditions. However, its primary disadvantage lies in its limited structural integrity, especially under high loads or dynamic conditions, as without additional reinforcements, the basic L-shape connection may struggle to provide the necessary strength and stability required for demanding applications. Several examples may be seen in Figure 3.3.



Figure 3.3: Several examples of L-shape basic connections [90].

- L-Shape Connection with Triangular Reinforcement:** The triangular reinforcement addresses the defects of the basic design by improving structural resistance, as it significantly improves the connection's ability to withstand bending and torsional forces, enhancing overall stability. Furthermore, the triangular reinforcement contributes to improved load distribution, reducing stress concentrations and mitigating the risk of premature failure, however, this design has its drawbacks. The inclusion of additional components and machining increases manufacturing complexity and cost, while the added weight may impact the UAV performance, particularly in terms of maneuverability and endurance. An example of this geometry is observed in Figure 3.4.

3.1. Connection to the fuselage

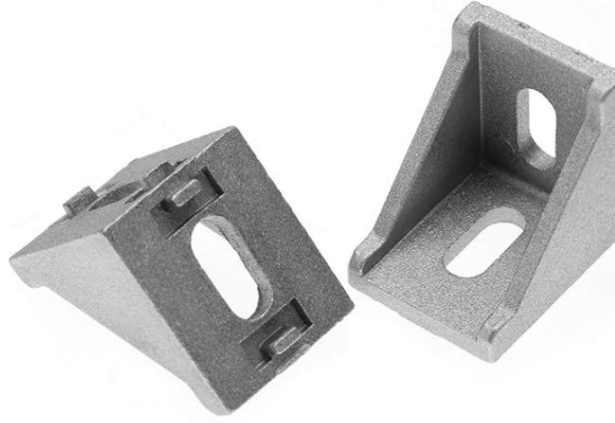


Figure 3.4: Example of an L-shape with triangular reinforcement [90].

- **Adjustable L-Shape Connection:** The adjustable L-shape connection offers great flexibility and adaptability, and its ability to accommodate variations in the assembly or load requirements through adjustable angles and dimensions makes it a versatile choice for dynamic environments. This flexibility enables fine-tuning during installation, ensuring optimal fit and alignment for improved performance. Nonetheless, the adjustable design introduces complexities as, mechanically, the incorporation of adjustable features may increase the risk of potential points of failure or necessitate increased maintenance requirements, and achieving proper adjustment may require precise measurements and careful calibration during assembly, adding to the overall complexity of the connection, and one example of this geometry is seen in Figure 3.5.



Figure 3.5: Example of an adjustable L-shape connection [91].

It is important to note that the use of a composite L-shape connection stands out for the unique properties of composite materials, presenting an interesting solution that balances lightweight construction with great durability, and by utilizing composite materials, such as carbon fiber reinforced polymers (CFRP) or fiberglass reinforced polymers (FRP), this connection will offer a high strength-to-weight ratio, effectively minimizing the added weight to the UAV while simultaneously enhancing overall performance, which contributes to improved fuel efficiency, extended flight endurance, and enhanced maneuverability. In addition to its lightweight properties, composite materials offer great corrosion resistance, providing durability and longevity, even in the presence of difficult environmental conditions, which ensures that the composite L-shape connection maintains its structural integrity over extended periods of operation, reducing maintenance requirements and enhancing mission readiness. However, despite its numerous advantages, the composite L-shape connection also presents unique challenges, as composite materials possess certain material limitations, particularly in terms of lower shear and bearing strengths compared to metals. As such, careful design considerations are necessary to ensure that the connection maintains adequate structural integrity under anticipated loads and operating conditions. Moreover, the manufacturing of composite components often requires specialized techniques and equipment, such as autoclaves for curing processes or precise lay-up procedures, which can increase production costs and lead times. This way, it is important to balance the benefits of these materials with its limitations and manufacturing complexity in order to obtain the best solution for the connections.

3.2 Extraction of the Cargo Compartment

The efficient loading and unloading of cargo in this project poses significant challenges, particularly when considering the placement and accessibility of the cargo compartment within the fuselage, as opening it downwards presents certain limitations and operational difficulties that require the exploration of alternative solutions. This way, in this subsection, the hypothesis of a lateral extraction of the whole cargo compartment is studied, starting from the challenges associated with a downward opening to the advantages of lateral extraction and how would this system behave.

Opening the cargo compartment downward from the belly of the UAV presents several practical challenges that might impact both operational efficiency and even safety considerations. In fact, this type of opening mechanism requires the whole structure to be elevated to a significant height to facilitate cargo loading and unloading, necessitating specialized equipment or infrastructure, and even introduces safety risks, as the potential of accidents having the drone elevated increases significantly.

Given the challenges posed by the downward opening mechanisms, the exploration of a lateral extraction mechanism emerges as a viable solution to improve the efficiency, safety, and flexibility of cargo loading and unloading in this vehicle. This system enables easy access to the cargo compartment without the need for elevated positioning of the UAV, and enables ground-level loading and unloading operations, simplifying logistics and minimizing operational complexities. This way, by eliminating the need for elevated positioning and complex handling procedures, lateral extraction mechanisms optimize operational efficiency and reduce the time for cargo loading and unloading, improving the effectiveness of the whole process. In Table 3.1, it is possible to see a direct comparison between these two systems.

3.2. Extraction of the Cargo Compartment

Table 3.1: Direct comparison between the possible openings of the cargo compartment in loading and unloading scenarios.

Characteristic	Downward Opening	Lateral Opening
Accessibility	Requires UAV to be elevated for loading/unloading	Ground-level access facilitates loading/unloading
Safety	Elevated positioning poses safety risks during operations	Reduced safety risks with ground-level access
Operational Flexibility	Limited maneuverability in confined spaces	Greater adaptability in diverse environments
Handling Complexity	Complex handling procedures may require additional equipment	Simplified handling procedures with direct access
Loading/Unloading Time	Elevated positioning may increase loading/unloading time	Reduced loading/unloading time with ground-level access
Infrastructure Dependence	Requires specialized equipment or infrastructure for UAV deployment	Less reliance on infrastructure for loading/unloading
Mission Adaptability	Limited applicability in scenarios with height restrictions	Suitable for a wide range of mission scenarios

Having all of this into account, it is now relevant to study the different systems that can be incorporated to create this lateral opening. Various systems can reach the desired outcome, and through a detailed analysis of the principles of functioning of each one, as well as their advantages and disadvantages, it is possible to define what is the best solution to create this lateral opening.

- **Sliding Rail System:** this system uses rails mounted along the inner surface of the UAV fuselage, allowing the cargo compartment to slide laterally for loading and unloading, and the cargo compartment is equipped with corresponding sliders that glide along the rails, facilitating the smooth movement in this lateral direction, allowing it to be taken off sideways. Then, for the locking mechanism, a locking pin or latch mechanism secures the cargo compartment in place when it is fully inserted into the fuselage, and this system engages automatically when the cargo compartment reaches its fully closed position, providing a secure hold during flight.

It is essential to ensure structural integrity of the whole system when designing this mechanism, as the locking mechanism must be robust and well connected both to the fuselage and the cargo compartment. For the fuselage, the rails are mounted along the inner surface of the UAV, and they incorporate locking pins or latches that will engage with its corresponding slots on the cargo compartment sliders, and when the compartment is fully inserted into the fuselage, these automatically engage, providing a stable connection between the fuselage and the cargo compartment. In the cargo compartment, similarly, the locking mechanism are installed on the sliders to ensure a secure attachment to the rails, and these mechanisms engage with the fuselage locking components upon its insertion, reinforcing the structural integrity of the connection.

This mechanism provides a simple and reliable design, offering a smooth and controlled lateral movement for the cargo compartment, providing an easier loading and unloading of the cargo, and its implementation imposes minimal additional weight on the UAV, preserving its overall efficiency. However, the sliding rail system is constrained by the limited extension distance dictated by the length of the rails, potentially limiting its applicability, and its prolonged use may lead to friction and wear over time, necessitating periodic maintenance. Furthermore, precise alignment is crucial for ensuring a correct and reliable operation. In Figure 3.6 it is possible to see an example of the design of a sliding rail system.

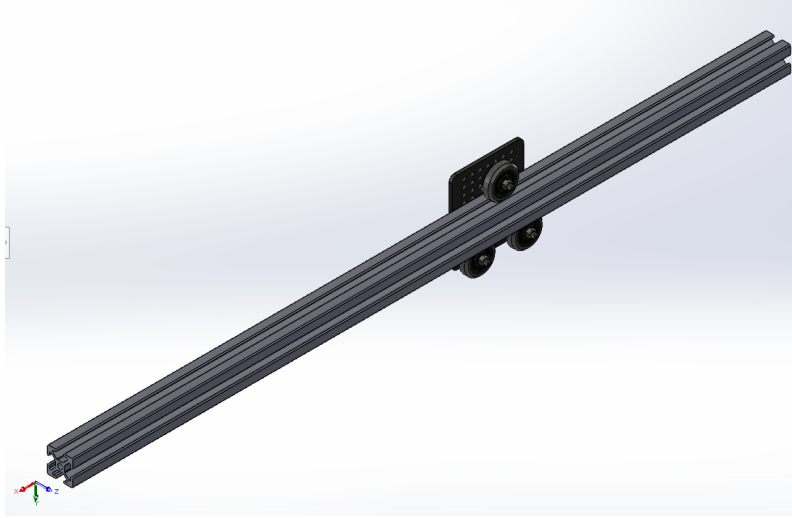


Figure 3.6: Example of the design of a sliding rail system.

- **Telescopic Arm System:** the telescopic arm system consists of extendable arms mounted between the fuselage and the cargo compartment, and these arms can extend outward to facilitate the lateral movement of the compartment and retract when not in use. Then, a locking mechanism integrated into the telescopic arms secures the cargo compartment in place during flight, and it engages automatically when the arms are fully extended, providing a stable connection.

In order to ensure structural integrity of the structure, a reliable connection must be designed between these structures. The cargo compartment is securely attached to the telescopic arms, serving as the primary load-bearing structure, with robust mounting points and reinforcements in the structure design, to distribute the loads evenly and minimize stress concentrations. The telescopic arms are connected to the fuselage through mounting points and reinforced mounting brackets or plates, that are securely fastened to the inner surface of the fuselage, providing a stable foundation for this system.

This system offers robust structural support for the cargo compartment, distributing the loads evenly and minimizing stress concentrations, and the telescopic arms offer adjustable extension ranges, enabling the system to adapt to different mission requirements. Its smooth design also ensures a smooth extension and retraction of the arms while minimizing friction and resistance, improving the reliability and performance of the mechanism. On the other hand, this mechanism may add significant weight to the UAV, impacting the payload capacity and the overall performance of the structure, so efforts must be made to minimize excess weight without compromising the structural integrity of the cargo compartment. Naturally, regular inspection and maintenance is required to the telescopic arms, in order to monitor

3.3. Hinges to open the trapdoors

signs of wear or fatigue within its components and conduct periodic lubrication and precision adjustments. In Figure 3.7 a simple design of a telescopic arm is shown, that can be adapted to the structure at hand.

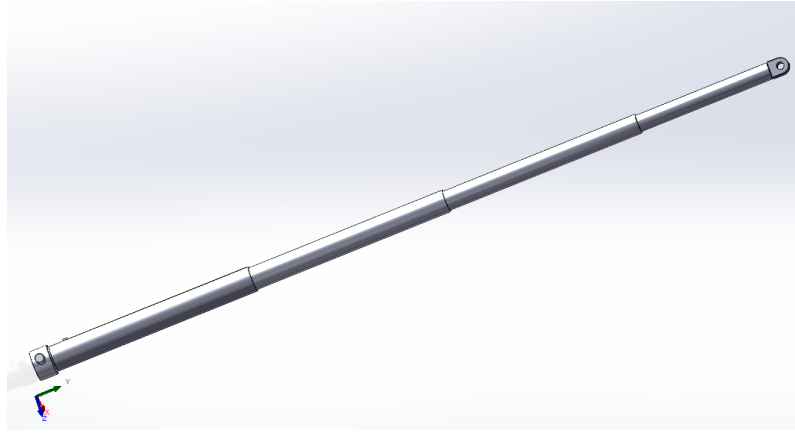


Figure 3.7: Example of the design of a telescopic arm system.

3.3 Hinges to open the trapdoors

The incorporation of hinges plays an important role in enabling the transformation of the cargo compartment into a functional trapdoor, and in this subsection, the focus will be on the design and modeling of hinges that facilitate the safe and reliable operation of the trapdoor mechanism within the project. The trapdoor mechanism is engineered to operate swiftly and reliably, allowing for precise deployment of payloads mid-flight, and the hinges serve as the components responsible for enabling the trapdoor to open smoothly and securely so their design must not only ensure structural integrity but also accommodate the unique operational requirements of the UAV, including mid-flight deployment and fail-safe operation. Key considerations must be taken when designing these mechanisms, such as:

- **Compatibility with the Cargo Compartment Structure and UAV Fuselage:** Ensure that the hinge design accounts for the specific geometry and attachment points of the cargo compartment structure and UAV fuselage without causing interference or compromising structural integrity.
- **Ability to Withstand Aerodynamic Forces and Vibrations During Flight:** Design the hinges to withstand the aerodynamic forces and vibrations experienced during flight operations, considering factors such as material selection, hinge geometry, and reinforcement features to improve structural stability and durability under dynamic loading conditions.
- **Incorporation of Redundant Locking Mechanisms for Fail-Safe Operation:** Integrate redundant locking mechanisms into the hinge design to ensure fail-safe operation of the trapdoor mechanism, such as including multiple latch mechanisms or secondary locking features to prevent accidental opening or disengagement during flight.
- **Ease of Assembly and Disassembly:** Design the hinges with considerations for ease of assembly and disassembly to facilitate maintenance and servicing tasks, incorporating features such as quick-release mechanisms, modular components, or accessible mounting points to simplify installation and removal of the hinge assemblies.

When starting the design of this structure, the first step is to define the optimal hinge design for this project, and given the requirements stated above, a continuous hinge design would likely be the most suitable option for this case. This type of design, also known as a piano hinge, offers several advantages that align well with the requirements of the trapdoor mechanism: it distributes the load evenly along the entire length, providing robust support and stability for the trapdoor during operation; the continuous design allows for smooth and precise movement of the trapdoor, ensuring swift and reliable operation upon activation of the solenoid; they can easily accommodate multiple locking mechanisms along their length, providing redundant security features for fail-safe operation of the trapdoor, and has an ease of maintenance, as these hinges can be easily installed and removed without requiring complex disassembly of the hinge assembly.

3.4 Actuation Mechanism of the Trapdoors

To open the trapdoor safely and reliably, it is crucial to correctly design the mechanism responsible for the opening of the trapdoor to release payloads during flights, always taking into account a fail-safe approach. Therefore, the primary objective of this subsection is to design a mechanism that enables the controlled and precise opening of the trapdoor when needed, allowing for the safe and efficient deployment of payloads mid-flight, and this mechanism must meet stringent performance criteria, including speed, force, reliability, and compatibility with the UAV's design and operational requirements. There are many possible options to select for the trapdoor operation, each offering several advantages and considerations, like linear actuators, servomechanisms, pneumatic or hydraulic cylinders, or electromechanical solenoids, and through a systematic evaluation and comparison, the objective is to identify the most suitable mechanisms that align with the project's objectives and constraints. It is important to define the most important characteristics that this mechanism must integrate, to analyze potential solutions and through a table of characteristics verify what is the best solution to this problem. This way, it becomes relevant to detail the main candidates to be integrated in this system:

- **Linear Actuator:** this mechanism converts rotary motion into linear motion, typically using a lead screw, belt, or hydraulic mechanism, and when activated, the actuator extends or retracts a rod or piston, thereby moving the trapdoor along a linear path to open or close it. This system enables precise control over the position and speed of trapdoor movement, it can generate high forces, and it has a compact design, suitable for integration into confined spaces within the cargo compartment. On the other hand, it may have limited travel distance, depending on the actuator's stroke length, and it might impose strict maintenance requirements over time. In Figure 3.8, it is possible to understand how this mechanism works:

3.4. Actuation Mechanism of the Trapdoors

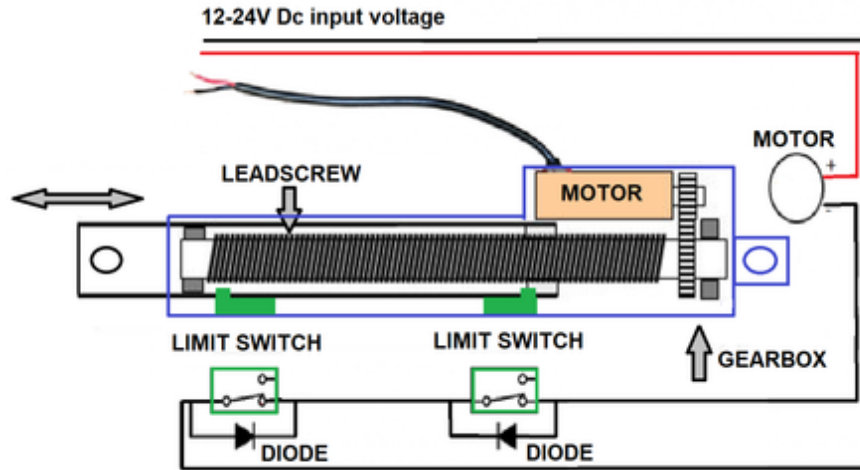


Figure 3.8: Example of how a linear actuator works [92].

- **Servomechanism:** a linear servomechanism, or servo motor, is a closed-loop control system that uses feedback to accurately control the position, speed, and torque of a rotating shaft, and it operates based on the principles of a rotary servo motor but produces linear motion instead of rotational motion. It consists of a stator with coils and a mover that contains magnets, and when current is applied to the coils, a magnetic field is generated, causing the mover to move along the stator's axis, resulting in linear motion. It is possible to visualize this mechanism in the figure below.

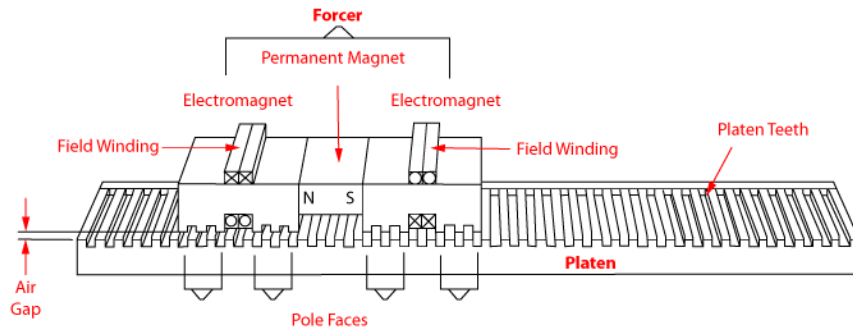


Figure 3.9: Working principle of a servomotor [93].

This system has the advantage of having high precision and accuracy in controlling its movement and can provide variable speed and torque, allowing for smooth and controlled operation. It can also be programmed and integrated with the flight control systems and has a compact and lightweight design, suitable for UAV applications, but it might have a higher cost compared to simpler mechanisms, it may be more susceptible to environmental factors such as temperature and vibration, and a complex setup and calibration process is required.

- **Electromechanical Solenoid:** it consists of a coil of wire wound around a movable ferro-magnetic core, typically made of iron or steel, and when an electric current is passed through the coil, it creates a magnetic field around the core, that induces magnetic flux within the core, causing it to become magnetized. The magnetized core experiences a force in the direction of the magnetic field, causing it to move linearly along the axis of the solenoid, and this movement is typically used to actuate a mechanical mechanism, such as a plunger or rod, which is connected to the core. When the current is removed, the magnetic field collapses, and the core returns to its original position due to springs or other restoring forces.

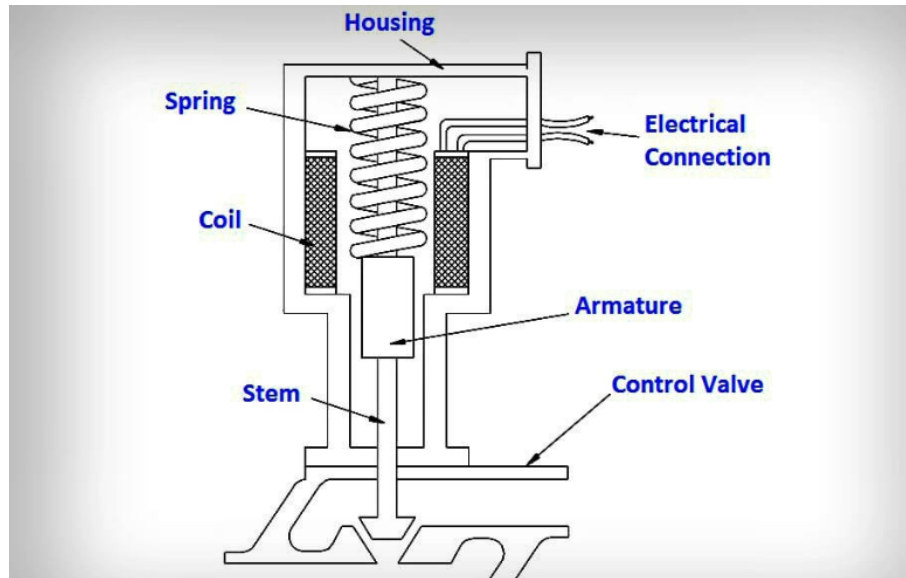


Figure 3.10: Working principle of an electromechanical solenoid. [94].

This mechanism offers a simple design, making them easy to manufacture and install, they have a fast response time and a high force output, as they can generate significant force relative to their size, and they have a low power consumption and provide reliable and repeatable operation over long cycles of use (when properly designed and maintained). However, they have limited stroke length, and while they can provide high force output, their speed and force characteristics may not be as easily controllable or adjustable as other actuation methods, such as linear actuators or servo systems. It is also relevant to note that this component must be properly isolated, as it can produce electromagnetic fields during operation, which may interfere with nearby electronic devices or systems.

To effectively choose the most suitable mechanism for opening the trapdoors, it's crucial to conduct a structured analysis, and beginning with a table of characteristics allows for a direct comparison of the available systems, aiding in the selection process. This is a valuable tool for directly comparing the various available systems across crucial components, and by meticulously evaluating these components, we can observe the nuances and complexities of each mechanism, thus facilitating a deeper understanding of their respective strengths and weaknesses, gaining a clearer understanding of which option aligns best with our objectives and operational requirements.

3.4. Actuation Mechanism of the Trapdoors

Table 3.2: Table of Characteristics of the possible mechanisms to the opening of the trapdoors.

Characteristic	Linear Actuator	Servomechanism	Electromechanical Solenoid
Control Method	Open/Closed-loop	Closed-loop	Direct electrical activation
Precision	Moderate	High	Moderate
Force Output	High	High	High
Power Consumption	Low	Moderate to High	Low
Size and Weight	Moderate	Moderate	Small to Moderate
Complexity of Installation	Low	Moderate to High	Low to Moderate
Reliability	Moderate to High	High	Moderate
Cost	Moderate	High	Low to Moderate
Ease of Integration	Moderate	High	High
Control over Speed and Force	Moderate	High	Limited

Having these three options under consideration, the appropriate mechanism can be selected for the project at hand. The correct engagement and disengagement of the trapdoors of the cargo compartment are critical for ensuring the reliability of the entire structure and the safe and reliable mid-flight payload deployment, and each analyzed option offers unique characteristics and trade-offs, which must be carefully considered to determine the most suitable choice for the project's requirements.

Linear actuators offer a versatile and pragmatic solution for the operation of the trapdoor in the UAV cargo compartment, as while other options such as servomechanisms and electromechanical solenoids possess distinct advantages, the specific requirements of the project dictate the preference for a linear actuator. One of the key advantages of linear actuators is their ability to provide open/closed-loop control, facilitating precise positioning of the trapdoor, and while servomechanisms also offer this feature, the level of precision provided by linear actuators is adequate for the intended purpose of the trapdoor mechanism. Additionally, the high force output of linear actuators makes them well-suited for lifting payloads, ensuring efficient operation of the cargo compartment. Moreover, linear actuators exhibit moderate power consumption, contributing to energy efficiency during operation, and whereas servomechanisms may offer comparable performance in this regard, linear actuators excel in terms of simplicity and straightforwardness in their installation process. This characteristic is particularly advantageous for integration into the UAV, minimizing assembly time, effort, and potential maintenance requirements.

In contrast, while servomechanisms provide excellent precision and accuracy, their higher cost and complexity of installation may outweigh these benefits for the current application. Similarly, while electromechanical solenoids offer simplicity and low power consumption, their limitations in precision and force output make them less suitable for the project's requirements. Therefore, after a careful evaluation of the characteristics and trade-offs associated with each option, the linear actuator emerges as the most suitable choice for the trapdoor mechanism in the UAV cargo compartment, as its combination of precise positioning, high force output, moderate power consumption, and ease of installation aligns closely with the project's objectives, prioritizing functionality, efficiency, and practicality in the UAV operation.

Taking this into account, and with the decision to use a linear actuator as the preferred option for the trapdoor mechanism in the cargo compartment, the next step was to model the open-

ing mechanism based on this selection, and two distinct modes of operation were considered to accommodate the various operational scenarios and requirements.

In the first iteration, the focus was on a straightforward linear actuation mechanism, and in this configuration, the linear actuator was designed to extend or retract its rod, exerting linear force directly on the trapdoor assembly. This mode of operation offered simplicity and reliability, using the positioning capabilities of the linear actuator to achieve accurate and controlled movement of the trapdoor. However, recognizing the potential benefits of incorporating rotational movement into the trapdoor mechanism, a second case was modeled, where a pivot point was designed in the connection between the actuator and the cargo compartment, allowing for the transformation of the linear motion of the actuator into rotational movement of the trapdoor. This integration of the linear actuator with a rotational mechanism offered several advantages, as it provided enhanced flexibility and adaptability in controlling the movement of the trapdoor, and by enabling rotation around a pivot point, the mechanism allowed for varied opening angles and trajectories, accommodating different payload deployment scenarios.

In Figure 3.11 it is possible to see the modelled actuators, where the first one has a stroke of 50 mm, while the second one has a stroke of 100 mm. The next step is to define which linear actuator is the best option for this application, having into account project requirements and the advantages and disadvantages of each system.

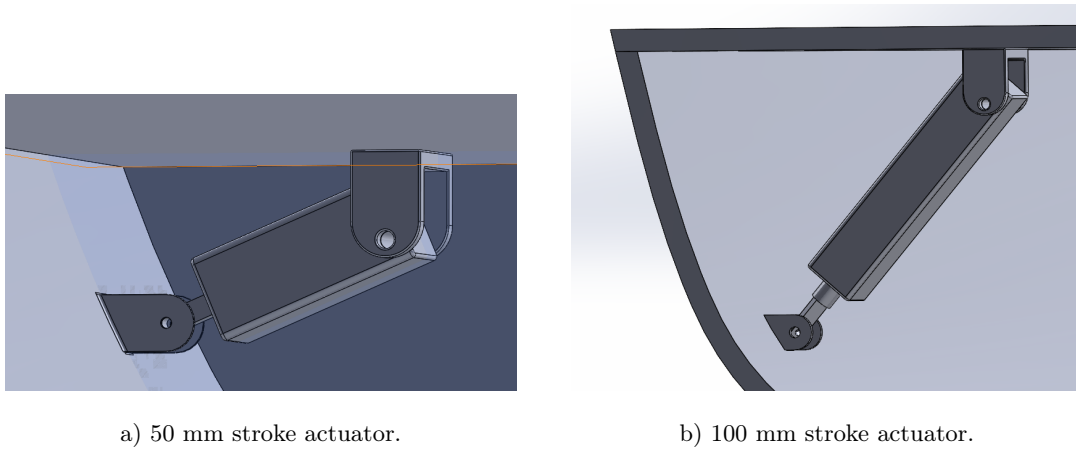


Figure 3.11: Modelled versions of linear actuators designed to open the trapdoors.

Now, comparing the two actuators, there are important categories that need to be evaluated in order to carry out a detailed and correct analysis on the option that best suits the project, such as mechanical advantage, stability and force distribution. This way, a complete analysis will be performed, starting with a table of characteristics followed by a detailed analysis on each topic, allowing to determine the most suitable linear actuator to use to open the trapdoor of the cargo compartment.

3.4. Actuation Mechanism of the Trapdoors

Table 3.3: Comparison between the 50 mm stroke linear actuator and the 100 mm stroke linear actuator.

Characteristic	50 mm Actuator	100 mm Actuator
Mechanical Advantage	Lower mechanical advantage due to shorter length	Higher mechanical advantage due to longer length
Leverage	Moderate horizontal distance, limited leverage	Increased horizontal distance, greater leverage
Force Distribution	May require higher force, potential for uneven distribution	More even force distribution along trapdoor
Efficiency	May require more force for desired torque	Requires less force for desired torque
Structural Integrity	Potential stress concentration due to higher force	Reduced risk of stress concentration with lower force
Complexity	Simplified design with shorter length	More complex design with longer length
Space Requirement	Takes up less space due to compact size	Requires more space due to longer length
Operational Efficiency	May experience operational inefficiencies with higher force requirements	More efficient operation with lower force requirements

In terms of mechanical advantage, the 100 mm actuator offers a distinct advantage over its 50 mm counterpart due to its longer length, as it provides a greater lever arm, resulting in a higher mechanical advantage and consequently reducing the force required to open the trapdoor, as compared to the 50 mm stroke linear actuator, that will require a higher force to produce the desired torque. Leverage also plays a crucial role in determining the effectiveness of the actuators, as the 100 mm actuator, with its increased horizontal distance between the connection point at the top of the cargo compartment and the trapdoor pivot point, provides greater leverage compared to the 50 mm actuator, that has a smaller horizontal distance between these two points. This increased leverage translates to a more efficient distribution of force, making it easier to open the trapdoor with less effort made by the actuators.

Regarding force distribution, the longer length of the 100 mm actuator allows for a more even distribution of force along the trapdoor, and this helps mitigate the risk of stress concentration and potential structural issues, crucial for the trapdoor functioning, ensuring smoother and more reliable operation than the other option. Adding to this, the shorter length of the 50 mm actuator may lead to an uneven force distribution, increasing the likelihood of operational inefficiencies and structural problems, where the components might fail in an easier way. Efficiency is also another critical factor to consider, as the 100 mm actuator, with its greater mechanical advantage and leverage, requires less force to produce the desired torque compared to the 50 mm actuator, resulting in improved operational efficiency and a smoother trapdoor operation. Additionally, the reduced force requirements of the 100 mm actuator would contribute to lower energy consumption and improved overall performance of the structure.

When assessing the structural integrity of the trapdoor mechanism, it's essential to consider how the chosen actuator may interact with the overall system, as this is a critical aspect of the project. The 100 mm linear actuator, with its longer length and greater leverage, is less likely to

interfere with the structural integrity of the trapdoor, and its extended reach allows for a more distributed application of force along the length of the trapdoor, reducing the risk of localized stress concentrations, helping to maintain the integrity of the trapdoor and minimizing the potential for structural damage over time. On the other hand, the 50 mm stroke linear actuator, being shorter in length, may present challenges in terms of structural interference, as its limited reach may need positioning closer to the center of the trapdoor, which could result in uneven force distribution and localized stress points. This has the potential to compromise the structural integrity of the trapdoor, particularly if the actuator is not properly aligned or if excessive force is required to overcome the resistance and weight of the trapdoor and the cargo inside the compartment.

Furthermore, the connection points between the actuator and the trapdoor are critical areas where structural integrity must be ensured, as any misalignment or inadequate reinforcement at these connection points could lead to premature wear or failure of the trapdoor mechanism. This way, the shorter length of the 50 mm actuator may increase these concerns, as it may require additional support or reinforcement to withstand the forces exerted during the operation of the trapdoor. In summary, while both actuators may be capable of opening the trapdoor, their differing lengths and leverage can impact the structural integrity of the mechanism, and the 100 mm actuator offers advantages in terms of longer reach and more even force distribution, reducing the likelihood of structural interference and ensuring the long-term reliability of the trapdoor system. Therefore, for applications where structural integrity is a priority, such as in aeronautical or critical engineering environments, as is the situation of study, the 100 mm linear actuator is the preferred choice.

In conclusion, after careful evaluation of the key characteristics, the 100 mm linear actuator emerges as the optimal choice for trapdoor operation, as its longer length, greater mechanical advantage, and improved leverage contribute to a more efficient and reliable trapdoor operation. While the 50 mm actuator may offer potential cost savings, its shorter length, and inferior performance in terms of force distribution and efficiency make it less suitable for the task at hand. Therefore, using the 100 mm linear actuator is recommended, prioritizing performance, reliability, and long-term operational efficiency in the trapdoor operation.

In Figure 3.12 it is possible to see the chosen linear actuator in both closed and open position, where it is possible to see the translation and rotation of both the actuator rod and body, respectively.

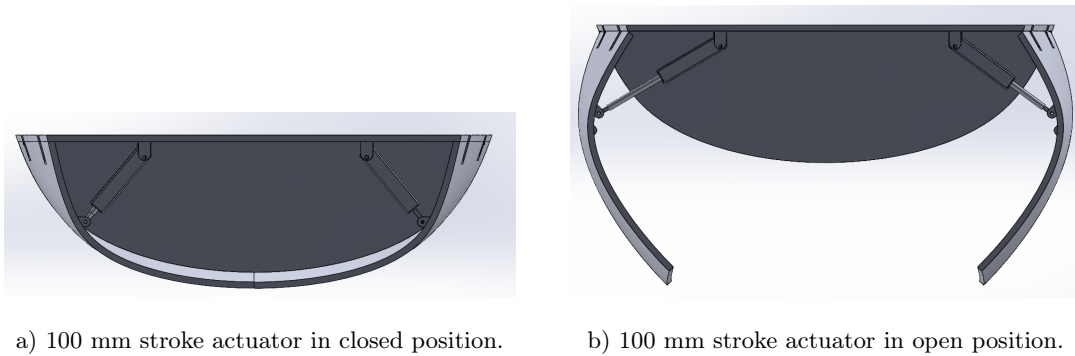


Figure 3.12: Visualization of the chosen linear actuator in both closed and open positions, respectively.

3.5 Locking Mechanism

Before selecting the appropriate locking mechanism for the UAV cargo compartment trapdoor, it is essential to establish the requirements that the mechanism must comply with, and these requirements are critical for ensuring the security, reliability, and functionality of the locking system, particularly in the context of mid-flight payload deployment operations. In this subsection, the key points that the locking mechanism must meet will be outlined and analyzed, considering factors such as operational needs, safety considerations, and system integration requirements, in order for the different options of mechanisms can be detailed, analyzed, and an informed choice of the optimal locking mechanism be made.

The locking mechanism must offer automatic operation to enable the opening and closing of the trapdoor during mid-flight payload deployment, as well as a fail-safe functionality, a critical requirement for the system, ensuring that the trapdoor remains securely locked at all times, even in the event of system failures or power outages, as well as preventing accidental opening and safeguard the payload during flight operations. It is also crucial for the mechanism to demonstrate high reliability, ensuring consistent performance under varying environmental conditions and operational scenarios, as in a normal flight different critical scenarios will regularly appear. Ease of integration into the overall design of the cargo compartment is also important, as the locking mechanism should have minimal impact on the overall system architecture, aerodynamics and cargo space, and this characteristic also simplifies the assembly and disassembly processes, reducing maintenance time and effort. Finally, the system should be durable and resistant to wear, particularly in demanding flight environments, and this can be achieved by using high-quality materials and robust construction techniques to enhance the longevity and performance of the locking system. This way, different mechanisms will be analyzed:

- **Solenoid Lock System Operation:** this system uses an electromechanical solenoid to control the locking and unlocking of the trapdoor and operates based on the principles of electromagnetic induction, where an electrical current passing through a coil of wire generates a magnetic field, and the solenoid consists of a coil of wire wound around a plunger, which is free to move back and forth within a cylindrical housing.

When the solenoid is energized by applying an electrical current, the coil generates a magnetic field, that causes the plunger to be pulled or pushed into the solenoid housing, depending on its design, and as the plunger moves, it engages with a corresponding latch mechanism on the trapdoor, securely locking it in place. Once the plunger is fully extended or retracted, it holds the latch mechanism in place, preventing the trapdoor from opening, providing a secure locking mechanism for the cargo compartment, and ensuring that the payload remains safely housed within. To unlock the trapdoor, the solenoid must be deactivated by cutting off the electrical current flowing through the coil, interrupting the magnetic field generated by the solenoid, and allowing the plunger to return to its neutral position, therefore releasing the locking mechanism, making the trapdoor free to open.

This system offers automatic locking and unlocking, making it suitable for automated systems and mid-flight operations, and when properly maintained, solenoid locks offer reliable performance, ensuring consistent locking and unlocking of the structure. On the other hand, solenoid locks require continuous power to maintain the locked or unlocked state, which could be a concern in the event of a power failure, and integrating these locks into the UAV system may require additional wiring and control circuitry, increasing the complexity of the whole project.

- **Magnetic Lock System Operation:** a magnetic lock is an electromagnetic locking device designed to secure doors and operates based on the principle of electromagnetism, as when electrical power is applied to the electromagnet, it generates a magnetic field that attracts the armature plate, creating a strong bond that locks the trapdoor in place.

Once engaged, the magnetic lock provides a secure locking mechanism, preventing the trapdoor from opening unintentionally, as the strength of the magnetic force ensures that the trapdoor remains firmly locked, even under external forces or vibrations. To unlock the trapdoor, electrical power to the electromagnet must be interrupted, as when power is cut off, the magnetic field dissipates, releasing the armature plate from the electromagnet, allowing the trapdoor to open freely.

This system provides a strong locking mechanism, but it relies on continuous electrical power to maintain the locked state, and in the event of a power outage or electrical failure, the lock may release, compromising the cargo inside the compartment. This lock also requires complex wiring and mechanical connections, and they require high compatibility with other components, such as control systems or power supply units.

- **Electric Strike Lock System Operation:** this system is designed to secure the trapdoor in place using an electrically controlled strike mechanism, relying on electrical activation to engage and disengage the locking mechanism.

When electrical power is applied to the electric strike lock, the strike mechanism is activated, causing it to extend or retract into the door frame, and it interfaces with a corresponding latch or bolt mechanism on the trapdoor that locks it in place, preventing it from opening. To unlock the trapdoor, electrical power to the electric strike lock must be cut off, deactivating the strike mechanism and subsequently disengaging from the latch mechanism on the trapdoor, making the mid-flight payload deployment possible.

The electric strike locks offer versatility in installation options, as they can be configured with various types of materials and can be customized to meet specific security requirements, with options for adjustable latch positioning and different strike plate configurations. They also generally require minimal maintenance once installed, with durable components and reliable operation over extended periods, but their installations may require modifications to the door frame or the strike plate, and they may be more expensive than other locking mechanisms due to their additional components and installation requirements.

In Table 3.4, it is possible to resume the most important characteristics and discuss the implications of these systems, to decide what is the best option to use in this project.

3.5. Locking Mechanism

Table 3.4: Table of Characteristics of the possible mechanisms for the locking mechanism

Characteristic	Electric Strike Lock	Magnetic Lock	Electromechanical Solenoid
Fail-Safe Operation	Yes	Yes	Yes
Reliability	High	High	Moderate
Security	High	High	Moderate
Precision Control	High	Moderate	Moderate
Power Consumption	Low	Low	Moderate
Ease of Installation	Moderate	Moderate	High
Size and Weight	Moderate	Moderate	Low
Cost	Moderate	Moderate	Low

Now it is possible to make a decision on what is the best choice for the locking mechanism, as each system offers unique features and characteristics that must be carefully evaluated in order to make the optimal decision.

The electric strike lock is a robust and reliable option for securing the UAV's trapdoors, as its fail-secure operation ensures that the trapdoor remains securely closed even during power outages, providing uninterrupted protection for the cargo. Furthermore, its precise control and precision over the locking and unlocking process allow for accurate operation of the system, and while the installation may require moderate expertise, the moderate size, weight, and cost of electric strike locks make them well-suited for unmanned aerial vehicle applications. The magnetic lock is another strong contender, as it offers high levels of reliability and security, and while the installation is relatively straightforward, this system may not offer the same level of precision control as electric strike locks. However, their moderate size, weight, and cost make them suitable alternatives for securing the vehicle's cargo compartment. Finally, the electromechanical solenoid presents a cost-effective option with fail-safe operation, but while they are generally reliable, solenoids may not offer the same level of robustness as electric strike locks or magnetic locks. With good control over locking and unlocking processes, this system offers simplicity and efficiency in operation, and with their small and lightweight form factor, they are well suitable for UAV cargo compartment applications where space and weight are critical factors.

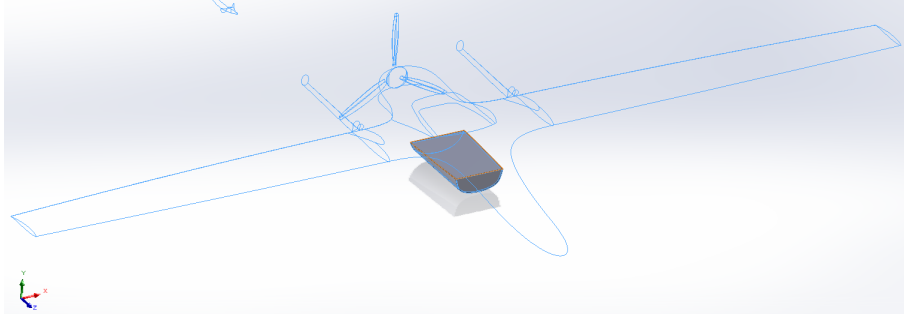
After careful analysis and consideration of the strengths and limitations of each locking mechanism, the electric strike lock emerges as the recommended choice for securing the UAV cargo compartment trapdoors, as its combination of fail-safe operation, reliability, precision control, and moderate cost makes it well-suited to meet the project's needs. Furthermore, its moderate size and weight, along with a reasonable power consumption and installation time and maintenance further enhance its suitability for the application.

Chapter 4

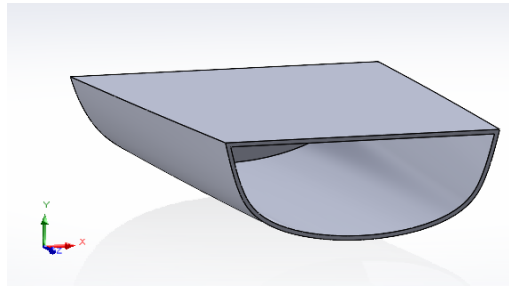
Structural Analysis of the Cargo Compartment

The present section focuses on the modeling and structural analysis of the cargo compartment of the UAV, as it is a critical component, that must be designed to securely house and transport the desired payloads. Starting with the provided initial geometry, the primary objective is to develop a robust structure capable of withstanding the loads generated by the cargo's weight, and this will be achieved through a comprehensive structural analysis that examines various geometric configurations and material combinations, with the ultimate goal of having a robust, fail-safe structure. In Figure 4.1, it is possible to visualize the location of the cargo compartment in the whole structure (a)), as well as the initial shell structure provided by the company (b)).

Key parameters to be evaluated include maximum stress, stress concentration regions, weight, maximum deflections of the structure, and given the use and application of composite materials, particular attention will be paid to Hashin's damage criterion, which is essential for assessing the structural integrity under the imposed loads. By investigating these factors, the analysis aims to ensure that the cargo compartment can effectively endure the operational stresses that will be subjected to. This approach not only provides a detailed understanding of the mechanical behavior of the cargo compartment but also guides the optimization process, as the use of different materials and geometric configurations will help identify the most efficient design, balancing strength and weight considerations. Ultimately, the objective of this analysis is to optimize the performance and durability of the UAV while also ensuring that its cargo compartment meets all necessary structural requirements.



a) Relative position of the cargo compartment in the whole model.



b) Shell structure of the cargo compartment.

Figure 4.1: Initial geometry of the cargo compartment.

Taking this into account, a structured analysis will be performed, and will be carried out as follows:

1. Establish the most appropriate boundary conditions to apply to the model;
2. Determine the critical load that the structure will be subjected to;
3. From the various options of load application, define the most realistic possible application of the critical loads;
4. Create the necessary constraints to approximate the model to the reality as much as possible;
5. Evaluate the created model and, if necessary, modify the geometry and possibly the materials to obtain a structure closer to the desired;
6. Re-evaluate the most recent geometry until the expected results are obtained;

4.1 Boundary Conditions

Establishing realistic boundary conditions is an important initial step, as these conditions represent how the compartment is physically constrained and connected to the UAV's overall structure. Given that the cargo compartment is expected to be bolted along the longitudinal edges of its top to the rest of the UAV, these edges can be considered to be in an encastre condition, as seen in Figure 4.2 for the initial model.

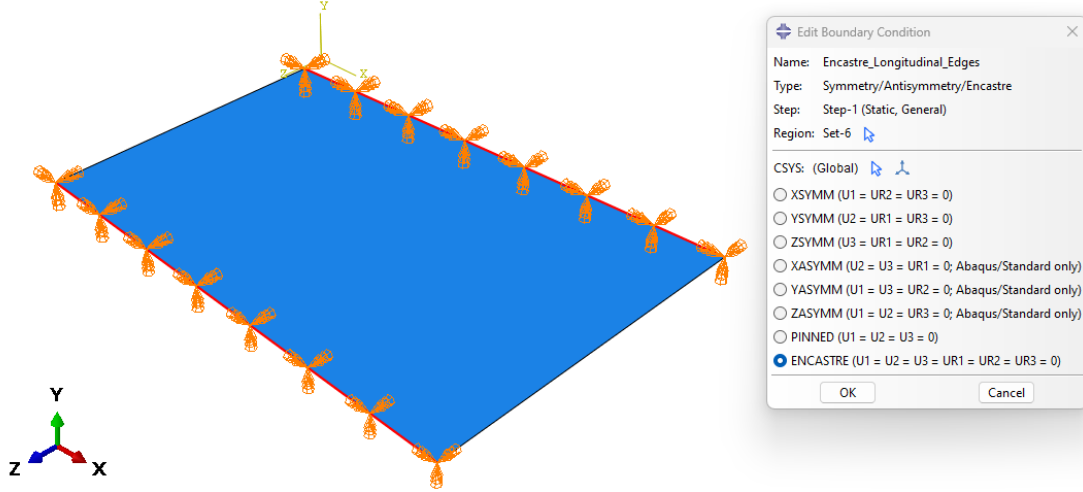


Figure 4.2: Applied boundary conditions on the model.

An encastre or fixed condition implies that there is neither rotation nor displacement along these edges, meaning that the longitudinal edges of the top of the compartment are rigidly attached, preventing any movement or angular shifts, effectively simulating the attachment points that exist in the actual UAV assembly. In practice, this means that when loads are applied to the compartment, the fixed edges will not allow any bending or twisting, thus focusing the structural response on other parts of the compartment. It is expected to see higher stress concentrations around these fixed edges and a more pronounced deflection in areas further away from these constraints, and understanding these effects is essential for identifying potential weak points and areas that may require additional reinforcement.

4.2 Loads

In the structural analysis of the cargo compartment, it is essential to identify and evaluate the critical loads that the structure will be subjected to, and this conservative approach ensures that the design can withstand the most demanding conditions it might encounter during operation. By analyzing the structure under these extreme conditions, we can predict that the compartment will perform reliably under all smaller loads within this envelope. The critical load scenario represents the worst-case conditions the UAV might face, such as maximum payload capacity, severe aerodynamic and inertial forces during maneuvers, and impact forces during landing. This way, to accurately determine the critical loads for the structural analysis of the UAV's cargo compartment, a systematic approach was employed to obtain the maximum loads the structure will need to withstand.

4.2. Loads

Firstly, the maximum payload capacity of the cargo compartment was identified as 100 kg, and this value represents the heaviest load the compartment is expected to carry under normal operating conditions. However, to ensure the design is robust and capable of handling unpredicted circumstances, a margin of safety must be applied, and the safety factor value of 1.5 was chosen, a standard practice in aeronautical applications to account for uncertainties and variations in material properties, load estimations, and operational conditions. To convert this value into a force, it must be multiplied by the acceleration due to gravity (9.81 m/s^2), providing the total load in Newtons (N), representing the actual force that the structure must support.

Next, this adjusted payload is further multiplied by the maximum possible load factor that the UAV will experience. The load factor, which accounts for the additional forces experienced during maneuvers such as turns, climbs, and descents, ensures that the structure can endure dynamic stresses, and this factor is critical in aviation and aerospace applications, where the forces exerted on the structure can vary significantly during flight. To accurately determine the maximum load factor for the structural analysis, it is essential to obtain the V-n diagram by the ASTM F3116-18 norm. The V-n diagram is a crucial tool in aerospace engineering that illustrates the relationship between the aircraft's speed (V) and the corresponding load factors (n) it experiences. In this diagram, it is possible to identify the critical load factors that the UAV will encounter during its operational envelope, therefore allowing it to obtain the critical load that the compartment must withstand. Therefore, and guided by the ASTM F3116-18 document for Standard Specification for Design Loads and Conditions, it is possible to create the full envelope of both Gust and Maneuvre diagrams, as can be seen in the next subsection:

4.2.1 V-n Diagram

The V-n diagram, also known as the flight envelope diagram, is a crucial tool in aerospace engineering that graphically represents the operational limits of an aircraft in terms of airspeed (V) and load factor (n), and constructing this diagram involves two primary components: the maneuver diagram and the gust diagram. By combining these two diagrams, we can delineate the complete flight envelope, which provides a prediction of the aircraft's performance under various flight conditions, and this envelope helps in understanding the critical loads and the operational boundaries within which the UAV can safely function. To begin constructing the V-n diagram for the UAV, it is important to define all of the initial necessary data from both the characteristics of the UAV to air properties, and they go as follows:

- **Wing Area (S):** 108.554 ft^2
- **Gross Weight (W):** 1322.77 lb
- **Three-Dimensional Curve Slope (a):** 5.6 /rad
- **Maximum Lift Coefficient (CL_{max}):** 1.5
- **Minimum Lift Coefficient (CL_{min}):** -0.8
- **Maximum Positive Load Factor (n_{max}):** 3.8
- **Maximum Negative Load Factor (n_{min}):** -1.52 (40% of n_{max})
- **Air Density (ρ):** $0.00238 \text{ slugs/ft}^3$
- **Cruising Speed (V_c):** 194.098 ft/s (115 knots)
- **Dive Speed (V_d):** $1.4 \times V_c = 271.6 \text{ ft/s}$

With this information, it is now possible to obtain the Manoeuvre diagram:

- **Manoeuvre Diagram**

1. **Calculate Stall Speeds:**

- Positive stall speed:

$$V_{s1g+} = \sqrt{\frac{W}{0.5 \cdot CL_{max} \cdot \rho \cdot S}} \quad (4.1)$$

- Negative stall speed:

$$V_{s1g-} = \sqrt{\frac{-W}{0.5 \cdot CL_{min} \cdot \rho \cdot S}} \quad (4.2)$$

- Stall speeds at maximum and minimum load factors:

$$V_{s1} = V_{s1g+} \cdot \sqrt{n_{max}} \quad (4.3)$$

$$V_{s2} = V_{s1g-} \cdot \sqrt{-n_{min}} \quad (4.4)$$

2. **Plot Positive and Negative Stall Lines:**

- Positive stall line:

$$n = \left(\frac{V}{V_{s1g+}} \right)^2 \quad (4.5)$$

- Negative stall line:

$$n = - \left(\frac{V}{V_{s1g-}} \right)^2 \quad (4.6)$$

3. **Draw Horizontal Limit Lines:**

- Positive limit line:

$$n = n_{max} \quad \text{from} \quad V = V_{s1} \quad \text{to} \quad V = V_d \quad (4.7)$$

- Negative limit line:

$$n = n_{min} \quad \text{from} \quad V = V_{s2} \quad \text{to} \quad V = V_c \quad (4.8)$$

4. **Vertical Limit Line at Dive Speed:**

- At V_d , draw a vertical line from $n = 0$ to $n = n_{max}$

4.2. Loads

5. Connect Relevant Points:

- Connect stall speed at 1g to stall speeds at maximum and minimum load factors.
- Draw lines to represent the operational boundaries and significant speeds (V_c and V_d).

Following this procedure, we obtain the Manoeuvre diagram, as seen in Figure 4.3.

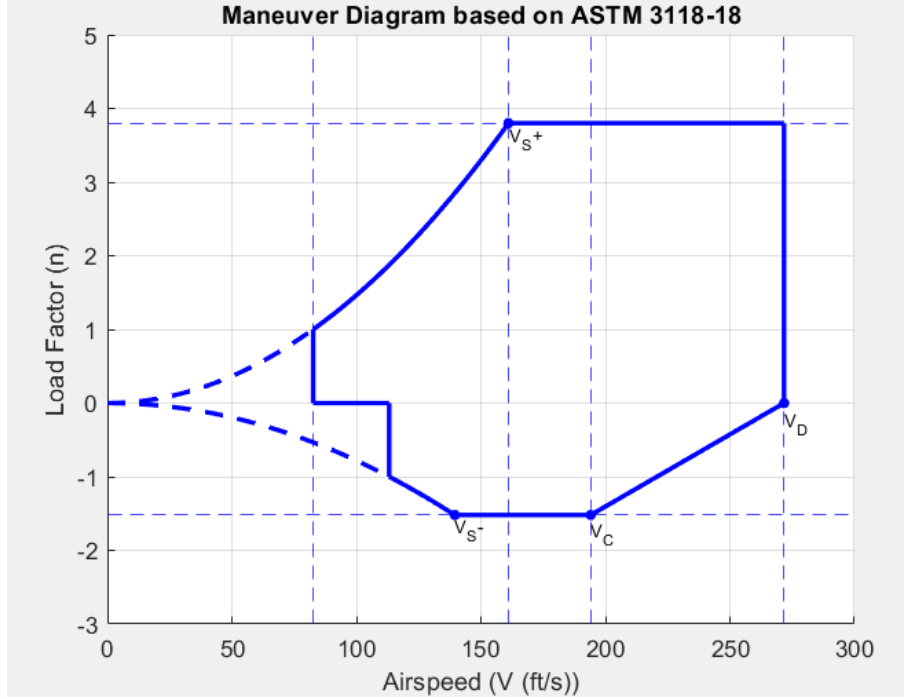


Figure 4.3: Manoeuvre diagram.

• Gust Diagram

For the gust diagram, additional parameters must be taken into account, such as:

- **Wing Span (C):** 2.7559 ft
- **Acceleration due to Gravity (g):** 32.185 ft/s²
- **Cruising Speed Gust Velocity (U_c):** 50 ft/s
- **Dive Speed Gust Velocity (U_d):** 25 ft/s

It is now possible to construct the gust diagram of the UAV through the following steps:

1. Calculate Gust Alleviation Factor:

- Airplane Mass Ratio:

$$\mu_g = \frac{2 \cdot (W/S)}{\rho \cdot C \cdot a \cdot g} \quad (4.9)$$

- Gust Alleviation Factor:

$$K_g = \frac{0.88 \cdot \mu_g}{5.3 + \mu_g} \quad (4.10)$$

2. Calculate Maximum Load Factors:

– At cruising speed V_c :

* Positive load factor:

$$n_{max_{V_c}} = 1 + \frac{K_g \cdot U_c \cdot V \cdot a}{498 \cdot (W/S)} \quad (4.11)$$

* Negative load factor:

$$n_{min_{V_c}} = 1 - \frac{K_g \cdot U_c \cdot V \cdot a}{498 \cdot (W/S)} \quad (4.12)$$

– At dive speed V_d :

* Positive load factor:

$$n_{max_{V_d}} = 1 + \frac{K_g \cdot U_d \cdot V \cdot a}{498 \cdot (W/S)} \quad (4.13)$$

* Negative load factor:

$$n_{min_{V_d}} = 1 - \frac{K_g \cdot U_d \cdot V \cdot a}{498 \cdot (W/S)} \quad (4.14)$$

3. Plot Gust Lines:

– Positive and negative gust lines at V_c :

* Positive gust line:

$$V_{50_{pos}} = 1 + n_{max_{V_c}} \quad (4.15)$$

* Negative gust line:

$$V_{50_{neg}} = 1 - n_{max_{V_c}} \quad (4.16)$$

– Positive and negative gust lines at V_d :

* Positive gust line:

$$V_{25_{pos}} = 1 + n_{max_{V_d}} \quad (4.17)$$

* Negative gust line:

$$V_{25_{neg}} = 1 - n_{max_{V_d}} \quad (4.18)$$

This way, the gust diagram is obtained, as seen in Figure 4.4.

4.2. Loads

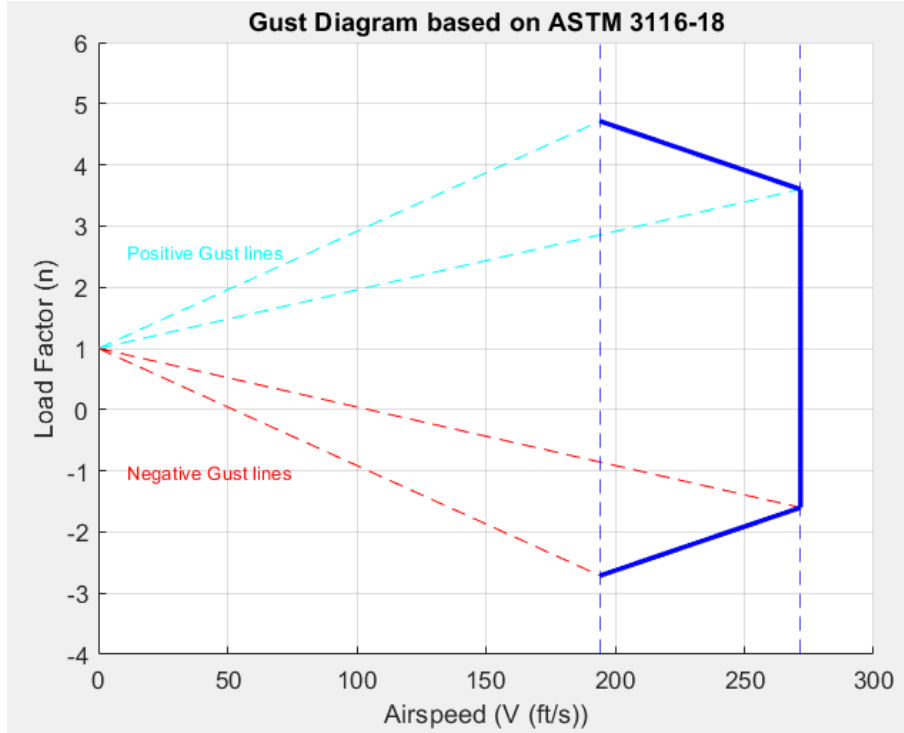


Figure 4.4: Gust diagram.

- **Final Envelope**

With both the maneuver and gust diagrams constructed, it is now possible to obtain the final flight envelope by intersecting these two diagrams, and this envelope delineates the operational limits within which the UAV can safely function under all considered conditions, encompassing both maneuver-induced loads and gust-induced loads. Therefore, it is obtained by identifying the intersection points between the maneuver diagram and the gust diagram, and these intersections represent the critical boundaries where the combined effects of aerodynamic maneuvers and atmospheric gusts dictate the maximum and minimum load factors the UAV can endure without structural failure.

The final envelope is of extreme importance, as considering both maneuver and gust loads, it ensures that the UAV structure can withstand the most extreme conditions it may encounter during its operational life, essential for maintaining airworthiness and operational safety, and the intersection of both diagrams validates the structural design against realistic and conservative load conditions, as this helps in identifying potential weak points and areas where additional reinforcement may be necessary. It is also important in providing clear operational limits for the UAV, as pilots and operators can refer to this envelope to understand the safe operating speeds and load factors, thereby avoiding conditions that could lead to structural damage or failure. Finally, the construction of the V-n diagram is also crucial for meeting regulatory standards and certification requirements, as ensuring compliance with these standards means that the UAV is fit for service and meets all necessary safety criteria.

In Figure 4.5 we can see the final V-n diagram obtained through the ASTM 3118-18 norm.

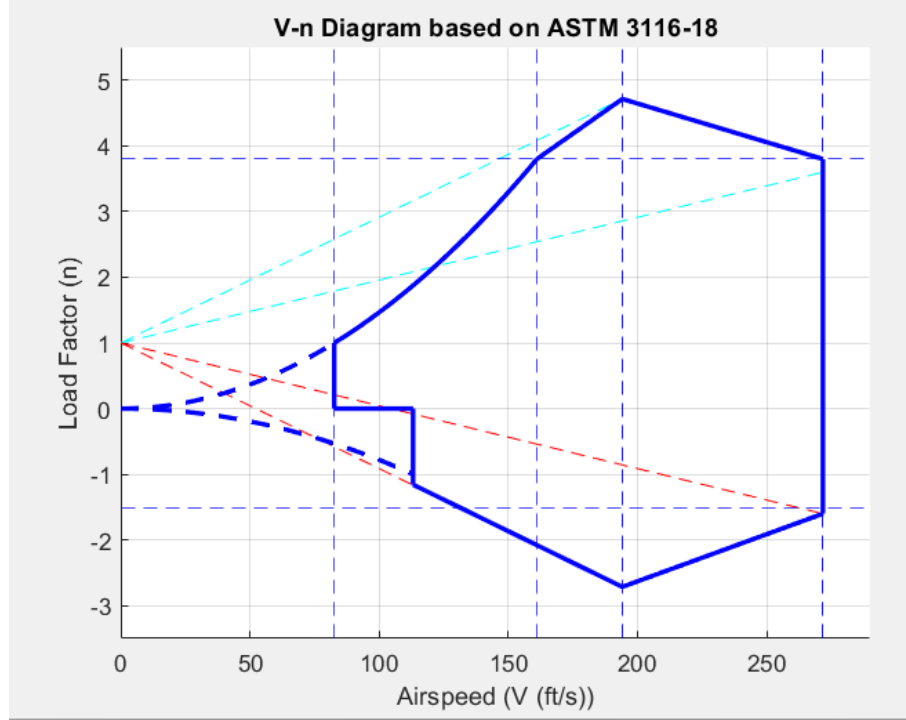


Figure 4.5: V-n Diagram - Final Envelope.

In the final V-n diagram shown in Figure 4.5, the most critical points are found at the boundaries of the envelope where the load factors reach their maximum and minimum values, and the value of 3.8, which is the maximum positive load factor for V_D , is a significant point of interest, as this load factor represents the highest stress condition the UAV structure will encounter during positive maneuvers, such as sharp turns or pull-ups at high speeds. This point is critical because it defines the upper limit of the UAV's structural capability under maneuvering conditions, and is where the structure experiences the greatest aerodynamic forces, and ensuring it can withstand this load without failure is crucial for maintaining airworthiness and safety of the overall structure.

For the structural analysis and optimization of the cargo compartment, it is essential to select the most critical load factor that the structure will be subjected to, and based on the V-n diagram, the maximum positive load factor of 3.8 should be chosen as the critical load factor for several reasons: being the maximum stress condition at the stall speeds, this load factor of 3.8 represents the highest aerodynamic stress that the structure will encounter during flight, and it is also a conservative approach, as by selecting the maximum load factor, we ensure that the design is robust and can handle unexpected conditions or variations in material properties and load distributions, as well as providing a safety margin, ensuring that the whole structure of the UAV remains within safe operational limits under all possible flight conditions.

It is important to note that the landing load factors were not selected for the critical load condition because they are typically lower than the maneuvering load factors as, during landing, the UAV operates at lower speeds and experiences reduced aerodynamic forces compared to in-flight maneuvers [95].

4.2. Loads

Although landing loads are significant, they do not reach the extreme values seen during high-speed maneuvers or gust encounters, and with the aim of being conservative, the value of 3.8 was chosen, ensuring that the structure is evaluated under the most demanding conditions, providing confidence in its ability to perform safely and reliably throughout its operational life.

4.2.2 Final Load Calculation

Having obtained all the necessary elements, it is now possible to calculate the total load that will act on the cargo compartment structure, always ensuring that all critical factors, including the maximum payload, margin of safety, and the most critical load factor, are considered. Therefore, the total load acting on the structure can be expressed with the following equation:

$$F_{total} = \text{Weight (kg)} \times \text{MS (-)} \times \text{Load factor (-)} \times g \text{ (m/s}^2\text{)} \quad (4.19)$$

Where:

- **Weight** represents the maximum payload of the cargo compartment in kilograms.
- **MS** is the margin of safety applied to account for uncertainties and conservative purposes.
- **Load factor** is the critical load factor determined from the V-n diagram, representing the highest aerodynamic force condition.
- **g** is the acceleration due to gravity, which is 9.81 m/s^2 .

$$F_{total} = 100 \text{ (kg)} \times 1.5 \text{ (-)} \times 3.8 \text{ (-)} \times 9.81 \text{ (m/s}^2\text{)} = 5592\text{N} \quad (4.20)$$

Now that the total load acting on the structure is determined, it is essential to define how this load will be applied to the model to achieve the most realistic characterization of the real structure, as accurately simulating the load application is crucial to ensure that the analysis reflects the true behavior and performance of the cargo compartment under operational conditions. Since the exact method of connecting the payload to the top of the cargo compartment has not yet been defined in the overall UAV project, several options for modeling the load application can be considered, and the two primary approaches are:

- **Applying a Pressure Load:** This method involves distributing the load uniformly over the top surface of the compartment or over a smaller, defined region, simulating a scenario where the payload exerts an evenly distributed pressure on the structure. In Figure 4.6 it is possible to see an example of a pressure load acting on the total surface of the top of the cargo compartment in the initial model. Note that the value of the pressure to apply is obtained through Equation 4.21.

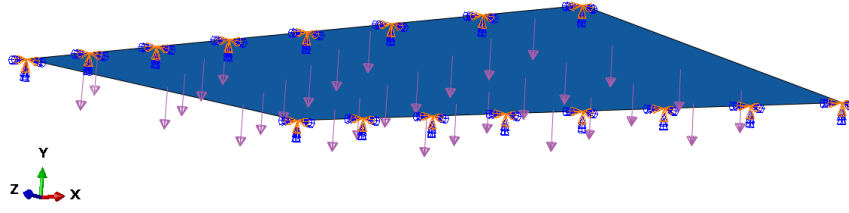


Figure 4.6: Pressure Load acting on the initial model.

$$\text{Pressure} = \frac{F_{total}}{\text{Area}} \quad (4.21)$$

Where F_{total} is the total force, in N, obtained this subsection, and the Area is the total area of application of said load, in mm^2 , therefore obtaining a pressure in MPa, as desired.

- **Applying the Load as a Concentrated Force:** This method involves applying the load at specific points, simulating a more localized interaction between the payload and the structure, and this could represent the payload being supported by a few distinct points of contact, such as cables with hooks or even structural supports.

Initial simulation results indicated that applying a constant pressure load to the model did not accurately represent the real structural interaction, as the structure remained significantly distant from failure, suggesting that the applied load distribution was not reflective of how the actual payload would be connected to the compartment, and this discrepancy highlighted the need for a more realistic load application method. Consequently, it was decided that the most realistic approach to simulate the real structure was to apply the load through four concentrated forces, as illustrated in Figure 4.7. This configuration simulates scenarios such as the payload being supported by four cables with hooks or four supports located at specific points on the top of the compartment, and by applying the load in this manner, the model more accurately reflects the potential points of stress concentration and structural behavior under the actual loading conditions expected during operation.

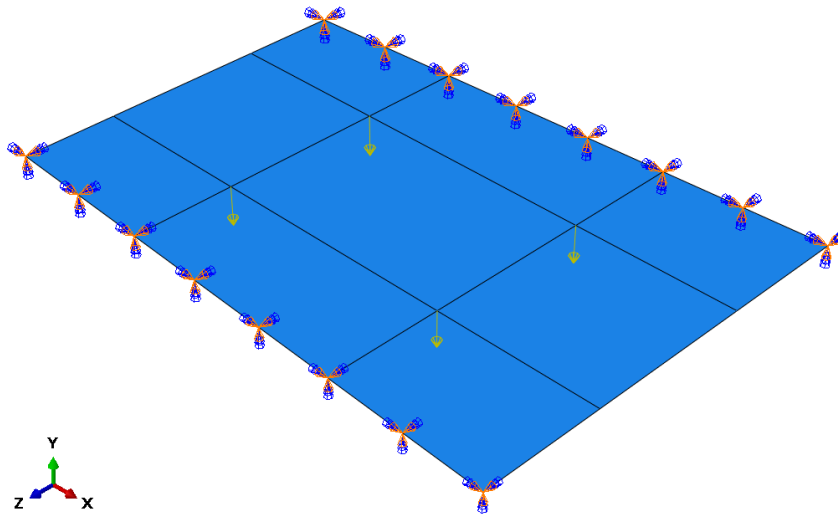


Figure 4.7: Concentrated Forces acting on the initial model.

4.3. Materials

Note that, for all of the geometries, to be consistent with the analysis, the four loads were applied in the same region, as one can see in the sketch in Figure 4.8, as the concentrated forces are represented by the red dots, and the total load already determined was divided by these four points, obtaining a value of 1398 N for each one of these, as stated in Equation 4.22.

$$F_{1_{point}} = \frac{F_{total}}{4} = 1398N \quad (4.22)$$

Compared to the pressure load, the application of the load on these four points creates significant stress concentrations in these regions, and these are areas where the structure experiences higher levels of stress and deflections, which could potentially lead to failure if not properly managed. To address this, it is essential to introduce reinforcements in these regions, to ensure that the localized loads are adequately supported, distributing the stress more effectively throughout the structure, and reinforcements might include adding additional material, creating sandwich structures, or incorporating structural elements designed to dissipate the load more evenly, like stringers.

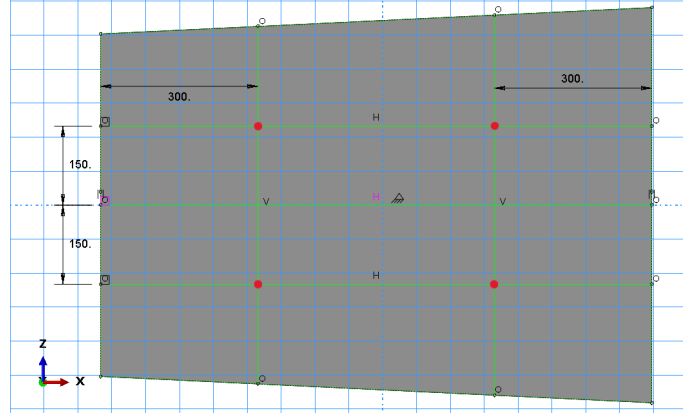


Figure 4.8: Location of the concentrated forces acting on the initial model.

4.3 Materials

The materials selected for this analysis are already used by Tekever in their other projects, and to ensure consistency with the company's established practices and manufacturing processes, given the proven performance of these materials in similar applications, they will also be selected for this project. Therefore, the primary materials to be utilized in the structural analysis of the UAV cargo compartment are a carbon unidirectional (UD) composite and AIREX 7075 foam. In the next subsections, the properties of each material will be detailed, in order to introduce them into the FEM software.

4.3.1 Carbon Unidirectional (UD) Composite

The carbon UD composite will be primarily assigned to the composite layups, and this material is known for its high strength-to-weight ratio, excellent stiffness, and superior fatigue resistance, and these properties make it ideal for aerospace applications, where both structural performance and weight efficiency are critical. The unidirectional fibers in the carbon UD composite provide maximum strength along the direction of the fibers, allowing for tailored mechanical properties in specific load-bearing directions. This material will form the main structural element of the composite layups in the analysis [96].

Chapter 4. Structural Analysis of the Cargo Compartment

In Table 4.1 it is possible to see all of the relevant properties of this material.

Table 4.1: Properties of the Carbon Unidirectional Composite [14].

Property	Value
Grammage	<i>Classified</i>
E_1 (Young's Modulus in fiber direction)	<i>Classified</i>
E_2 (Young's Modulus perpendicular to fiber direction)	<i>Classified</i>
G_{12} (Shear Modulus)	<i>Classified</i>
ν_{12} (Poisson's Ratio)	<i>Classified</i>
X_t (Tensile Strength in fiber direction)	<i>Classified</i>
X_c (Compressive Strength in fiber direction)	<i>Classified</i>
Y_t (Tensile Strength perpendicular to fiber direction)	<i>Classified</i>
Y_c (Compressive Strength perpendicular to fiber direction)	<i>Classified</i>
S (Shear Strength)	<i>Classified</i>
ρ (Density)	<i>Classified</i>
Thickness of each Ply	<i>Classified</i>

4.3.2 Airex 7075 Foam

AIREX 7075 foam is a high-performance core material that might be implemented when working with sandwich composite structures, that are often used in aerospace applications to achieve high stiffness and strength while maintaining low weight. This material provides excellent shear strength and stiffness, thermal insulation, and resistance to moisture and chemicals, and these properties make it an ideal candidate for the core material in sandwich composites, where it can enhance the overall structural performance without significantly increasing weight. This way, its properties are stated in the table below:

Table 4.2: Properties of the Airex 7075 foam [97].

Property	Unit	Value
Density	tonne/mm ³	8×10^{-8}
Compressive Strength Perpendicular	MPa	1.45 (Minimum: 1.10)
Compressive Modulus Perpendicular	MPa	104 (Minimum: 80)
Tensile Strength in Plane	MPa	2.0 (Minimum: 1.6)
Tensile Modulus in Plane	MPa	66 (Minimum: 50)
Shear Strength	MPa	1.2 (Minimum: 1.0)
Shear Modulus	MPa	30 (Minimum: 24)
Shear Elongation at Break	%	18 (Minimum: 10)
Thermal Conductivity at Room Temperature	W/m·K	0.033
Standard Sheet Dimensions	mm	Width: 1020, Length: 2180, Thickness: 3 to 68
Color		Green

4.4 Structural Analysis

A systematic approach will be employed to conduct the structural analysis of the cargo compartment, and this process will begin with an initial model, representing a flat composite panel as the top of the compartment, and the primary objective is to optimize the structure to achieve the best geometry and material combination, ensuring optimal load distribution, minimal deflections, and favorable results concerning Hashin's failure criteria.

Therefore, the analysis will be performed through several iterative steps as, starting with the baseline model, detailed finite element analysis (FEA) will be performed in ABAQUS software to assess the structural performance under the defined loads and boundary conditions, and key parameters such as stress distribution, deflection, and failure indices will be evaluated. Based on these results, specific modifications will be implemented to improve the model's performance, such as adjusting the thickness of the panel, introducing reinforcements or stringers in critical points, or even creating different structures such as a sandwich composite structure.

This way, and given the initial geometry of the structure with the dimensions seen in Figure 4.9, we can start to model and analyze the structure.

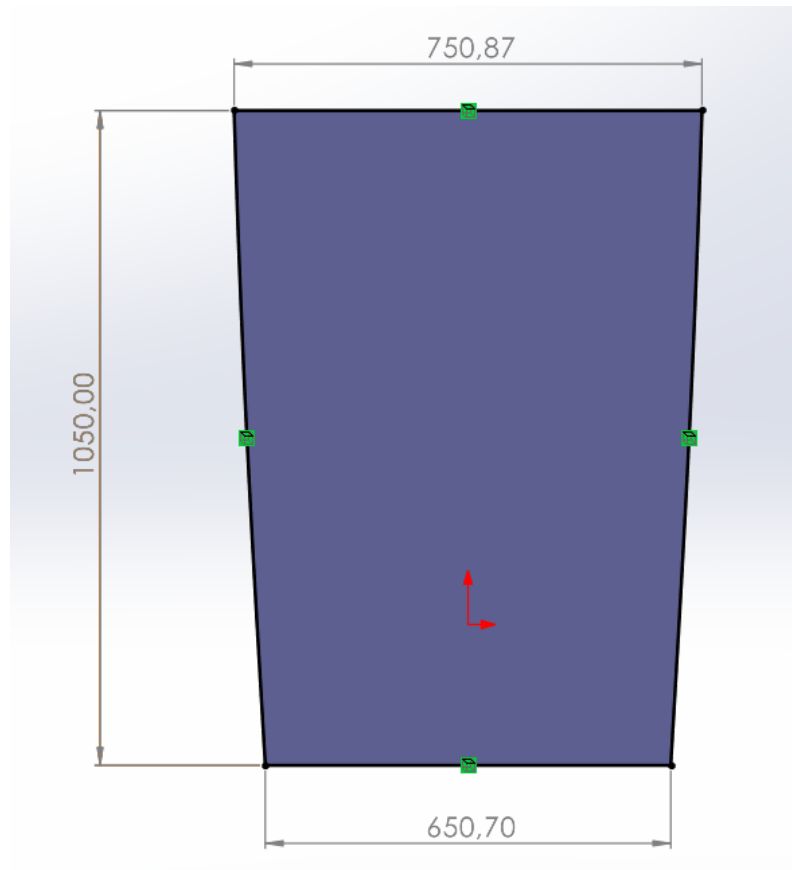


Figure 4.9: Initial geometry of the top of the cargo compartment.

4.4.1 Flat Carbon UD Panel

The initial model consists of a flat composite panel representing the top of the cargo compartment and, using the material from 4.3.1, a symmetric composite layup was created, as depicted in Figure 4.10. This way, since the layup consists of 8 plies, each with a thickness of 0.25 mm, a total thickness of 2 mm is obtained.

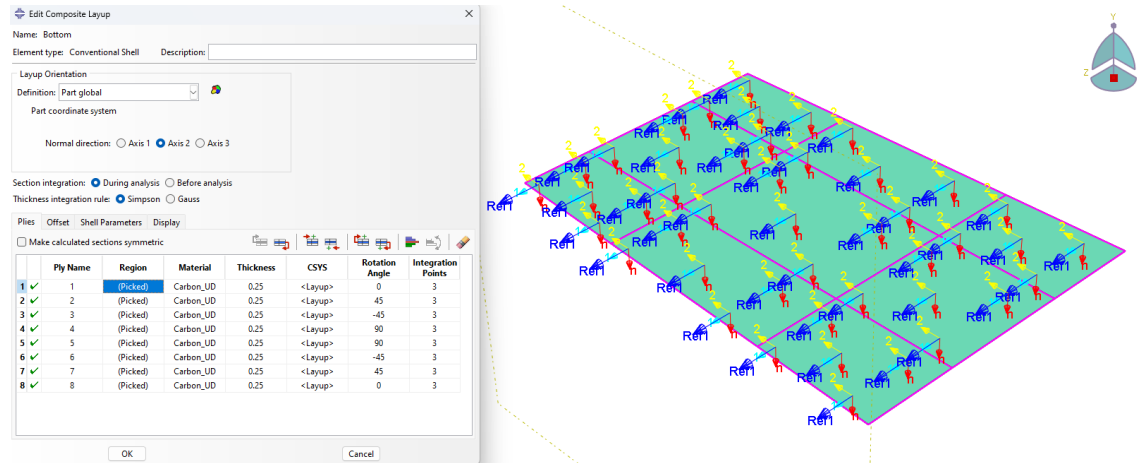


Figure 4.10: Symmetric composite layup.

Regarding loads and boundary conditions, the same approach from Figure 4.7 was implemented, and a structured mesh consisting of 15582 elements was created for the finite element analysis. Having submitted the model to the finite element software, it is now possible to analyze the results.

• Deflection Analysis

The global results of the deflection of the whole structure are displayed in Figure 4.11. Therefore, the maximum deflection observed is approximately 135.2 mm, located near the center of the panel where the concentrated loads are applied, indicating that the panel exhibits significant bending in the regions between the applied forces, while the edges remain fixed due to the boundary conditions. This deflection pattern suggests that the load is effectively transferring to the fixed edges, but the central region of the panel experiences the highest deformation due to the localized application of the concentrated forces, and the minimal deflection occurs at the fixed edges, as expected because these edges are restrained from any movement.

4.4. Structural Analysis

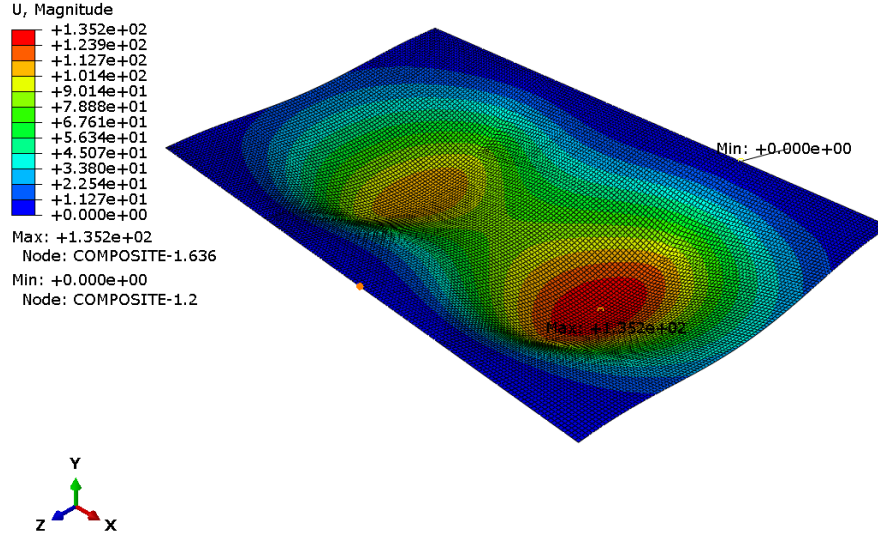


Figure 4.11: Global deflection of the structure.

Since the top of the compartment is a fixed structure, it is crucial that it maintains its shape and does not undergo substantial changes in volume mid-flight, even under extreme conditions, so even if the composite material was not expected to fail according to certain criteria (Hashin's damage initiation criteria), deflections as large as 135.2 mm (13.52 cm) are unacceptable, as they could compromise the structural integrity and operational efficiency of the UAV, leading to potential issues during flight.

- **Stress Analysis**

As one can observe in Figure 4.12, the maximum S11 stress is 1366 MPa, occurring near the points where the concentrated forces are applied and near the applied boundary conditions in the transversal direction aligned with the application of the concentrated forces. The stress contours reveal high-stress concentrations around these points, while the stresses are relatively lower and more uniformly distributed in other regions of the panel, and this difference is due to the localized nature of the applied zones.

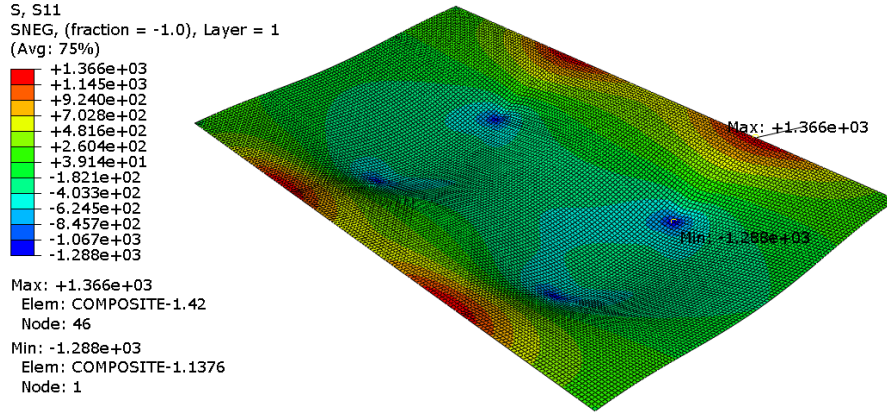


Figure 4.12: Global stress distribution of the structure.

• Hashin's Failure Criteria Analysis

Regarding compressive fiber failure, we can see that the maximum value observed is approximately 1.157, indicating potential failure at the locations of the applied forces, as this value exceeds the failure threshold of 1, suggesting that the fibers are likely to fail at these points, whereas for tensile fiber failure, the maximum observed value is approximately 0.830 in the edge of the applied boundary conditions, indicating that there is also a significant risk of tensile fiber failure in the analyzed regions.

On the other hand, when evaluating the matrix failure, it is visible that the obtained values for both tensile and compressive regions are less than 1, indicating that there is no significant risk of failure of the composite. In concordance with the fiber compressive analysis, the matrix compressive criterion also displays critical values in the concentrated points where the load is applied, showing elevated but non-critical values, and for the matrix tensile initiation criteria, slightly different results are obtained, as the critical values are obtained in between the applied loads, as this is a region where the material is being "pulled" both ways, it is natural that the matrix is more likely to fail in this region. In Figure A.1 we can see the results for Hashin's Fiber compressive damage initiation failure criteria, and the results for Hashin's failure criteria for all of the four failure modes are shown in the Appendix A, and important conclusions are taken from this analysis.

4.4. Structural Analysis

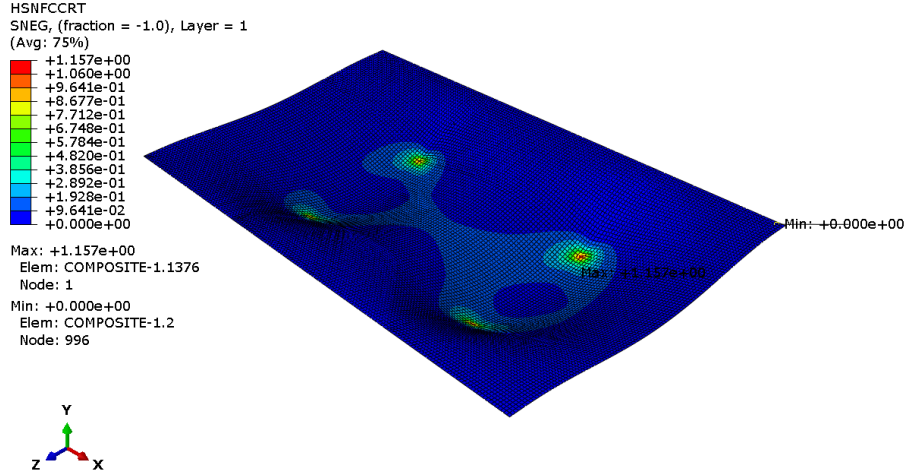


Figure 4.13: Fiber compressive initiation criterion.

• Global Failure Analysis

From the stress and Hashin's failure criteria results, it is evident that the regions near the concentrated forces are critical points for potential failure, as well as the regions next to the edge where boundary conditions are applied and the concentrated forces are also near. The compressive fiber failure criteria have exceeded the threshold, indicating a high risk of failure in these areas, and the matrix tensile failure criteria is approaching the limit value of 1, suggesting some risk in those regions as well. The remaining criteria are within acceptable limits, indicating that the overall structure is relatively safe except for the critical points, but the deflection values are much higher than expected, therefore changes in the structure are needed. In Table 4.3, the critical values and important regions of the structure are summarized, in order to have an organized perspective of the whole analysis.

Table 4.3: Summary of the obtained critical values for analysis 1.

Maximum Stress [MPa]	Maximum Deflection [mm]	Fiber Compressive [-]	Fiber Tensile [-]	Matrix Compressive [-]	Matrix Tensile [-]
1366	132.2	1.157	0.830	0.625	0.350

4.4.2 Flat Sandwich Panel

From the obtained results of the first analysis, it was obvious that a simple composite panel would not be enough to withstand the payload, as the global deflections observed were unacceptable, reaching up to 135.2 mm, which is not permissible for a fixed structure that must maintain its shape even under extreme conditions. Additionally, the values of stress were significantly higher than expected, and the obtained failure index for tensile fiber failure exceeded the threshold, indicating a high risk of material failure in those regions.

These results clearly indicated the need for a more robust structural solution, and to address this issue, a sandwich panel composite was modeled to improve the global structure's ability to withstand the load. This design incorporates the same carbon UD composite material used in the initial model but with an additional layer of Airex 7075 foam sandwiched between two layers of carbon UD. The foam core is intended to improve the material's behavior by enhancing its stiffness

and reducing deflections, without adding excessive weight to the structure, and the sandwich configuration is expected to distribute the stresses more evenly and provide better overall performance under the applied loads. In Figure 4.14 it is possible to see the carbon composite structures in light blue (top and bottom), and the foam in the middle in orange.

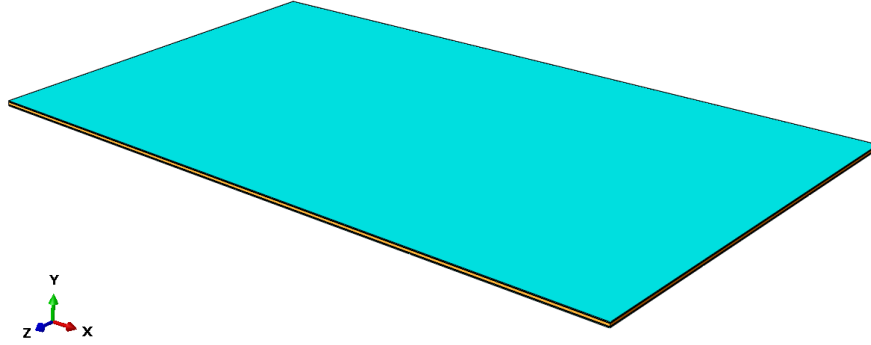


Figure 4.14: Different parts of the sandwich structure.

In order to accurately simulate the interaction between the different materials in the sandwich panel, it is essential to establish realistic connections that replicate the actual behavior of these components under load, and to achieve this, tie constraints were applied between each of the surfaces. Specifically, the top surface of the solid Airex 7075 foam was tied to the bottom surface of the top carbon UD shell, and the bottom surface of the foam was tied to the top surface of the bottom carbon UD shell, obtaining the structure in Figure 4.15, using a surface to surface discretization method. Note that, by connecting these different sections using tie constraints, a simplification is made, as the failure of the adhesive is not being considered, however, that is not the focus of this analysis.

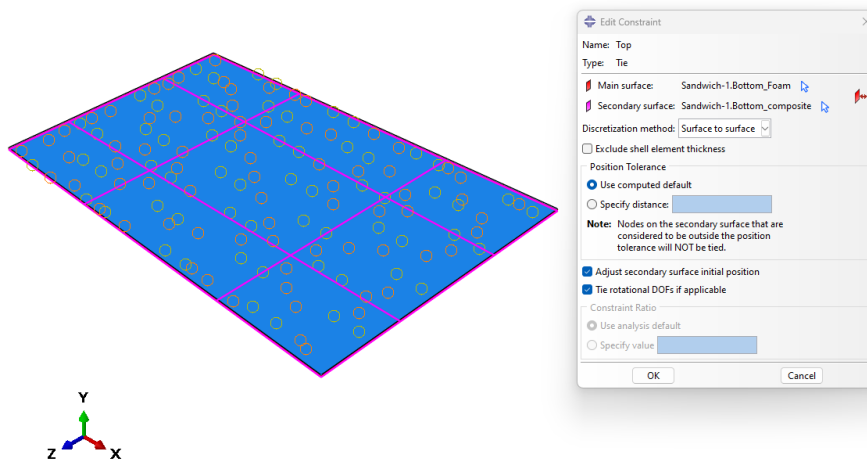


Figure 4.15: Tie constraints used to connect the different parts of the structure.

The application of tie constraints ensures that the surfaces remain perfectly bonded throughout the analysis, meaning there is no relative motion between the connected surfaces, effectively simulating a continuous bond between the layers, and ensuring that the load is transferred efficiently from one material to another. The top and bottom composite layers will act in unison with the

4.4. Structural Analysis

foam core, distributing the applied loads across the entire structure and preventing any potential delamination or separation between the layers.

For the loads and boundary conditions, the same approach from 4.4.1 was implemented, and a structured mesh consisting of 25777 elements was created for the finite element analysis, having obtained the following results:

- **Deflection Analysis**

Figure 4.16 shows the global deflection of the flat sandwich panel under the same loading conditions and boundary constraints as the initial simple composite panel and the maximum deflection observed in this model is approximately 32.41 mm, which is a significant reduction compared to the 135.2 mm deflection seen in the first model analysis. This substantial decrease in deflection indicates that the sandwich panel configuration has improved the structural stiffness of the structure, as the incorporation of the Airex 7075 foam core between the two layers of carbon UD composite has effectively increased the overall thickness and moment of inertia of the panel, resulting in enhanced resistance to bending and deflection.

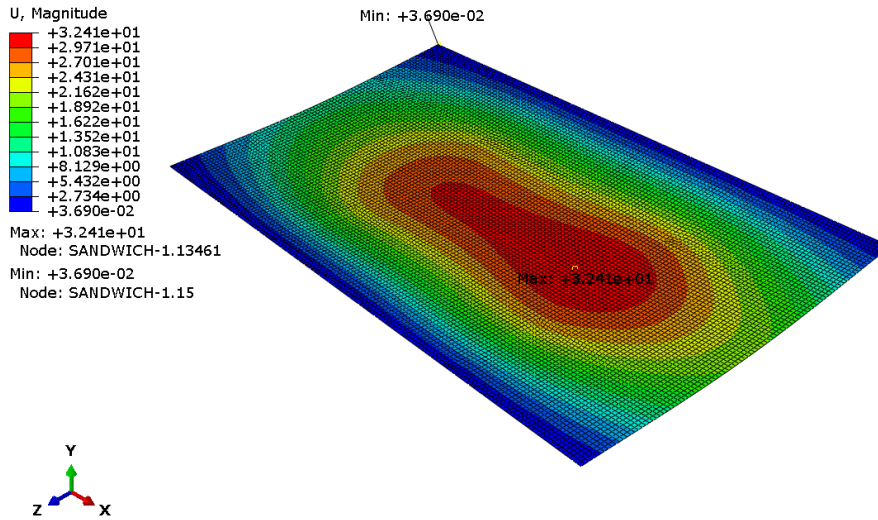


Figure 4.16: Global deflection of the structure.

The maximum deflection of 32.41 mm is located at the center of the panel, which is the region directly between the applied concentrated loads, and this area is where the panel experiences the highest bending moment, naturally leading to the greatest deflection, and it is relevant to note that higher deflections are found closer to the region where the transverse distance between the fixed edges is higher, where a bigger area is located. On the other hand, the minimum deflection is found at the fixed edges of the panel, consistent with the encastre boundary conditions that prevent any movement at these locations.

Although the sandwich panel's maximum deflection is reduced by approximately 76% compared to the simpler composite panel, there is still a lot of room for improvement, as excessive deflection can lead to misalignment and potential failure during operation, as well as reducing the risk of fatigue and damage over time, therefore extending the service life of the structure

• Stress Analysis

In Figure 4.17 the S11 stress distribution in the carbon composite layers of the sandwich panels is illustrated, and the maximum value observed is approximately 579 MPa located, as expected, near the points of the applied concentrated forces, as these regions experience the most significant load transfer to the whole panel.

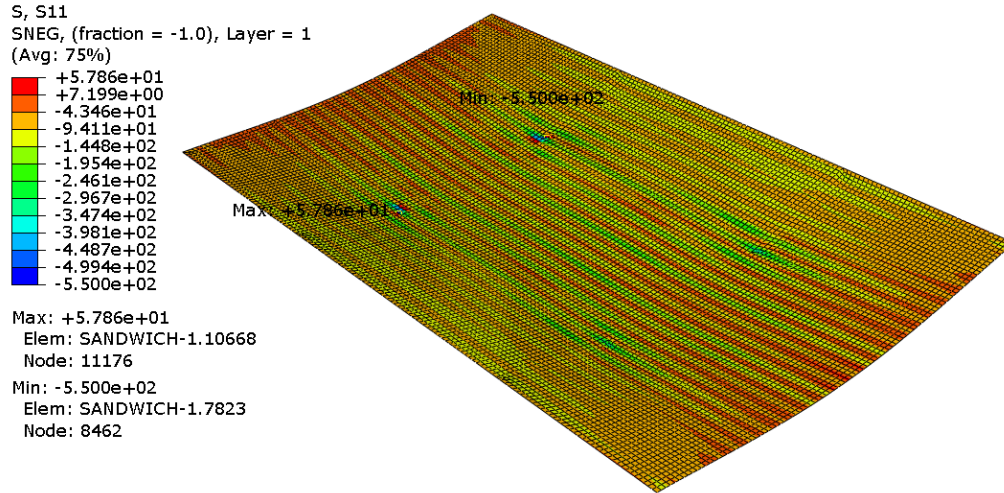


Figure 4.17: Stress distribution of the two carbon components.

The stress distribution in these components reveals that the stresses decrease progressively from the points of force application toward the edges, indicating that the sandwich structure is effectively distributing the applied loads across the panel, as the presence of the foam core helps in spreading the stresses more uniformly compared to a single composite layer, reducing the peak stress values significantly. In fact, compared to the first analysis of the simple composite panel, where the maximum stress was significantly higher, the sandwich panel shows a marked reduction in stress concentrations, indicating an improved load distribution and enhanced structural performance.

The maximum S11 obtained stress should be compared with the material properties of the carbon composite, and given that the tensile strength of the carbon UD composite (X_t) is 1500 MPa, the maximum observed stress is well within the material's capacity, ensuring that the composite layer will not fail under the applied loads.

Regarding the foam core stresses, important analysis must also take place. As seen in Figure 4.18, the maximum von Mises stress in this component is approximately 1.658 MPa, and this value is observed in regions that are not directly under the applied loads but rather in areas adjacent to the load application points, indicating that the loads are being transferred through the foam core, causing stress concentrations at these particular locations. On the other hand, the low-stress regions are found toward the free edges and in the center of the panel itself, indicating a correct load transfer between the foam and the carbon composite layers, and that there are certain high-stress areas due to the structural interactions between these components-

4.4. Structural Analysis

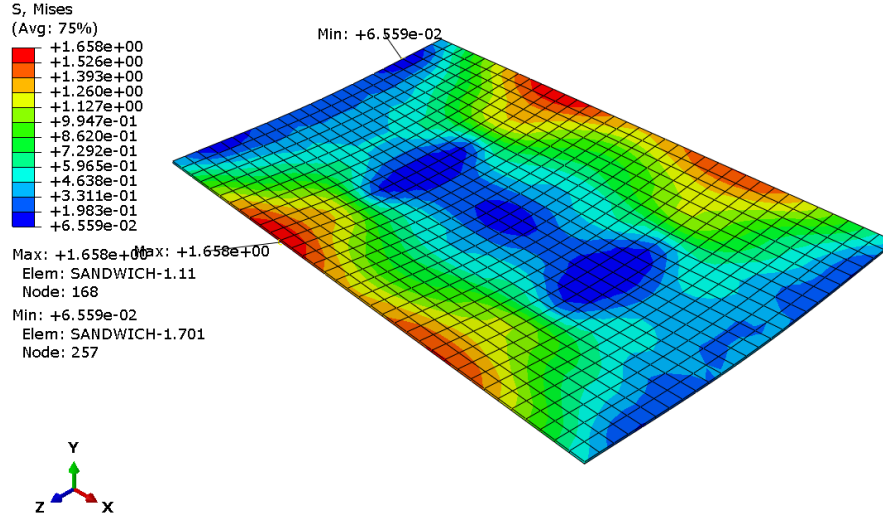


Figure 4.18: Stress distribution of the foam core of the structure.

Comparing the obtained results with the material's properties in Table 4.2, we see that the compressive strength of Airex 7075 foam is 1.45 MPa, and the maximum stress observed in the foam core is 1.658 MPa, which exceeds the compressive strength of the foam, indicating that the foam core is likely to fail under the applied load conditions, as the stress values surpass the material's compressive capacity. This way, this suggests a risk of failure in the regions of high stress, and this failure could compromise the overall structural integrity of the sandwich panel. Also, given that the foam core is a critical component for distributing loads and enhancing the stiffness of the overall structure, its failure could lead to significant issues, including increased deflections and potential damage to the composite layers.

To mitigate this issue, the design of the model must be adjusted, and potential solutions may include the increase of the thickness of the foam core to distribute the loads more efficiently, or adding additional reinforcements to the regions of high stress to reduce stress concentrations.

- **Hashin's Failure Criteria Analysis**

Figure A.2 shows the obtained results for the composite layers regarding Hashin's Matrix Tensile damage initiation failure criteria. Regarding the fiber compressive failure index, the highest value is approximately 0.110, located around the regions close to the applied loads, and although this region is very concentrated, this low value indicates that the composite fibers are not at risk of compressive failure under the current loading conditions. The values of both fiber tensile and matrix compressive criterion are very close to zero, indicating that neither the fiber is being tested under tension nor the matrix is under critical compressive loadings, so there is no relevance in evaluating where the maximum values are, as they are very small. Regarding the matrix tensile initiation criterion, similar results to the fiber compressive initiation criterion are found, with a value of 0.286.

The uniform distribution of these low failure indices across the panel suggests effective load distribution and structural integrity, as the sandwich panel design, incorporating Airex 7075 foam and carbon UD composite layers, is performing well under the applied loads, ensuring both safety and reliability for the UAV's cargo compartment under this failure criteria.

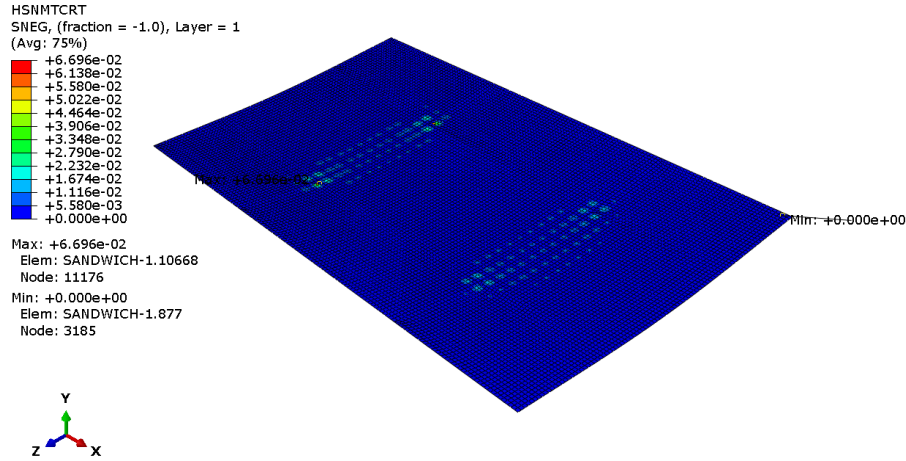


Figure 4.19: Matrix tensile initiation criterion.

• Global Failure Analysis

Although Hashin's failure criterion values are well below the threshold values, indicating that the composite layers are not at immediate risk of failure, there are several concerning aspects that must be taken into account to ensure the structural integrity and performance of the UAV cargo compartment. First, while the deflection was significantly reduced compared to the initial simple composite panel, where it reached 135.2 mm, the observed deflection in the sandwich panel is still 32.41 mm, and this level of displacement, although improved, remains considerable and may not be acceptable for the structural requirements of the UAV cargo compartment, as excessive deflection could lead to issues with the alignment and function of the cargo compartment, potentially affecting the performance and overall stability of the UAV.

The stress analysis of the composite layers showed a substantial reduction in global stress levels, as the maximum S11 stress observed in the composite layers was 579 MPa, which is well within the tensile strength limit of the carbon UD composite, indicating that the composite layers are effectively distributing the applied loads without reaching critical stress levels that could lead to failure. Hashin's criteria for fiber tensile, fiber compressive, matrix tensile, and matrix compressive failure modes were all significantly below the critical values, further confirming the structural soundness of the composite layers under the given loading conditions. However, the stress analysis of the foam core revealed critical issues, as the maximum von Mises stress observed in the Airex 7075 foam core was 1.658 MPa, which exceeds the compressive strength of the foam (1.45 MPa), and this indicates that the foam core is expected to fail under the applied load conditions, an unacceptable condition, as the failure of the foam core would compromise the overall structural integrity of the sandwich panel, leading to increased deflections and potential damage to the composite layers. This failure could also result in a loss of load-bearing capacity and structural stiffness, thereby affecting the UAV's performance and safety.

To address these issues and enhance the performance of the sandwich panel, several improvements and alterations can be considered for further analysis, such as increasing the foam thickness, to help distribute the loads more effectively, reducing the stress concentrations and deflections, and a thicker foam core would increase the panel's moment of inertia, thereby enhancing its stiffness and reducing overall deflection. The incorporation of reinforcements

4.4. Structural Analysis

such as stringers in the structure could also provide additional support and stiffness, as they can be strategically placed to support the regions experiencing the highest stresses, thereby reducing the overall deflection and stress levels in the foam core and composite layers. In Table 4.4, critical values of the performed analysis are shown.

Table 4.4: Summary of the obtained critical values for analysis 2.

	Maximum Stress [MPa]	Maximum Deflection [mm]	Fiber Compressive [-]	Fiber Tensile [-]	Matrix Compressive [-]	Matrix Tensile [-]
Carbon Layers	578.6	32.42	0.110	0.0267	0.001564	0.286
Foam	1.658	32.42	-	-	-	-

4.4.3 Sandwich Panel with Two Stringers

Given the challenges identified in the previous two analyses, a new structural configuration was developed to address the observed problems, as the earlier analyses showed significant issues with deflection and stress distribution, particularly within the foam core, and to mitigate these problems, a new structure was created by incorporating two transversal stringers into the sandwich panel.

The addition of transversal stringers is expected to significantly improve the structural performance by providing additional support and stiffness, as the stringers, each with a thickness of 5 mm, the same as the main foam surfaces, are strategically placed to enhance the load distribution and reduce the overall deflection of the panel. By reinforcing the panel in the transverse direction, the stringers are anticipated to reduce the stress concentrations in both the composite layers and the foam core, thus mitigating the risk of failure. Initial simulations explored the addition of longitudinal stringers along the cargo compartment, however, these simulations revealed that longitudinal stringers did not yield significant improvements in structural performance, primarily due to the applied boundary conditions, which limited the effectiveness of longitudinal reinforcements. Consequently, the focus shifted to optimizing the transversal stringer configuration, which showed greater potential for enhancing the panel's load-bearing capacity and reducing deflection. The creation of stringers with a T-section or C-section was considered, however, for the sake of simplicity regarding manufacturing methods, it was decided to design the stringers merely as additional reinforcements. This approach allows the mold to already include the shape of the stringers, making it easier to simply bond them with the foam.

Therefore, this section will focus on the analysis of the improved sandwich panel with transversal stringers, evaluating the deflection, stress distribution, and overall structural performance, and the expected outcomes include a marked reduction in deflection, improved stress distribution in the composite layers and foam core, and overall enhanced structural integrity of the UAV cargo compartment. In Figure 4.20 it is possible to see this new geometry, where the composite layers are shown in light blue and the foam is the orange part. The same tie constraints were applied in this structure, in order to have a correct interaction between the two structures, and a total structured mesh with 14498 elements was created.

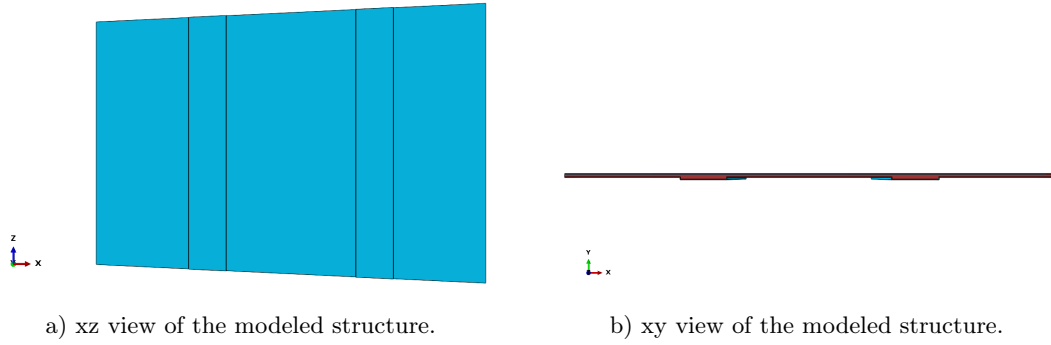


Figure 4.20: Different views of the new modeled structure.

• Deflection Analysis

The analysis of the enhanced sandwich panel with transversal stringers shows a marked improvement in structural performance compared to the previous configurations, as in this new configuration, the maximum deflection observed was 6.76 mm, a significant reduction from the 135.2 mm and 32.41 mm seen in the simple composite panel and sandwich composite panel, respectively. The deflection distribution in this structure panel is considerably more uniform across the structure, as the addition of the transversal stringers, each with a thickness of 5 mm, has provided additional stiffness and support, effectively reducing the deflection even more efficiently than the foam core alone, and these stringers act as reinforcements that improve the load distribution, ensuring that the stresses and deflections are managed more effectively throughout the panel, as seen in Figure 4.21.

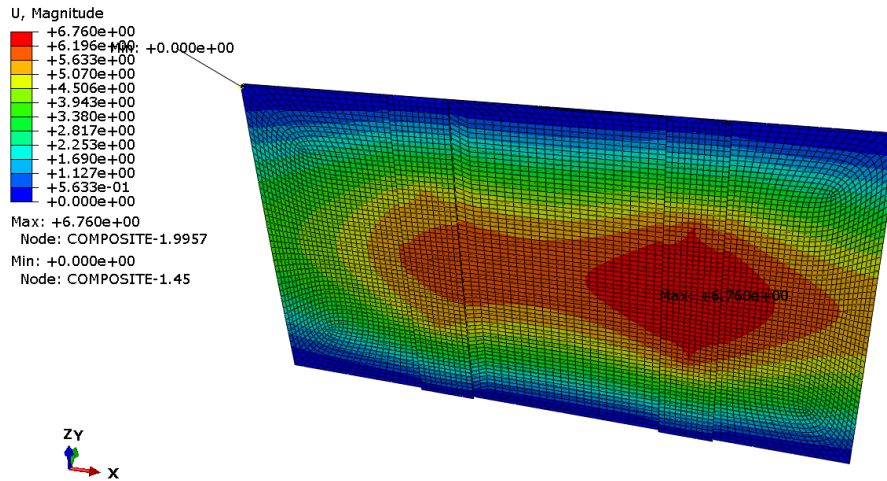


Figure 4.21: Global deflection of the structure.

The regions near the load application points showed much lower deflection values compared to the previous configurations, indicating the stringers' effectiveness in improving the structural integrity of the panel. Also, the deflection gradient is smoother, demonstrating a more even distribution of the applied loads and indicating that the structure is capable of withstanding the loads without significant deformation. Lower deflections are also beneficial in reducing the risk of fatigue failure, as high deflections can lead to increased cyclic stresses during

4.4. Structural Analysis

operation, which in turn can accelerate the fatigue process in the material. This reduction in deflection helps maintain the integrity of the material over an extended period, reducing the likelihood of crack initiation and propagation, and consequently, a structure with lower deflection not only performs better under immediate load conditions but also ensures long-term durability and reliability, which are crucial for the operational safety and maintenance of the UAV cargo compartment.



Figure 4.22: Deflection of the structure along a longitudinal path of the structure.

In Figure 4.22 a representation of the deflection along a longitudinal path of the structure is visible, all along the total distance of 1050 mm. Starting from a null deflection in the initial position, the deflection gradually rises until it reaches a relative maximum of approximately 4.5 mm, in the region of the first stringer and the first two applied loads. Then, the slope of the curve starts to decrease, indicating a less rapid increase in deflection, which means that the structure is distributing the load more effectively in this area, thanks to the added stiffness from the transversal stringers. From 400 mm to 600 mm, the deflection continues to increase but at a reduced rate, and the maximum deflection of about 5.5 mm is observed around the 800 mm mark, and this peak indicates the point of maximum displacement, which is located near the second stringer, where the panel experiences the greatest bending moment due to the applied loads. Beyond the 800 mm mark (and the second stringer), the deflection starts to decrease gradually, and this decrease continues towards the end of the path at 1050 mm, where the deflection drops back down to approximately 4.5 mm, indicating that the stringers and the boundary conditions are effectively restraining the panel and redistributing the loads towards the supports. Note that the deflection path is not symmetric due to the increase length in the transversal direction from the 0 mm position to the 1050 mm.

- **Stress Analysis**

In the composite layers of the structure with transversal stringers, the maximum S11 stress observed is approximately 396 MPa, and this value is significantly lower than the maximum stress observed in the flat sandwich composite panel, which was 578 MPa. As the tensile strength X_t of the carbon composite is 1500 MPa, it is predicted that, since the stress levels are well below this threshold, the composite layers are not expected to fail under the applied loading conditions.

This way, it is seen that the introduction of transversal stringers has effectively reduced the maximum stress in the composite layers, indicating a better load distribution and increased structural integrity. The stress is, therefore, more evenly distributed across the composite

layers, with high-stress concentrations primarily located at the intersections of the stringers and the applied load points, suggesting that the stringers are effective in mitigating the overall stress experienced by the panel, and with this lower maximum stress in the whole structure, it is implied that the composite layers are less likely to experience failure.

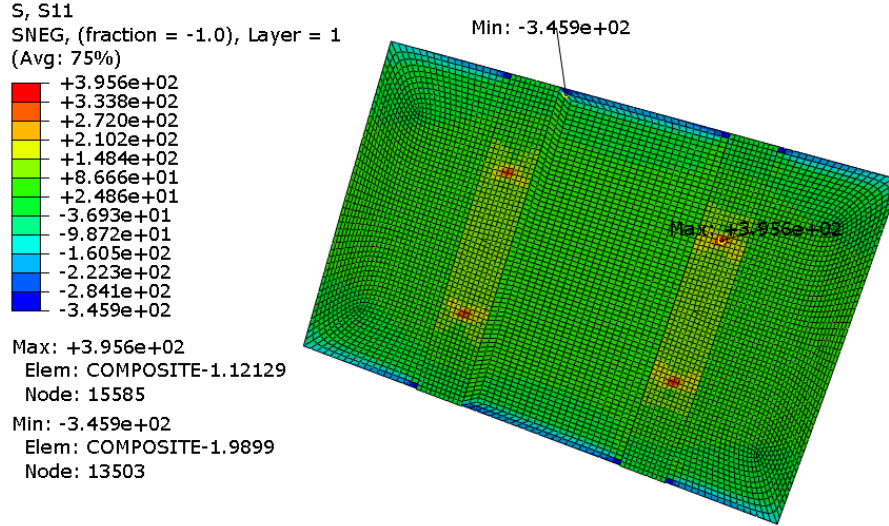


Figure 4.23: Stress distribution of the two carbon components.

Regarding the maximum stresses in the foam layer, it is seen that with the addition of the transversal stringers, the maximum Von Mises stress observed is approximately 1.379 MPa, representing a significant reduction compared to the maximum stress observed in the foam layer of the flat sandwich composite panel, which was 1.658 MPa. Since the compressive strength X_c of the Airex 7075 foam is 1.45 MPa, we see that the maximum obtained stress is below this threshold, suggesting that the foam layer will not fail under the applied loading conditions.

The introduction of the two stringers has effectively reduced the maximum stress in the foam layer to a value below the foam's compressive strength, preventing failure, and it is also seen that the stress is more evenly distributed across the foam layer, with high-stress concentrations primarily located around the intersections of the stringers and the applied load points, instead of having much more critical points near the fixed edges of the structure as seen in the last analysis (Figure 4.18).

4.4. Structural Analysis

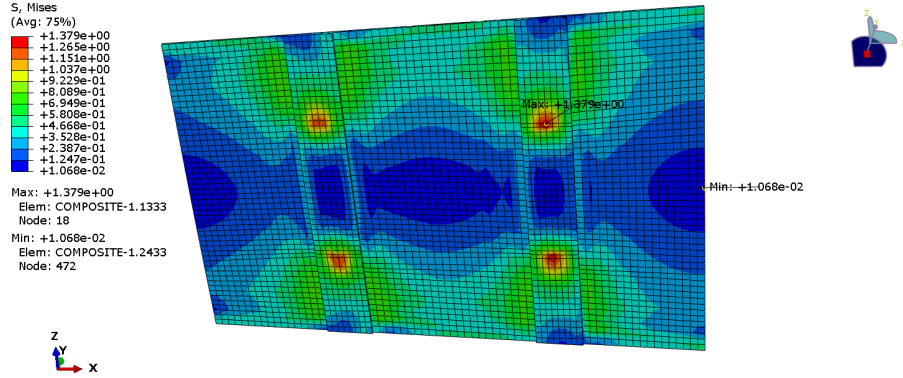


Figure 4.24: Stress distribution of the foam core of the structure.

Nonetheless, although the global stress levels are within acceptable limits, localized stress concentrations may still require additional reinforcements to further enhance structural integrity, such as adjusting the thickness of the foam layer in these critical regions to mitigate stress concentrations and improve the overall performance of the structure.

• Hashin's Failure Criteria Analysis

Having employed Hashin's criterion for the structure, it is seen that only the matrix tensile initiation criterion is worth analyzing (Figure 4.25), as the other three are all very close to zero, thus indicating that there is no expected failure. Regarding the matrix tensile failure, the maximum observed value was 0.663, and since it is still below the threshold value of one, the Hashin's criteria values confirm that the composite layers are performing well within their safe limits, with no imminent risk of failure in any of the evaluated modes.

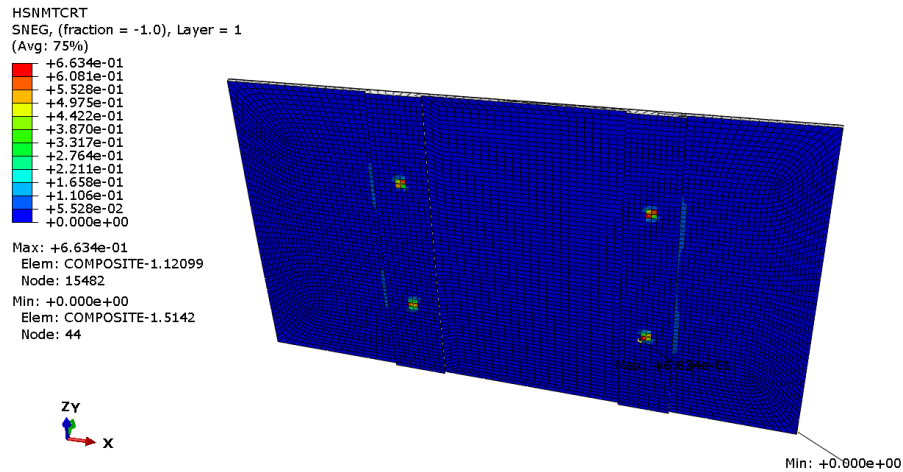


Figure 4.25: Matrix tensile initiation criterion.

• **Global Failure Analysis**

The global analysis of the results for the sandwich panel with two transversal stringers indicates a substantial improvement in structural performance compared to the previous configurations, as the addition of the stringers has markedly reduced the maximum deflection to 6.76 mm, a significant reduction from the 135.2 mm and 32.41 mm observed in the simple composite and flat sandwich panels, respectively. This reduction in deflection is crucial as it not only demonstrates increased stiffness and better load distribution but also implies a lower risk of fatigue failure, and the smoother deflection gradient across the structure confirms a more uniform load distribution, indicating that the applied loads are being managed more efficiently throughout the panel.

The stress analysis further supports the effectiveness of the stringer-reinforced design, as in the composite layers, the maximum S11 stress has been reduced to 395 MPa, well below the tensile strength of 1500 MPa for the carbon composite, and this significant reduction from the 578 MPa observed in the flat sandwich panel suggests that the composite layers are now less likely to experience failure under the applied loading conditions. Similarly, the maximum stress in the foam layer has been reduced to 1.379 MPa, below its compressive strength of 1.45 MPa, indicating that the foam core is no longer at risk of failing, further enhancing the structural integrity of the panel. In Table 4.5 the relevant results of the analysis are depicted.

Table 4.5: Summary of the obtained critical values for analysis 3.

	Maximum Stress [MPa]	Maximum Deflection [mm]	Fiber Compressive [-]	Fiber Tensile [-]	Matrix Compressive [-]	Matrix Tensile [-]
Carbon Layers	395.6	6.76	0.083	0.085	0.00508	0.663
Foam	1.379	6.75	-	-	-	-

Overall, the introduction of transversal stringers has proven to be an effective strategy in addressing the issues identified in the previous analyses, as the improved stress distribution and reduced deflection highlight the enhanced structural performance and integrity of the UAV cargo compartment. However, despite these improvements, localized stress concentrations around the stringers suggest that further refinements, such as increasing foam thickness in critical areas or adding additional reinforcements may be necessary to optimize the design fully.

4.4.4 Sandwich Panel with Two Thicker Stringers

Given the insights gained from the previous analyses, a final structural configuration was developed to further optimize the performance of the UAV cargo compartment. The earlier analysis with transversal stringers showed significant deflection and stress distribution improvements, however, localized stress concentrations around the stringers indicated that additional reinforcements could further enhance the structural integrity of the overall structure. Thus, the final configuration involves increasing the foam thickness in the stringers from 5 mm to 8 mm, aiming to provide additional strength in these critical zones where the applied loads are concentrated.

The objective of increasing the foam thickness in the stringers is to enhance the structure's ability to withstand loads in critical regions, particularly around the application points, and since the deflection values observed in the previous analysis were around 6 mm, which is considered to be within a reasonable range, there is no immediate need to add more transversal stringers. Instead, focusing on reinforcing the existing stringers is expected to reduce deflection even further

4.4. Structural Analysis

and improve the overall load-bearing capacity and durability of the structure, as the increased foam thickness is anticipated to mitigate the localized stress concentrations and distribute the loads more evenly across the panel, enhancing both the short-term performance and long-term reliability of the structure, as already depicted in the previous analysis.

• Deflection Analysis

The overall deflection distribution, as shown in Figure 4.26, indicates that the maximum deflection observed is 5.61 mm, a noticeable reduction from the 6.76 mm observed in the previous analysis with thinner stringers, demonstrating the effectiveness of increasing the foam thickness to enhance the structural stiffness and reduce deflection. The deflection distribution remains relatively uniform, but the increased stiffness of the stringers helps in managing the applied loads more efficiently.

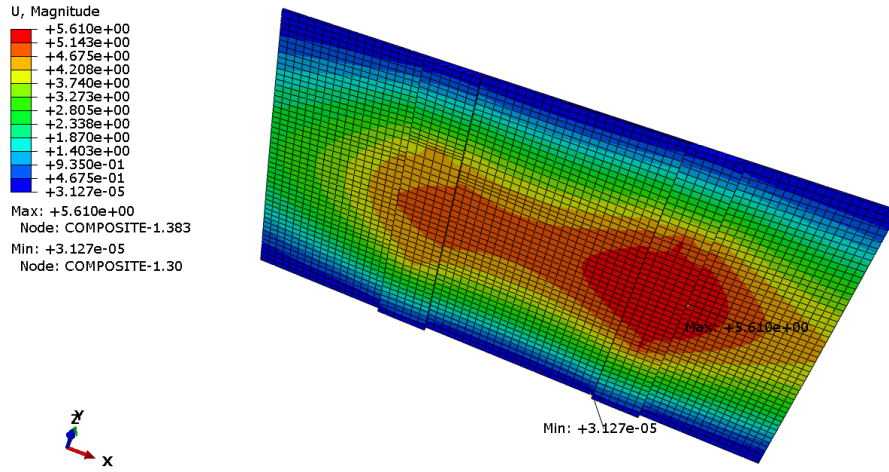


Figure 4.26: Global deflection of the structure.

In the longitudinal path analysis, as seen in Figure 4.27, the deflection gradually increases from 0 mm to a maximum of approximately 5.5 mm near the second stringer of the structure, before gradually decreasing again, and this smooth gradient suggests an effective load distribution across the length of the panel. The peak deflection near the center (this maximum deflection is moved closer to the second stringer due to the trapezoidal shape of the top compartment) indicates the region of maximum bending, which is expected in such configurations, and the smoother gradient compared to previous configurations highlights that the structure is handling the load more effectively due to the increased stiffness of the stringers.

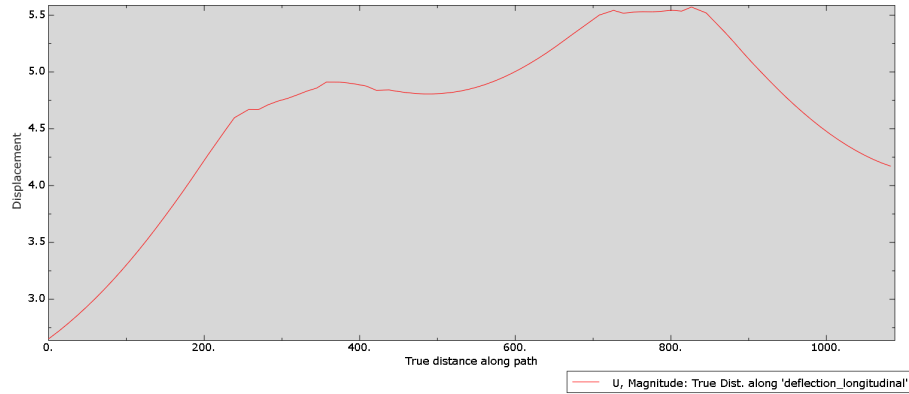


Figure 4.27: Deflection of the structure along a longitudinal path of the structure.

The transversal path analysis through the most critical stringer (Figure 4.28) shows a significant reduction in deflection and depicts how the deflection is distributed along this direction, as from the 200 mm mark to approximately the 600 mm mark, the deflection is constant, without having critical points that could lead to abnormalities in the structure, and this distribution of the deflection along the transversal path indicates an effective load transfer and improved stiffness in the critical regions of the structure.

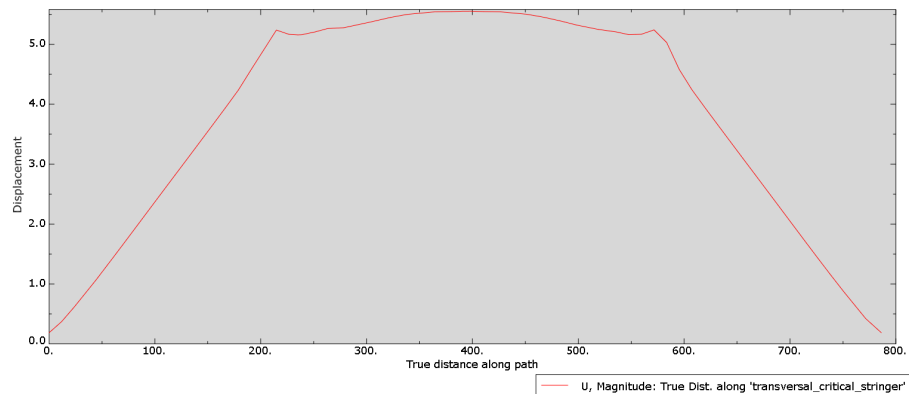


Figure 4.28: Deflection of the structure along a transversal path of the critical stringer.

• Stress Analysis

In this analysis, the stress distribution in the composite layers shows significant improvements compared to the previous configurations, as the maximum S11 stress observed is 331.9 MPa, a substantial reduction from the 395 MPa observed in the previous configuration with thinner stringers and the 578 MPa seen in the initial flat sandwich composite panel.

The stress concentrations are primarily located around the intersections of the stringers and the applied load points, as well as near the boundaries where loads are transferred, and these high-stress regions indicate that the stringers are effectively redistributing the loads and reducing the overall stress experienced by the composite layers. The areas away from these intersections exhibit significantly lower stress levels, demonstrating a more uniform stress distribution across the panel. The introduction of increased foam thickness in the stringers has further enhanced the structural performance by providing additional stiffness and support in critical regions, as this modification has led to a notable reduction in stress concentrations,

4.4. Structural Analysis

thereby mitigating the risk of failure, and the overall stress distribution indicates that the structure can now handle the applied loads more efficiently, with reduced peak stresses and improved load distribution.

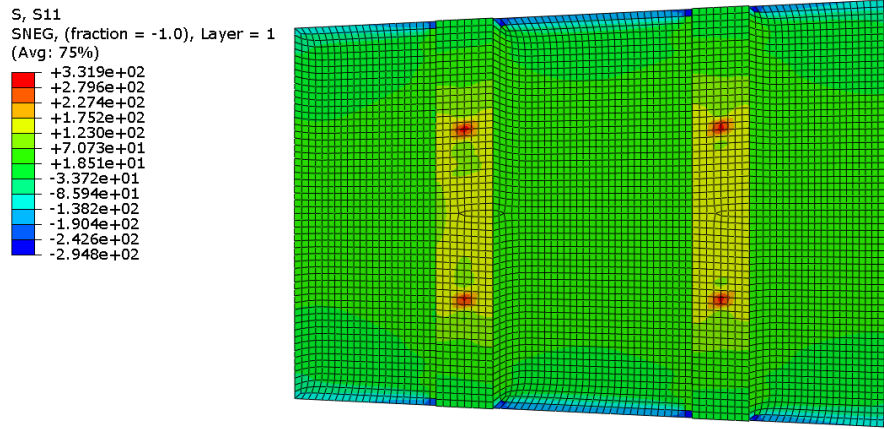


Figure 4.29: Stress distribution of the bottom carbon UD layer.

In the analysis of the foam core structure with increased thickness in the stringer regions (Figure 4.30), the stress distribution shows a notable improvement in the overall performance of the panel, and as the foam core is correctly connected to the composite layers, it ensures proper load transfer and interaction between the different materials. The maximum Von Mises stress observed in the foam core is approximately 1.134 MPa, which is below the compressive strength threshold of 1.45 MPa for the Airex 7075 foam, indicating that the foam layer will not fail under the applied loading conditions.

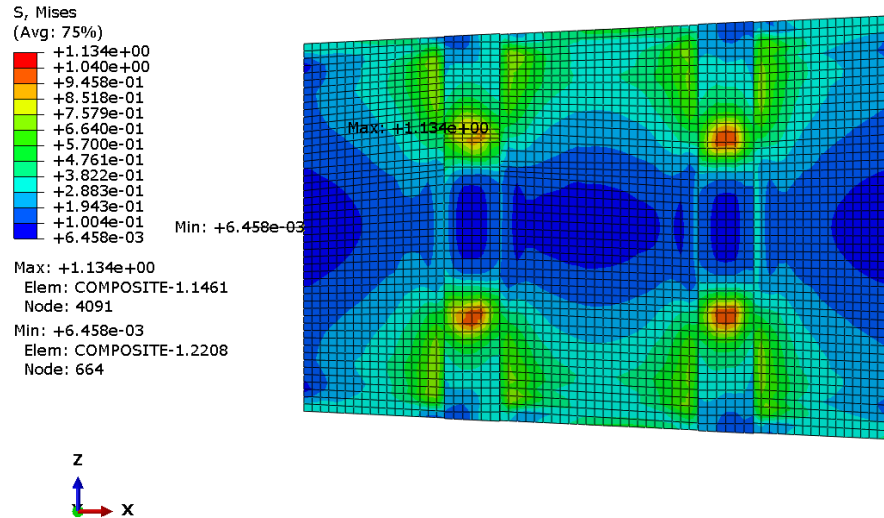


Figure 4.30: Stress distribution of the foam core of the structure.

The stress distribution in the foam is well-managed, with high-stress concentrations primarily located in the regions where the loads are applied, but these concentrations are expected due to the localized nature of the applied forces. However, the increased thickness of the foam in the stringer regions has effectively reduced these stress concentrations compared to the previous configurations, and this strategic reinforcement ensures that the stresses are more evenly distributed across the foam core, thus enhancing the structural integrity of the panel. Despite the presence of stress concentrations, the foam core maintains a safe stress level throughout the structure, and the addition of thickness in the stringer regions acts as a buffer, distributing the loads more efficiently and reducing the risk of localized failures.

• Hashin's Failure Criteria Analysis

The analysis of Hashin's failure criteria shows that the values for fiber compressive initiation, fiber tensile initiation, and matrix compressive initiation are very low, indicating no expected failure in these modes, and the matrix tensile initiation criterion shows a maximum value of 0.4055, which is below the threshold value of 1, confirming that the composite layers are performing well within their safe limits, with no imminent risk of failure in any of the evaluated modes. The low values for other criteria suggest that the structure is robust and well-designed, validating the model.

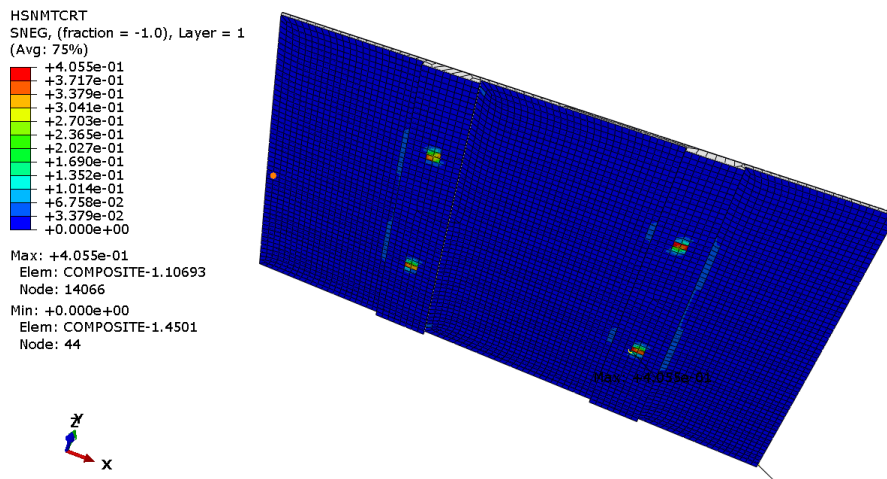


Figure 4.31: Matrix tensile initiation criterion.

• Global Failure Analysis

In conclusion, the final analysis of the sandwich panel with two stringers and increased foam thickness in critical zones to 8 mm demonstrates substantial improvements in structural performance, as the enhancements have successfully reduced the maximum deflection to 5.61 mm, indicating better load distribution and increased stiffness, and the stress analysis shows a significant decrease in the maximum S11 and Von Mises stress for both composite layers and foam core, respectively, ensuring that all stress levels remain well below their respective material strengths, thereby preventing any risk of failure under applied loading conditions.

4.4. Structural Analysis

The Hashin's failure criteria analysis further validates the robustness of the structure, with all values well below the critical thresholds, confirming no imminent risk of failure, and these improvements highlight the effectiveness of the structural modifications, resulting in a design that offers enhanced durability, reliability, and overall structural integrity. Having performed these analyses, this final structure is now ready to be optimized by the developed optimization code in both the number of layers and its directions. In Table 4.6, the critical obtained values for this final structure can be found.

Table 4.6: Summary of the obtained critical values for analysis 4.

	Maximum Stress [MPa]	Maximum Deflection [mm]	Fiber Compressive [-]	Fiber Tensile [-]	Matrix Compressive [-]	Matrix Tensile [-]
Carbon Layers	331.9	5.607	0.0604	0.0674	0.00112	0.405
Foam	1.134	5.610	-	-	-	-

4.4.5 Conclusion on the Performed Analysis

In this final subsection, the progression and improvements made through the various configurations tested are synthesized, culminating in the final validated structure with two thicker transversal stringers, and each iteration aimed to address specific structural deficiencies identified in the previous analyses, resulting in a design that effectively balances deflection, stress distribution, and material integrity. The table below summarizes the critical values obtained from each configuration.

Table 4.7: Global comparison of all of the performed analysis.

Configuration	Flat Carbon UD Panel	Flat Sandwich Panel	Sandwich Panel with Two Stringers	Sandwich Panel with Two Thicker Stringers
Maximum Stress (MPa)	1366	578	395	331
Maximum Deflection (mm)	135.2	32.42	6.76	5.61
Fiber Compressive (-)	1.157	0.210	0.083	0.025
Fiber Tensile (-)	0.830	0.0267	0.085	0.067
Matrix Compressive (-)	0.625	0.001564	0.00508	0.001123
Matrix Tensile (-)	0.350	0.286	0.663	0.4055

The initial configuration, a flat carbon UD panel, exhibited significant deflections and high-stress concentrations, as the maximum deflection was 135.2 mm, and the maximum S11 stress reached 1352 MPa. Hashin's failure criteria indicated a high risk of fiber compressive and tensile failure, highlighting the panel's inability to sustain the applied loads without significant deformation and risk of failure. Then, the introduction of a sandwich panel with an Airex 7075 foam core between carbon UD layers markedly improved the structural performance, as the deflection was reduced to 32.42 mm, and the maximum stress dropped to 575 MPa. However, the foam core stress exceeded its compressive strength, indicating a risk of failure in the foam, and while Hashin's criteria values were within safe limits for the composite layers, the need for further structural reinforcement was evident.

Incorporating two transversal stringers in the sandwich panel further enhanced the structure, as the deflection was significantly reduced to 6.76 mm, and the maximum stress in the composite layers was lowered to 395 MPa. The foam core stress was brought within safe limits (1.379 MPa), and Hashin's criteria values indicated no imminent risk of failure, confirming the effectiveness of the stringers in distributing the loads and reducing stress concentrations. The final configuration, with increased foam thickness in the stringer regions (from 5 mm to 8 mm), showed the best

Chapter 4. Structural Analysis of the Cargo Compartment

performance, as the deflection was further reduced to 5.61 mm, and the maximum stress in the composite layers dropped to 319.5 MPa. The foam core stress was well within the safe limit at 1.134 MPa, and Hashin's failure criteria confirmed the robustness of the structure, with all values below critical thresholds, indicating no risk of failure. This configuration effectively managed the applied loads, demonstrating optimal structural integrity and durability.

In summary, the progression from a flat carbon UD panel to a sandwich panel with thicker stringers highlights the iterative process of structural optimization, as each modification addressed specific weaknesses, resulting in a final design that combines low deflection, reduced stress concentrations, and compliance with failure criteria, ensuring a robust and reliable UAV cargo compartment structure. This way, it is now possible to optimize the final designed structure with the developed code, in order to obtain the lightest possible structure without compromising the structural integrity of the panel.

Chapter 5

Optimization Tool for Composite Structure

5.1 General Overview of the Optimization Tool

In this chapter, a detailed explanation of the development, improvement, and use of an optimization algorithm specifically tailored for composite structures is detailed, in this case its specific application in a UAV. Therefore, the optimization tool was initially developed by [1] and [2], and improvements were made to improve its effectiveness, quality of results and applicability to the specific challenges found in the developing process of this project.

In order to understand the optimization process, it is important to note that this tool is very adaptable to any geometry, and its general workings enable it to be used in various projects, each of which poses different constraints and problems that the algorithm is capable of overcoming. Being this versatile and flexible, it is crucial to present the priorities of this specific project, especially in the context of critical structures such as those found in UAVs, where the primary considerations revolve around weight reduction and ensuring the structural integrity of the system as a whole.

Central to the definition and creation of the optimization process is the formulation of the objective function, which must be tied to the ultimate goal of minimizing weight without compromising the airworthiness and structural integrity of the UAV. Therefore, by establishing a direct relationship between the number of layers and the direction of the fibers in each ply with the resulting weight of the structure, it is possible to create a robust objective function, the core of the optimization process. This process unfolds through distinct steps, beginning with the modeling of the structure using the ABAQUS interface, then importing the file to the script, or directly through Python scripting, and this phase also encompasses the definition of materials, loads, boundary conditions, and any relevant constraint, all defined in Python scripts.

Following the creation of the model, it is possible to segment the model into different sections, allowing for precise reinforcement strategies to be implemented, taking into account the different load requirements and applied boundary conditions across different parts of the structure. After all of these definitions, a genetic algorithm is used in conjunction with a finite element analysis through ABAQUS to evaluate the structural performance of the structure, where the algorithm systematically assesses failure criteria, including Tsai-Hill, Hashin, or Larc05, with the latter two

5.1. General Overview of the Optimization Tool

introduced to improve accuracy and efficacy based on found literature and obtained results in simple models. An important aspect of the optimization process lies in the treatment of constraints, particularly in penalizing ply failure within the laminate, as values obtained from the used failure criteria serve as critical indicators, with values below 1 indicating ply integrity and increasing values signifying progressive bigger failure within the laminate.

In Figure 5.1 it is possible to see the basic functioning of the optimization tool where, by starting with the initial parameters and the objective function, the optimization algorithm, using a genetic algorithm aligned with the finite element software, retrieves the values of the used failure criteria (Hashin or Larc05) for a multiple number of layers and direction of the fibers, and through these constraints finds the best individual, the optimal solution for each section of the structure.

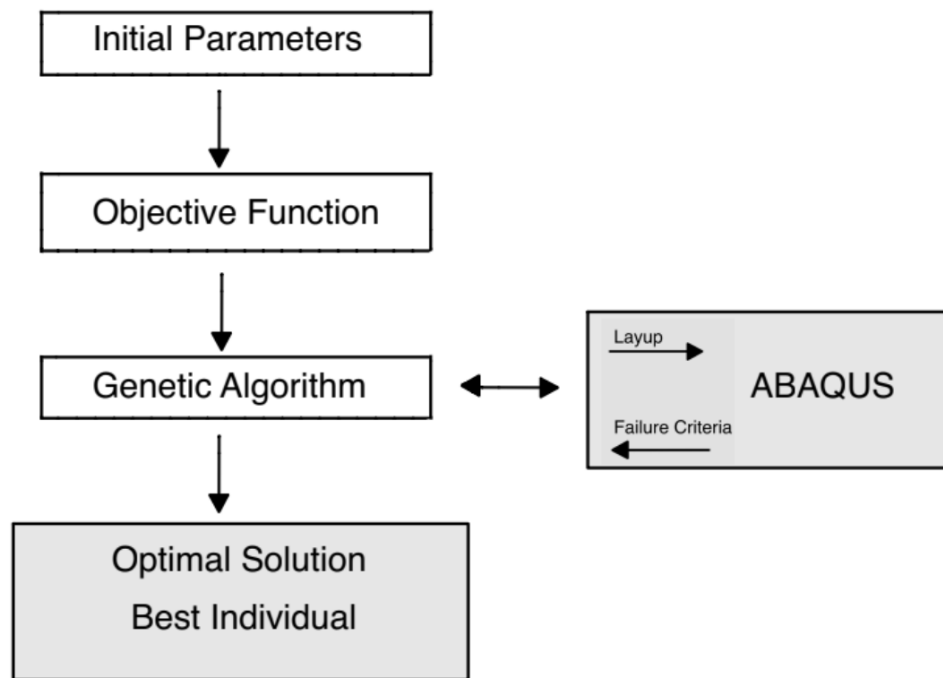


Figure 5.1: Flowchart representing the main functioning of the optimization tool.

5.2 Genetic Algorithm

5.2.1 Overview of the Genetic Algorithm

The original optimization tool was initially developed using a genetic algorithm, and given the success and robustness of this method in previous implementations from [1] and [2], it was deemed appropriate to continue utilizing this approach for the project at hand. However, an alternative method, such as a memetic algorithm was also considered, but the decision to continue with the genetic algorithm over it was driven by several key factors.

Firstly, genetic algorithms are well-suited for problems involving large and complex search spaces, such as those encountered in composite structure optimization, and they are particularly effective in exploring global optima without requiring extensive problem-specific knowledge, while memetic algorithms, which combine genetic algorithms with local search heuristics, can be more computationally intensive and require a more delicate balance between exploration and exploitation. This way, given the computational constraints and the primary objective of weight minimization, the genetic algorithm provided a more straightforward and efficient approach for this project. Nonetheless, it would be interesting to, in future works, explore the possibility of this application. It is important to note that the optimization tool is designed for versatile application across various composite structures, and by evaluating each section of the structure using the chosen failure criteria, the tool ensures the reliability and integrity of the structure, as whether assessing the Tsai-Hill, Hashin, or Larc05 failure criteria, the genetic algorithm systematically evaluates the performance of each section, optimizing the composite layup accordingly.

Upon confirming the suitability of the genetic algorithm, the development process began with the implementation of an elitist strategy, that involves retaining the best-performing individuals from one generation to the next, ensuring that the quality of solutions steadily improves over successive generations, enhancing the convergence rate and helping avoid premature convergence to suboptimal solutions. The genetic algorithm in this project aims to minimize the objective function, which is the weight of the composite structure and is intrinsically linked to the number of layers and their orientations in different sections, such as the cargo compartment, trapdoors, and connections. Therefore, a single-objective optimization is sufficient for this task, with weight minimization as the primary goal, where the constraints imposed by the failure indexes of the laminate ensure that the structural integrity is not compromised in the pursuit of lighter designs.

It is important to note that it is crucial to detail every aspect of the formulation of the genetic algorithm, as several tweaks and modifications were applied in order to optimize the results of the project at hand, so a detailed explanation of each topic of the algorithm will be held, from the definition of the objective function and design variables to the crossover and mutation operators.

5.2. Genetic Algorithm

5.2.2 Objective Function

In this project, we focus on a single-objective optimization approach of a composite structure, intending to minimize the objective function $f(x)$ which, in this case, represents the weight of the structure. Given the complexity and critical nature of composite structures, particularly in applications such as aeronautical structures like UAVs, the reduction of weight without compromising structural integrity is a crucial aspect on the study of the structure. This way, the problem can be defined as follows: with the geometry and material properties of the structure fixed as initial parameters, we aim to minimize the objective function, and this can be expressed mathematically as:

$$\text{Minimize } f(x), \quad x \in^n. \quad (5.1)$$

where x represents the design variables within the real number space, corresponding to the different parameters that influence the weight of the composite structure.

In this specific optimization problem, the objective function $f(x)$ is defined through the relationship stated in Equation 5.2:

$$f(x) = \sum_{i=1}^n \rho \times A_{\text{section}_i} \times \sum_{j=1,2,3} x_{ij}, \quad i = 1, 2, 3, \dots, n \quad (5.2)$$

where ρ represents the area density of the laminate, A_{section_k} denotes the total area of each analyzed section, i is the number of sections, j is the different ply orientations and x_{ij} is the number of layers of the j^{th} orientation in the i_{th} section, and by adding the multiplication of these factors for each section, we obtain the total weight of the laminate for the whole structure. Note that performing these calculations section by section also allows us to know the weight of each section, which may prove advantageous when optimizing only certain parts of the structure.

Therefore, the design variables x include the number of layers and their orientations in each section, which are critical parameters influencing the overall weight, so the optimization process involves finding the optimal combination of these variables to achieve the minimum weight while satisfying all necessary constraints related to structural integrity and performance criteria.

5.2.3 Design Variables

In genetic algorithms, the parameters of a problem that are the subject of optimization are called design variables, and these variables represent the characteristics of the solution space that can be manipulated to achieve optimal solutions. In the context of this problem, design variables typically include parameters related to the number of layers and the orientation of each layer within the laminate. As previously mentioned, the finite element model can be divided into any number of sections, and it is up to the user to determine an appropriate division of the structure, as each section in the model is associated with a set of design variables that dictate the number of layers and the orientation of the laminate plies.

For the optimization of both the number of layers and the ply orientation in each section, three design variables are assigned: one for the number of layers oriented at 0° , another for 90° , and a third for $\pm 45^\circ$ orientation. Notably, the $\pm 45^\circ$ orientation typically has the same number of layers, meaning that this simplification results in a total of three design variables per section, and these orientations are commonly employed in aeronautical structures to simplify manufacturing

processes and enhance structural integrity. Additionally, the order of the layup and the option for symmetrical layup can be defined in the initial parameters, showcasing the flexibility of the algorithm in accommodating various design configurations and constraints that best suit each problem, and this adaptability enables the optimization tool to explore a diverse range of solutions within the specified design space, leading to a better search of the optimal solution, resulting in improved structural performance and efficiency. Defining the design variables as in Equation 5.3, we can represent the problem as in Table 5.1.

$$X = x_{11}, x_{12}, x_{13}, x_{21}, \dots, x_{ij} \quad (5.3)$$

where, as previously said, $i = 1, 2, 3, \dots, n$ is the number of sections, and $j = 1, 2, 3$ represents the 3 possible ply orientations for each section, defined in the initial parameters.

Table 5.1: Definition of the design variables for the project at hand.

Section 1	x_{11}	x_{12}	x_{13}
Section 2	x_{21}	x_{22}	x_{23}
Section 3	x_{31}	x_{32}	x_{33}
Section ...	$x_{...1}$	$x_{...2}$	$x_{...3}$
Section n	x_{n1}	x_{n2}	x_{n3}

Therefore, the number of design variables present in the problem can be obtained by:

$$n = \text{Number of Sections} \times 3 \quad (5.4)$$

5.2.4 Fitness Function

The fitness function, in conjunction with the chosen encoding for the search space, plays a fundamental role in the performance of a genetic algorithm, and to promote the effectiveness of the algorithm, constructing the fitness function must consider several crucial parameters:

- The fitness function should be smooth and regular to ensure that chromosomes with reasonable fitness are spatially close to chromosomes with better fitness.
- The fitness function should not have too many local optima or a highly isolated global optimum.
- It should objectively reflect the value of the chromosome.
- Inadmissible solutions (invalid chromosomes) should guide towards the direction of feasible solutions.

Thus, quantifying the relative value of a solution or individual within the context of its population can be mathematically represented using the fitness function. Stemming from the objective function (a measure of performance relative to a specific set of genes), the fitness function aims to transform the objective function into a "pool" of reproductive opportunities concerning the rest of the population. The fitness function may be developed using a normalization process, and this process considers the presence of invalid chromosomes, products of violating imposed constraints

5.2. Genetic Algorithm

associated with infeasible solutions. The fitness function grounded in a normalization process can be expressed as follows:

$$\text{Mer}(\mathbf{x}_i) = \frac{1}{f(\mathbf{x}_i) + \Gamma(\mathbf{x}_i)}, \text{ where } \mathbf{x}_i + \Gamma(\mathbf{x}_i) \neq 0 \quad (5.5)$$

where $\Gamma(\mathbf{x}_i)$ represents the penalty function associated with the violation of constraints, ensuring that infeasible solutions are not favored in the optimization process.

5.2.5 Incorporation of Constraints

In the majority of real-world problems, constraints exist and significantly impact the performance of the optimization algorithm, necessitating the evaluation of how they are included in the process.

The integration of constraints into the search process does not follow a universally accepted method but allows for the selection of various methods that have been developed. Determining which method contributes most to the effectiveness of the genetic algorithm is still a subject of investigation and research. Methods based on the concept of exterior penalty are often used, where a penalty function is formulated based on the "distance" of the solution under consideration relative to the space of feasible solutions. The penalization is introduced by a set of penalty functions u_j , expressed as:

$$u_j(\mathbf{x}) = \max[0, g_j(\mathbf{x})], \text{ if } 1 \leq j \leq q \quad (5.6)$$

In each iteration k , the solutions of the minimization problem are evaluated using the method of adaptive penalties, given by:

$$\text{Aval}(\mathbf{x}) = f(\mathbf{x}) + (Ck)^\alpha \sum_{j=1}^m [u_j(\mathbf{x})]^\beta \quad (5.7)$$

where $f(\mathbf{x})$ is the objective function, C is a constant, α and β are parameters, and m is the number of constraints.

This way, and in this problem, the following constraints were applied (note that the upper and lower boundaries are defined for each section in the initial parameters):

1. $g_1(\mathbf{x})$: Ensuring the solution is below the upper boundary.
2. $g_2(\mathbf{x})$: Ensuring the solution is above the lower boundary.
3. $g_3(\mathbf{x})$: Ensuring that there is at least one ply in each section.
4. $g_4(\mathbf{x})$: Penalizing solutions that present Hashin values ≥ 1

5.2.6 Genetic Selection Operator

Selection is a mechanism for identifying individuals (chromosomes) for reproduction or survival in the population, and it can be performed using:

- Proportional selection methodology: selection of individuals according to the value of their fitness.
- Rank-based selection methodology: the fitness value of individuals is not directly considered, but the choice is based on a ranking according to the assigned classification.

There are various possible methodologies to adopt, for example, the proportional selection can be employed, and within this category, the roulette wheel selection can be chosen. As the name suggests, through the roulette wheel method, the possible solutions (chromosomes) are arranged on a roulette wheel, where individuals with higher fitness occupy a larger space on the wheel, thus being selected more frequently. The selection probability of an individual is given by the following stochastic function:

$$P(\mathbf{x}_j^k) = \frac{f(\mathbf{x}_j^k)}{\sum_{j=1}^{N_{\text{pop}}} f(\mathbf{x}_j^k)} \quad (5.8)$$

where $f(\mathbf{x}_j^k)$ represents the value of the fitness function.

This was the first selection method proposed for genetic algorithms and is still the most widely used by researchers. It offers the advantage of selection probability being proportional to fitness. However, premature convergence is observed, and selection intensity is generally low due to the presence of both highly fit and unfit individuals. The convergence rate decreases with each subsequent generation.

5.2.7 Crossover Operator

Crossover operators are responsible for generating a set of new solutions/individuals by combining the genetic material of two previously selected parents, and it is an action that complements the mutation operation and is typically applied to generate two offspring chromosomes for each pair of parents.

The operation of crossover operators is represented through a mask selection operation, where a vector M_i with binary values is generated. Considering p_1 and p_2 as the parents and s_1 and s_2 as the offspring to be generated, using the uniform crossover method, the parent from which the offspring is generated is selected based on the action of the operator. The operator tracks the elements of the vector M_i to determine which bit corresponds to a particular position:

- If $M_i = 0$, s_1 acquires the gene from parent p_1 and s_2 acquires the gene from parent p_2 .
- If $M_i = 1$, s_1 acquires the gene from parent p_2 and s_2 acquires the gene from parent p_1 .

Mutation Operator: Mutation operators are actions that introduce slight alterations in selected individuals within the population, as each gene is associated with a probability of mutation (P_m). In defining and using a mutation operator, it is crucial to ensure the possibility of reaching all solutions in the search space (ergodicity) and the production of valid solutions. It is also important to control the probability of mutation to ensure that the induced alteration by the mutation operator is minimal (locality). Thus, mutation operators capable of generating strong locality should be produced, meaning small changes in the genotype result in small changes in the phenotype. A mutation operator for binary representation may be employed, like a flip-bit mutation.

5.3. Validation of the Optimization Algorithm

This mechanism promotes random modifications of the binary code (and consequently, its genetic material) to occur with a probability P_m , and the mutation can occur bit by bit or in sequences of bits.

5.2.8 Convergence and Stopping Criteria

Traditionally, the stopping conditions that govern the search through a genetic algorithm include the maximum number of generations, the limit on the number of fitness function evaluations, and the increasingly scarce changes in subsequent generations. Thus, to avoid both excessively delayed convergence and very premature convergence, the search is bounded by a set of criteria that specify its scope.

In the development of a general genetic algorithm, the following convergence/stopping condition may be imposed:

- Maximum number of iterations: once the maximum number of iterations applied to the algorithm is reached, it stops.

Additional stopping criteria could be applied, following a more traditional approach more in line with simple genetic algorithms: a maximum limit on the number of fitness function evaluations and a criterion capable of evaluating the loss of diversity in future generations.

5.3 Validation of the Optimization Algorithm

The validation of the optimization tool is a fundamental step in ensuring its reliability and accuracy, particularly when applied to complex composite structures, and validating the tool with simple cases serves as a critical foundation, providing confidence that the underlying algorithms and methodologies are functioning correctly before being applied to more complex scenarios.

In the previous work developed by last year's colleagues, the optimization tool underwent extensive validation across various regression methods using known simple cases, and this comprehensive approach allowed for a detailed comparison of regression techniques, leading to the identification of the most effective method. Among the methods evaluated, Gaussian regression emerged as the best performer, demonstrating superior accuracy and consistency in predicting the optimization outcomes. Building on these findings, the current work adopts Gaussian regression as the primary regression method for validating the optimization tool, and the focus of this validation process is to test the new failure criteria implemented in the tool, specifically the Hashin failure criteria for composites, comparing it to results of both the Tsai-Hill and Larc05 failure criteria.

Therefore, to thoroughly validate the implementation of the Hashin failure criteria, two simple yet representative cases are selected, as it will be shown in the following subsections.

5.3.1 Plate with applied Tensile Load

The first validation case involves a tensile plate with dimensions of $100 \times 100 \text{ mm}^2$, the material properties for the shell elements have been previously defined and are consistent with those used in the rest of the project, and the plate is subjected to a tensile load of 1700 MPa applied along one of its edges.

To simulate the tensile stress condition accurately, specific boundary conditions are applied to the plate, as the edge opposite to the loaded edge is constrained to prevent displacement, and this is achieved by fully constraining a point in the middle of the edge (encastre point) and restricting

displacements along the entire edge. The applied boundary conditions are illustrated in the figure below:

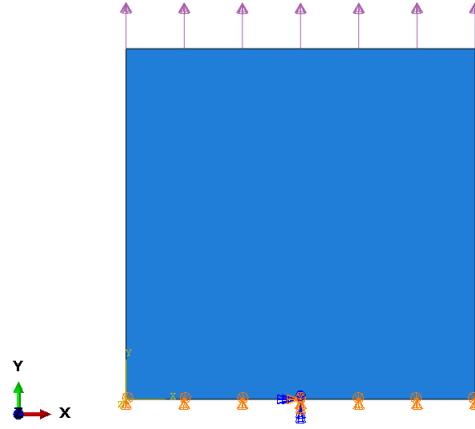


Figure 5.2: Boundary conditions for the tensile plate under 1700 MPa load.

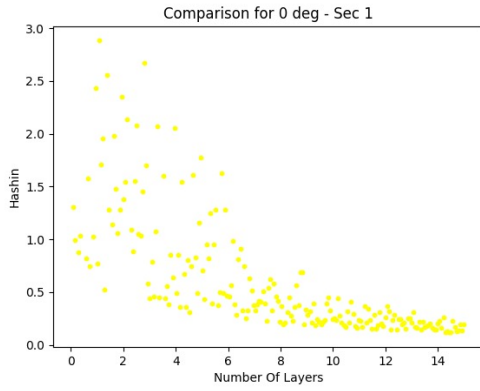
The plate is analyzed using a symmetric composite layup configuration of $[0, \pm 45, 90]$, and based on [1] and [2], the expected optimal layup configuration for this tensile load case is $[7, 0, 0]$ when the upper and lower ply boundaries are set to 15 and 0, respectively, indicating that the most optimized layup should consist entirely of 0° plies, maximizing the plate's load-carrying capacity under tensile stress.

The analysis of the results from Figure 5.3 provides insights into the effectiveness of different ply orientations in minimizing the Hashin failure criteria values, as each graph plots the number of plies in a specific orientation (0° , 45° , and 90°) against the corresponding Hashin values, and the goal is to determine the optimal ply configuration for minimizing the failure criteria.

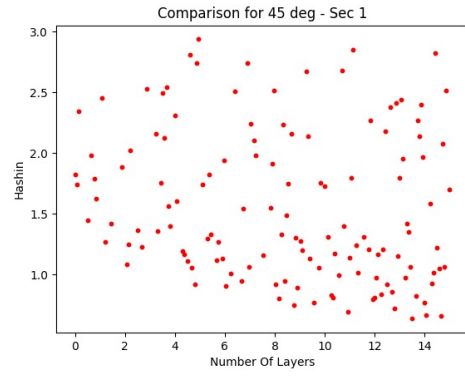
The first graph shows a clear trend: as the number of 0° plies increases, the Hashin values decrease, indicating a strong relationship between increasing the number of 0° plies and improved performance in terms of reducing the failure criteria. The trend suggests that a higher number of 0° plies leads to better load-carrying capacity and resistance to failure under tensile loading conditions, and the optimal value of 7 plies is obtained, in order to have Hashin's values lower than 1 having the least possible plies, to reduce the weight as much as possible.

The second graph does not exhibit a clear trend or pattern, as the Hashin values appear to be scattered with no significant correlation to the number of 45° plies, suggesting that varying the number of 45° plies does not have a significant impact on the failure criteria under the given loading conditions. Similarly, the third graph shows a scattered distribution of Hashin values with respect to the number of 90° plies, and there is no evident trend or correlation, indicating that 90° plies also do not play a significant role in minimizing the failure criteria for the tensile plate. This way, it is seen that the optimization tool is providing the expected and correct results for this geometry.

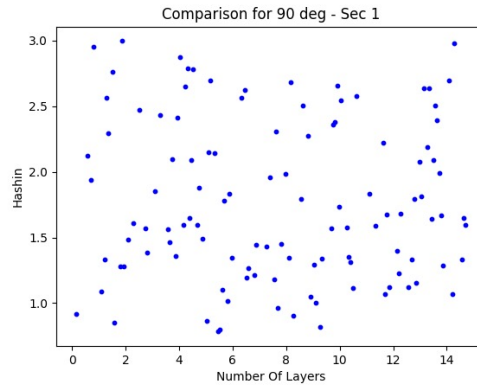
5.3. Validation of the Optimization Algorithm



(a) Hashin's Values x Number of Layers for 0 degrees.



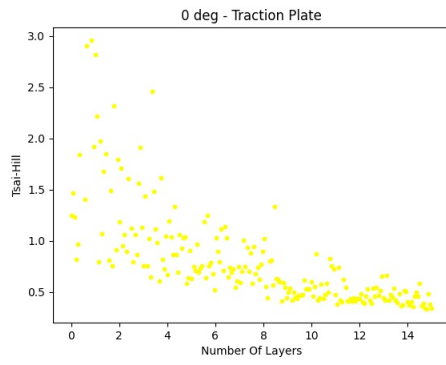
(b) Hashin's Values x Number of Layers for 45 degrees.



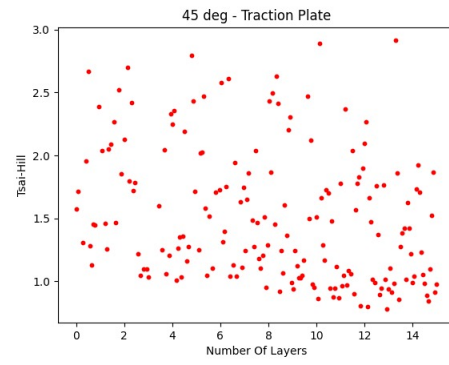
(c) Hashin's Values x Number of Layers for 90 degrees.

Figure 5.3: Results for the tensile plate loadcase for the Hashin's failure criteria.

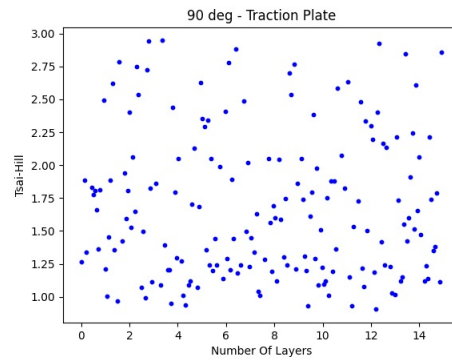
Comparing these results with the obtained for both the Tsai-Hill and Larc05 values (Figures 5.4 and 5.5), it is possible to further validate this failure criteria, as the obtained results go in line with what was expected for these two cases.



(a) Tsai-Hill Values x Number of Layers for 0 degrees.



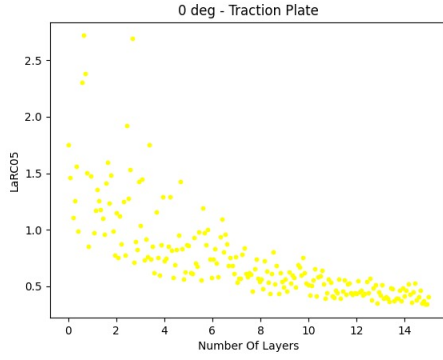
(b) Tsai-Hill Values x Number of Layers for 45 degrees.



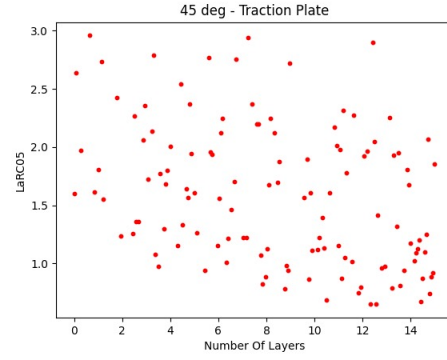
(c) Tsai-Hill Values x Number of Layers for 90 degrees.

Figure 5.4: Results for the tensile plate loadcase for the Tsai-Hill's failure criteria.

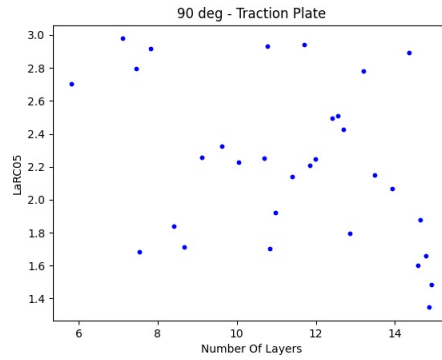
5.3. Validation of the Optimization Algorithm



(a) Larc05 Values x Number of Layers for 0 degrees.



(b) Larc05 Values x Number of Layers for 45 degrees.



(c) Larc05 Values x Number of Layers for 90 degrees.

Figure 5.5: Results for the tensile plate loadcase for the Larc05's failure criteria.

5.3.2 Plate with Applied Shear Load

The second validation case involves a shear plate subjected to edge loads, analyzed using the same symmetric composite layup configuration as the tensile plate, and similar to the tensile plate, the shear plate measures $100 \times 100 \text{ mm}^2$ and is constructed using shell elements from the previously defined material. The boundary conditions are designed to accurately simulate shear loading on the plate, as the left edge is constrained with $U_2=U_3=0$, restricting displacement in the vertical and out-of-plane directions, and the bottom edge is constrained with $U_1=U_3=0$, restricting displacement in the horizontal and out-of-plane directions. Also the shared corner point of these edges is pinned, providing a fixed point of reference and preventing any movement. For the load application shear load of 600 MPa is applied along two edges of the plate in the positive direction.

According to the studies by [2] and [1], the expected optimal layup configuration for the shear load case is 7 layers in the $\pm 45^\circ$ direction, indicating that the most efficient layup consists predominantly of plies oriented at ± 45 degrees. The applied loads and boundary conditions are depicted below:

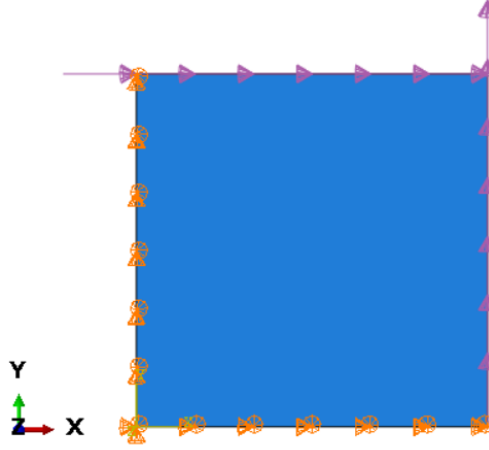
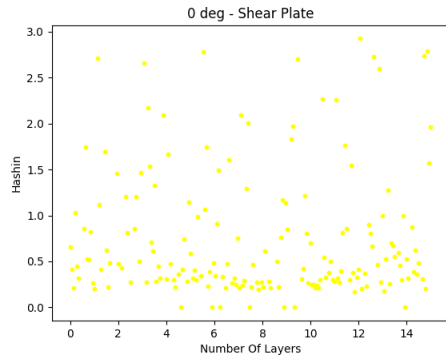


Figure 5.6: Boundary conditions for the shear plate under 600 MPa shear load.

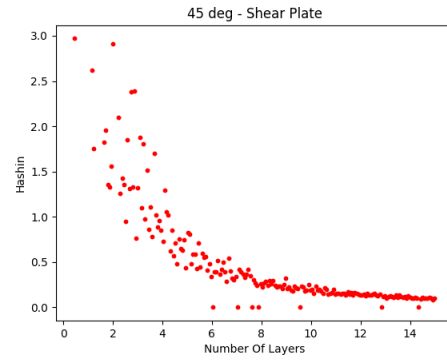
Analyzing the results from Figure 5.7, several conclusions can be drawn. The first graph shows a scattered distribution of Hashin values with respect to the number of 0° plies, indicating no clear trend or pattern, and suggesting that varying the number of 0° plies does not significantly impact the failure criteria under shear loading conditions. On the other hand, the second graph exhibits a more discernible trend: as the number of 45° plies increases, the Hashin values generally decrease, indicating a significant relationship between the number of 45° plies and improved performance in terms of reducing the failure criteria. The trend suggests that 45° plies are highly effective in resisting shear stresses, leading to better load distribution and lower failure values.

The optimal value of 7 plies in the $\pm 45^\circ$ direction is obtained, which aligns with the expected result from the literature, indicating that this configuration provides the best balance between minimizing Hashin values and maintaining structural integrity. Similar to the 0° direction, the 90° plies show no relation between the Hashin's values and the number of plies.

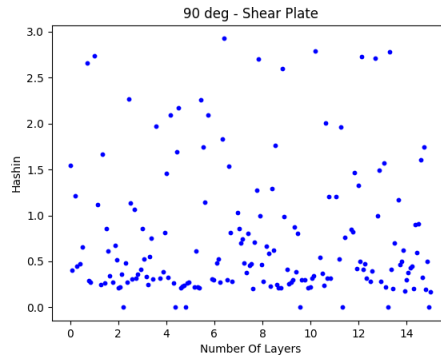
5.3. Validation of the Optimization Algorithm



(a) Hashin's Values x Number of Layers for 0 degrees.



(b) Hashin's Values x Number of Layers for 45 degrees.

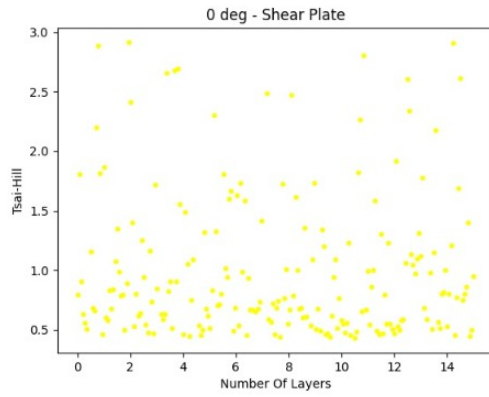


(c) Hashin's Values x Number of Layers for 90 degrees.

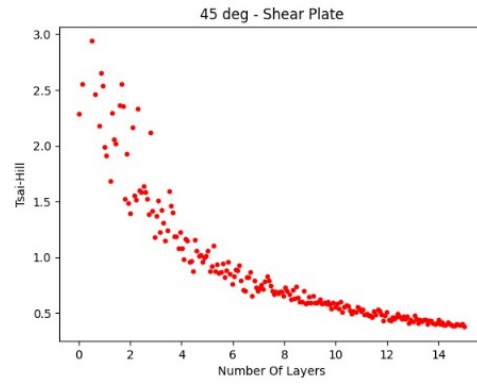
Figure 5.7: Results for the shear plate loadcase.

In this classical case, it is also possible to compare the obtained values for the Hashin's values with the obtained ones for both the Tsai-Hill and Larc05 values, provided in the following Figures.

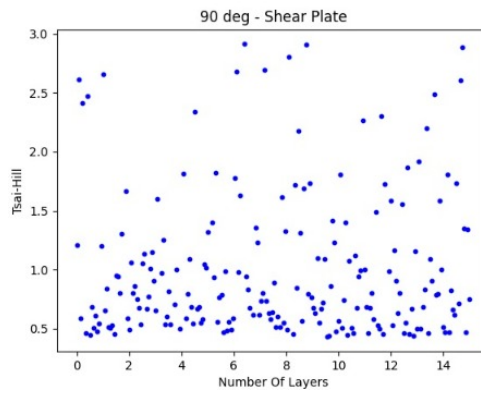
From the obtained results, it is seen that the tool correctly uses Hashin's criteria to predict the optimal number of layers in each direction of the plate.



(a) Tsai-Hill Values x Number of Layers for 0 degrees.



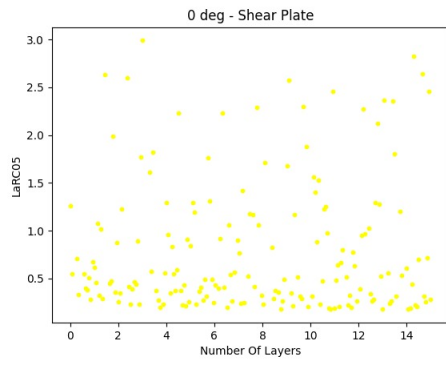
(b) Tsai-Hill Values x Number of Layers for 45 degrees.



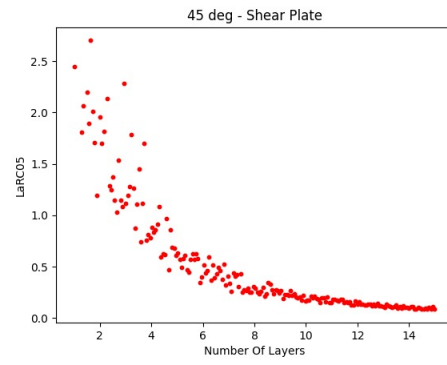
(c) Tsai-Hill Values x Number of Layers for 90 degrees.

Figure 5.8: Results for the shear plate loadcase for the Tsai-Hill's failure criteria.

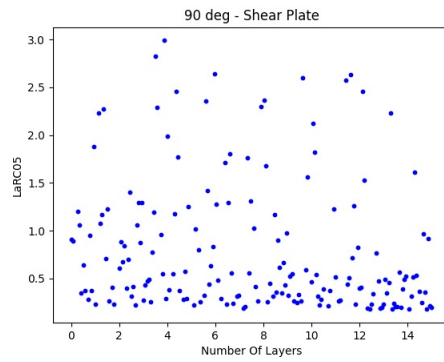
5.3. Validation of the Optimization Algorithm



(a) Larc05 Values x Number of Layers for 0 degrees.



(b) Larc05 Values x Number of Layers for 45 degrees.



(c) Larc05 Values x Number of Layers for 90 degrees.

Figure 5.9: Results for the shear plate loadcase for the Larc05's failure criteria.

5.3.3 Results from the Classical Cases

The validation of the optimization tool using the two classical cases— tensile plate and shear plate— demonstrates its accuracy and reliability in predicting optimal ply configurations for minimizing the Hashin failure criteria, and the expected results, derived from established results in the literature, provided a solid foundation against which the obtained results were compared.

For the tensile plate case, the expected optimal layup configuration was seven plies in the 0° direction, based on the understanding that 0° plies offer the best load-carrying capacity under tensile loads, and the analysis confirmed this expectation, with the obtained results showing a clear trend of decreasing Hashin values with an increasing number of 0° plies. The optimal configuration of seven 0° plies was identified, validating the tool's capability in this scenario.

In the shear plate case, the expected optimal configuration was seven plies in the $\pm 45^\circ$ direction, as these orientations are most effective in resisting shear stresses, and the analysis results supported this expectation, showing a significant reduction in Hashin values with increasing 45° plies. The obtained optimal configuration of seven $\pm 45^\circ$ plies aligns with the expected result, further validating the optimization tool.

The following table summarizes the expected and obtained results for both cases in terms of the number of layers and their orientations:

Table 5.2: Final comparison of the obtained results by different methods.

Method	Tensile Plate (Number of Layers) [0, ± 45 , 90]	Shear Plate (Number of Layers) [0, ± 45 , 90]
Abaqus	[0; 0; 7]	[7; 0; 0]
GA- Tsai-Hill	[0; 0; 9]	[7; 0; 0]
GA- Hashin	[0; 0; 7]	[6; 0; 0]
GA- Larc05	[0; 0; 7]	[6; 0; 0]

The validation results confirm that the optimized algorithm accurately predicts the optimal ply configurations for minimizing the Hashin failure criteria in both tensile and shear loading scenarios, and the obtained results match the expected results, demonstrating the tool's reliability and effectiveness.

With this validation, the optimization tool is now ready to be applied to the developed model in the project, and the tool's ability to optimize composite structures under various loading conditions ensures that it can be effectively used for the project's complex requirements, providing reliable and accurate optimization results for the developed composite structures.

Chapter 6

Application of the Tool on the Cargo Compartment

In this chapter, the application of the optimization tool on the developed structure will be detailed, starting from a mesh convergence analysis, to determine the ideal balance between accuracy and computation time, followed by a description of all of the changes to the code that were necessary to apply for the structure to be compatible to the code. Then, the obtained results are depicted and analyzed in the FEM software, and conclusions will be discussed.

6.1 Mesh Convergence Analysis

A mesh convergence analysis is a critical step in finite element analysis to ensure the accuracy and reliability of the simulation results, and the primary goal of this analysis is to determine an optimal mesh size that provides accurate results without unnecessarily increasing computational cost. In the context of this project, the mesh convergence analysis ensures that the stress and deflection predictions are precise and dependable. For the initial analysis with simpler geometries, since the used mesh was considered to be very refined, no mesh convergence study was performed, as the computational time was relatively low. On the other hand, for the optimization tool, since thousands of samples of different composite layups will be analyzed, it is crucial to find the correct balance between the precision of the variables and the computational time of each job.

This way, a mesh convergence analysis will be performed on a single element in the modeled structure, and the results are depicted in Table 6.1 and Figure 6.1. The chosen element to depict the stress and deflection values is away from the applied conditions and the applied concentrated loads, thus obtaining the following results:

Table 6.1: Mesh Convergence Study.

Approximate Size	Stress in Central Element (MPa)	Deflection in Central Element (mm)	Number of Elements	% Difference from Last Iteration (Stress)	% Difference from Last Iteration (Deflection)	Computation Time (s)
20	126.517	5.600	7,430	-	-	17
15	126.152	5.532	12566	0.28%	1.25%	27
13	124.596	5.521	15556	1.23%	0.18%	43
12	125.158	5.534	18931	0.45%	0.25%	46
11	125.553	5.533	22753	0.32%	0.02%	60
10	124.721	5.521	25881	0.66%	0.20%	76

6.1. Mesh Convergence Analysis

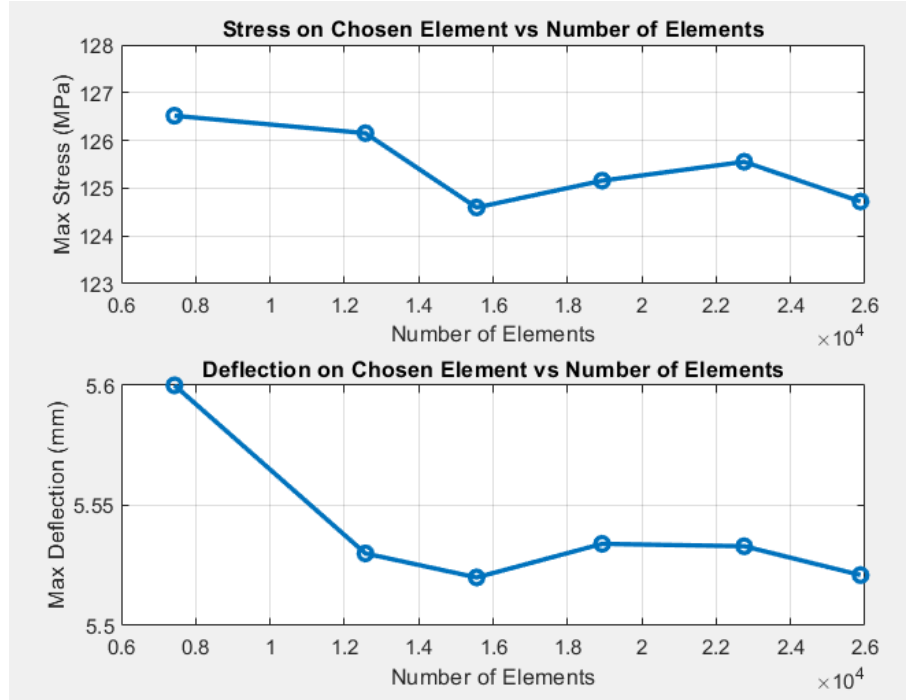


Figure 6.1: Evolution of maximum stress and deflection along the number of elements of the mesh.

Determining the optimal number of elements for the mesh involves balancing the need for precision with the computational resources and time required for the analysis, and the observed deflection across different mesh sizes is extremely precise, showing variations of less than 0.3% between successive iterations, indicating that the deflection values stabilize quickly as the mesh is refined, providing confidence that even relatively coarse meshes can capture the deflection behavior accurately.

The stress in the element is also extremely precise along different numbers of elements in the global mesh, and although the computation time for both an approximate size of 20 and 15 is much lower, it is seen that these analyses provide certain points with high-stress concentrations near the boundary conditions, that tend to decrease with a finer mesh. For an approximate size of 10 and 11, the computation time is relatively higher than for the sizes of 12 and 13, therefore it was chosen an approximate element size of 12 (with 18,931 elements) as the best option, as the stress value for this mesh size is within 0.2% of the final results obtained with an element size of 10 (with 25,881 elements), and the computation time is satisfactory for the obtained results.

6.2 Applied Modifications on the Code and Final Structure to Analyze

In this section, all of the performed modifications on the code to integrate the developed model are carefully described, as well as the description of the different sections that will and will not be a subject of analysis, starting from the division of the structure into different sections to the description on how the tool performs the optimization from the different existing scripts.

6.2.1 Applied Modifications to the Optimization Tool

The classical cases analyzed to validate the tool were composed of only one section, but in order to achieve more accurate and realistic results, it was decided to divide the structure into four distinct sections, as this approach allows for the optimization of the number of layers and their orientations for each specific section. Consequently, modifications were made to the code to increase the number of sections to analyze from one to four. This adjustment required the transformation of various variables to ensure the tool could retrieve and process the failure values for each of the newly defined sections.

As previously mentioned, the initial code was designed to work with the Tsai-Hill failure index, and one of the significant improvements successfully implemented in the tool was the incorporation of Hashin's failure criteria. This change was performed by changing the field output request for each job, and adapting the post-processing script to retrieve the four different values of this failure criteria and submit the maximum value to the database for each section. Additionally, and in order to reduce computation time and resources as much as possible, the code was adapted to be able to import CAE files, therefore not needing to directly model the geometry of the structure and instead import it from an already existing file.

Finally, the genetic algorithm parameters— such as population size, bits per variable, the fraction of the population selected for crossover, the fraction selected for mutation, and the fraction of bits selected for mutation— were optimized for the specific case at hand, and multiple tests were conducted to fine-tune these parameters to ensure the accuracy and efficiency of the genetic algorithm in delivering optimal results. This optimization process was crucial in enhancing the performance of the tool, ensuring it could handle the increased complexity of the multi-section analysis while maintaining a reasonable computational load.

6.2.2 Division of the Model into Different Sections

In order to perform a detailed analysis of the structure, it is important to divide it into different sections, to have more detailed results in every part of the geometry, and to assign different materials to each part of the sandwich structure. This way, the first set of the solid section is created, which represents the foam, and the Airex 7075 material is assigned to it, followed by the creation of 4 different sections from the shell elements that represent 4 important parts of the structure: the top and bottom composite layer and the 2 stringers, as seen in Figure 6.2, where each color represents a different section.

6.2. Applied Modifications on the Code and Final Structure to Analyze

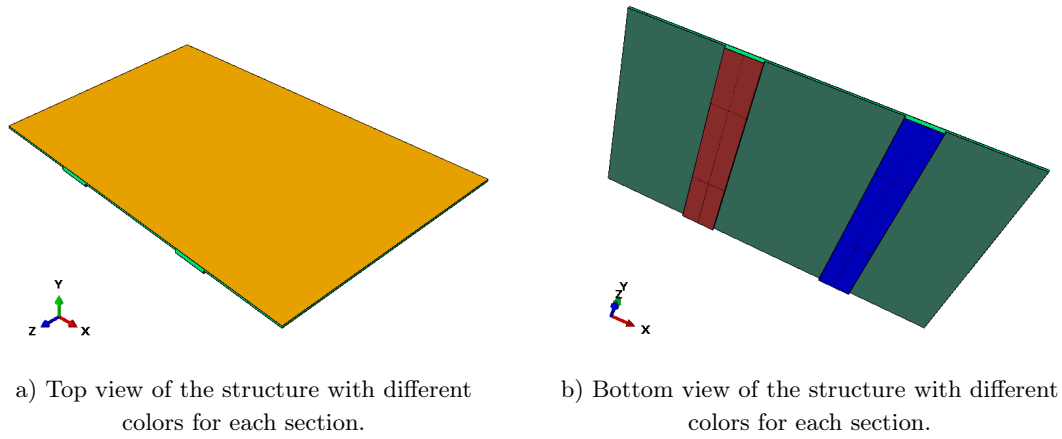


Figure 6.2: Created sections for analysis.

It is important to present the shell normal for each structure that will be analyzed, as the direction of the Ref1 reference orientation is crucial for the software to correctly analyze the composite layup, as this reference must always be in the same plane of the assigned surfaces. This way, the Axis-2 was used in the 4 sections, as it guarantees that this reference direction is at all times in said plane. In the next figures, each section is carefully shown with the proper assigned directions, and note that the Axis-1 could be used in both the top and bottom surfaces excluding the stringers, but it was chosen to use it in every section due to consistency purposes for the analysis of the results.

- **Top Composite Layup**

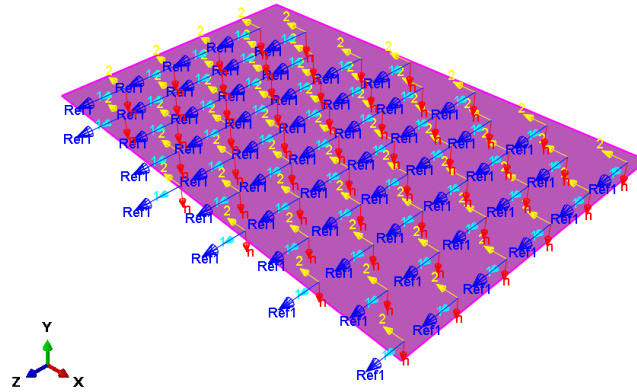


Figure 6.3: Shell reference on the upper skin.

- Bottom Composite Layup

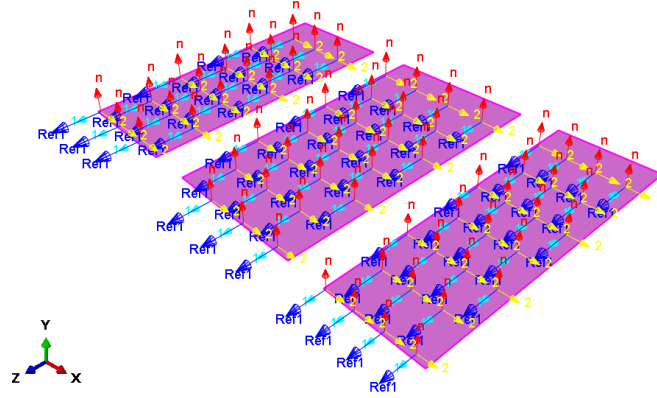


Figure 6.4: Shell reference on the bottom skin.

- Left and Right Stringers

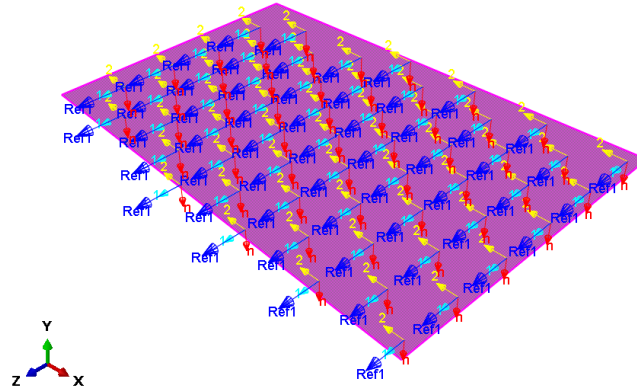


Figure 6.5: Shell reference on the stringers.

6.2.3 Description of the Optimization Tool

First, a Python script is created to automatically generate the developed Abaqus structure along with the defined initial parameters. After the creation of the geometry, the material properties of both the unidirectional carbon composite and the Airex 7075 are defined, according to Tables 4.1 and 4.2. Then, a solid section is created and assigned to the foam section, and the composite layups for each analyzed section are created. Note that the whole structure is generated as shell elements except for this solid section that represents the foam in the sandwich composite, and the whole model is created as one part in Abaqus, which is then inserted into the assembly. The boundary conditions and loads are then applied to the model, as already depicted in Chapter 4, and the interactions between different surfaces are created, to connect the foam with the carbon layers. The whole structure is then meshed according to the mesh convergence study already performed with quadrilateral shell elements, and it can be seen in Figure 6.6.

6.2. Applied Modifications on the Code and Final Structure to Analyze

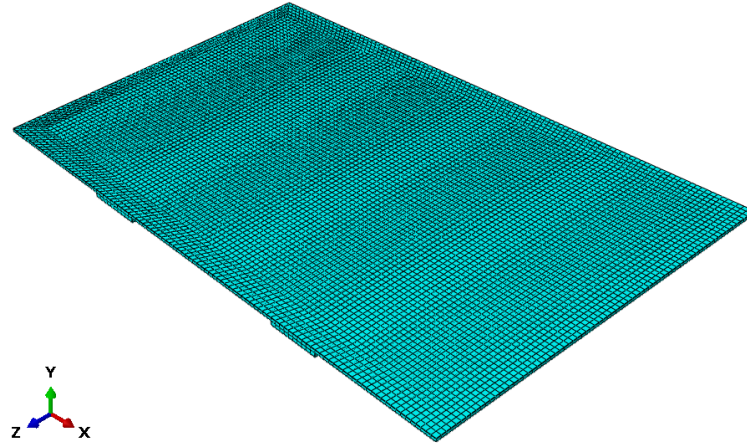


Figure 6.6: Generated mesh on the created structure.

After this definition, and according to the different composite layups generated in the DoE, the code modifies the initial structure with each of these layups, submits each one in a job in the software, and goes to the post-processing script, where the relevant values of stress and the Hashin's failure criteria are captured and stored in a database.

Then, a surrogate model of Hashin's failure criteria is created, and the number of samples to analyze in the training set should be obtained through a sensitivity analysis, but due to the long computational time to perform different analyses of the results (each analysis would take days or weeks), the value of 1200 samples was chosen, and the number of layers and directions of the composite in each section is randomly determined by the generation of the DoE with Latin Hyper Cubic technique with combinations of 0 to 4. Since the modeled structure has 4 different sections subject to analysis, the surrogate model will have 12 dependent variables. Combining the obtained training set with the Gaussian regression, it is possible to obtain the numerical surrogate model of the failure index, and a testing set is created to evaluate the created model with 250 samples. Finally, the genetic algorithm is applied to the obtained results, and a final optimized number of plies in each direction for each section is obtained.

6.2.4 Gaussian Regression Parameters

To obtain the optimal values to use in the Gaussian Regression, an iterative process was carried out in order to obtain the optimal values for the different variables (Alpha and Upper and Lower boundary constants), with the objective of obtaining the best possible values for both the R-Squared (as close as 1 as possible), and the Average mean error (as close as 0 as possible). Therefore, the final results of these variables were:

- Alpha = 0.1; It is a regularization parameter, that controls the strength of the regularization applied to the model.
- Upper Boundary Constant = 4; This is a threshold or constraint applied to the predicted values or model parameters to ensure they do not exceed a specified limit.
- Lower Boundary Constant = 1e-10; It is a constant that establishes the lower limit of the prediction range, ensuring that predictions do not approach zero.

With this parameters defined, the obtained results of both the R-Squared values and average mean error for each section in each direction are presented in Tables 6.2 and 6.3, showing that the number of samples is capable of providing accurate results, as the values of both the R-Squared and the AME are close to the expected values.

Table 6.2: Obtained R-Squared values for each section and each direction.

	0°	±45°	90°
	R-Squared	R-Squared	R-Squared
Section 1	0.852	0.805	0.675
Section 2	0.728	0.664	0.578
Section 3	0.721	0.223	0.320
Section 4	0.822	0.587	0.405

Table 6.3: Obtained Average Mean Error values for each section and each direction.

	0°	±45°	90°
	Average Mean Error	Average Mean Error	Average Mean Error
Section 1	0.004	0.002	0.001
Section 2	0.014	0.034	0.022
Section 3	0.233	0.339	0.056
Section 4	0.218	0.308	0.034

6.3. Results

6.2.5 Genetic Algorithm Parameters

Having the optimal parameters for the Gaussian regression defined, the next step is to perform another iterative process on the obtained results to obtain the optimal values for the different parameters of the genetic algorithm, with the objective of finding valid results while using the least computational results as possible. After the first results provided by the tool, it was clear that no variable would exceed the value of 3 layers in any direction, so the search space was narrowed and the number of bits reduced to 2, while maintaining the same population size, therefore increasing the number of explored individuals without using additional resources. The main goals of this optimization is to optimize the search process and its efficiency, and providing the best possible results using reduced computational power. The final values of the used parameters are stated below:

- Population = 100, represents the number of solutions analyzed by each iteration of the genetic algorithm.
- $L = 2$, the number of bits per variable.
- $P_c = 0.6$, the fraction of population to crossover.
- $P_m = 0.2$, the fraction of population to mutate.
- $P_g = 0.2$, the fraction of bits selected to mutation.
- $\lambda = 1$, the constraint penalty parameter

6.3 Results

Having applied the optimization tool on the designed structure, the process took approximately four days to complete, and this extended duration is justified by the relatively high number of design variables involved in the optimization problem. Specifically, each sample with different layers requires the submission of three results for each of the four sections, totaling twelve results per sample. Given this complexity, it was anticipated that the optimization process would take several days to finalize, and the results obtained provide insights into the optimal number of plies and their orientations for each section of the structure.

It is crucial to emphasize that the optimization tool should be viewed as an aid in the engineer's decision-making process rather than a definitive solution, and the results generated by the tool must be carefully analyzed to extract the most valuable information. Ideally, the number of samples generated for the Design of Experiments (DOE) and analyzed in each case should be around 3,000 to 4,000 [1]. However, completing this volume of analysis would take approximately three weeks or require a significantly more powerful computer to expedite the process. Given the constraints of time and available computational resources, 1,200 samples were used to analyze the model in this work.

Despite this limitation, it is essential to explore different possible solutions that are coherent with the results obtained from the optimization tool, as the optimum number of plies in each direction may slightly differ from the results provided by the tool, given the number of used samples. To ensure the reliability of the results and to obtain the most accurate optimization, various small variations of the obtained results were computed and analyzed in ABAQUS. This approach aims to validate the results from the optimization tool and to determine the optimal number of plies that ensure the structural integrity and prevent failure, and by performing these

Chapter 6. Application of the Tool on the Cargo Compartment

additional analyses, the objective is to fine-tune the solution and confirm the robustness of the optimized design.

Starting from the obtained results given by the samples, it is possible to analyze the failure indexes of Hashin's failure criteria for each direction in each section. In Figure 6.7, the Hashin's values for each direction in Section 4 is presented, and the plots for the other sections are presented in Appendix B.

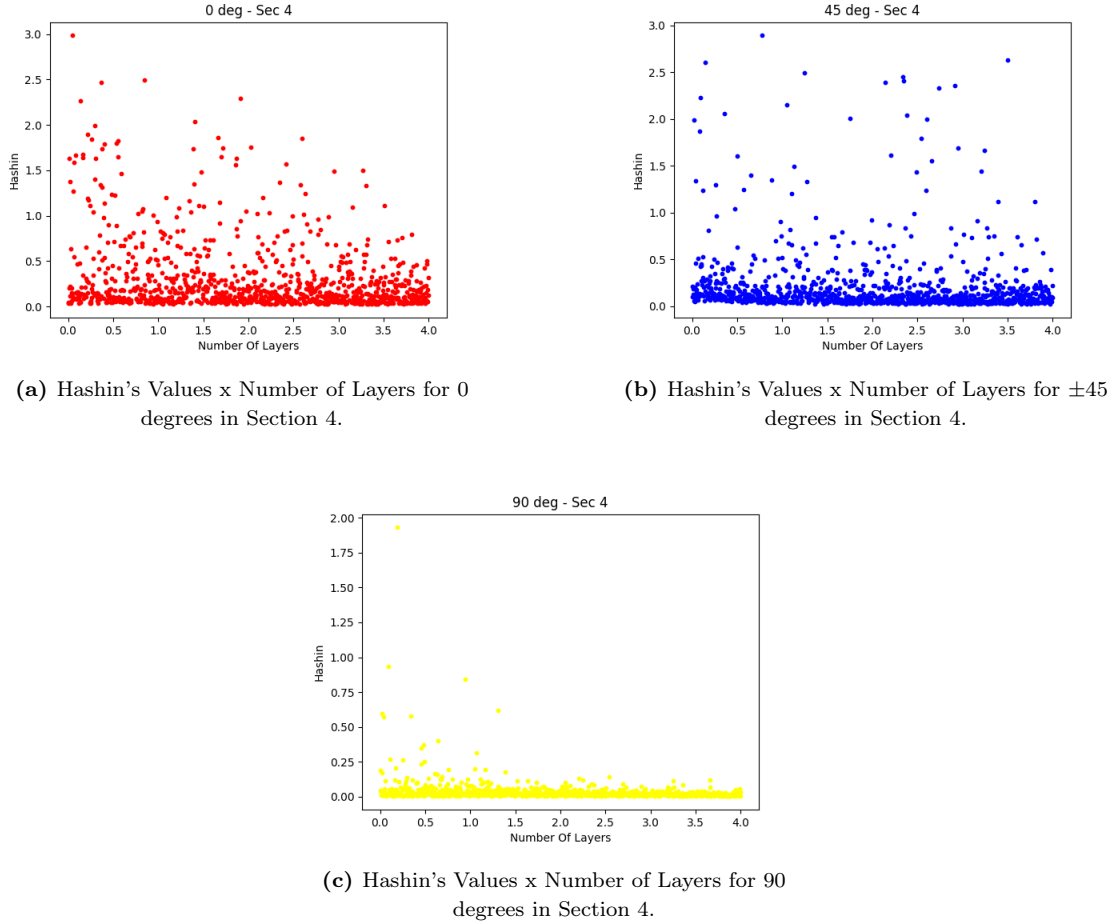


Figure 6.7: Hashin's values for each direction in Section 4.

The Genetic Algorithm successfully converged in 102 iterations, resulting in the optimal layup presented in Table 6.4. From these results, it is seen that, as expected, Section 1 is not a critical part of the structure, and a single ply in the 0° direction and another in the $\pm 45^\circ$ direction is enough for the composite layer not to fail. For section 2, since there is some high-stress areas around the stringers, it is coherent that additional plies are needed for the section not to fail, having 2 plies in the 0° direction, and one in both $\pm 45^\circ$ and 90° directions. Regarding the critical sections 3 and 4, different results were obtained. As it is known, the concentrated loads are directly applied in these sections, therefore it is expected that these are more prone to fail than the first 2 sections. This way, it is coherent that a larger number of plies is needed in these areas, as it was obtained from the optimization tool, with a total of 5 plies for each section, from which 3 are in the 90° direction.

6.3. Results

Table 6.4: Optimized Layup obtained by the optimization tool

	0°	45°	90°
	Number of Plies	Number of Plies	Number of Plies
Section 1	1	1	0
Section 2	2	1	1
Section 3	1	1	3
Section 4	1	1	3

Therefore, introducing these results in the FEM software ABAQUS, it is possible to analyze if the obtained results from the optimization tool are in compliance with the failure criteria. For the critical sections 3 and 4, the created layup is seen in Figure 6.8.

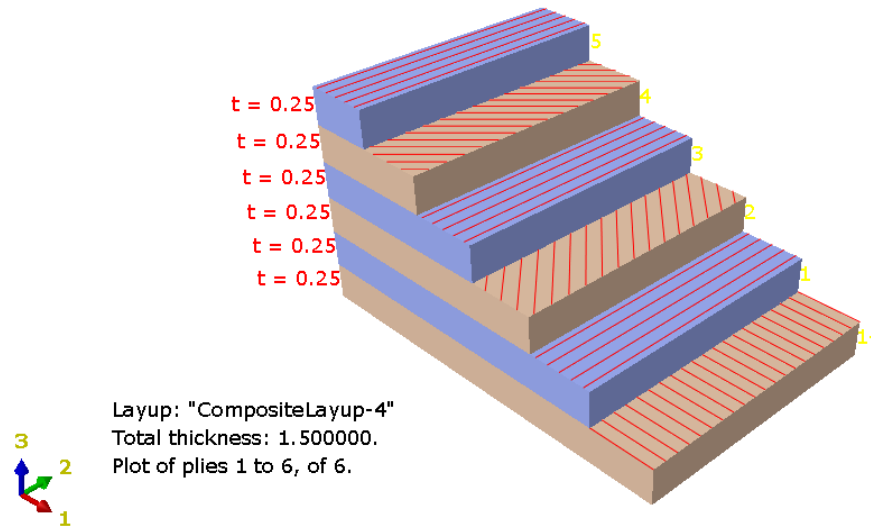


Figure 6.8: Visualization of the stacked plies in sections 3 and 4.

6.3.1 Failure Criteria

Performing an analysis in the software with these different composite layups, the following results were obtained regarding Hashin's failure initiation damage criteria:

Table 6.5: Obtained results regarding Hashin's failure criteria.

	Fiber Compressive	Fiber Tensile	Matrix Compressive	Matrix Tensile
Section 1	0.003	0.023	0.001	0.013
Section 2	0.001	0.271	0.278	0.349
Section 3	0.119	0.031	0.345	1.384
Section 4	0.114	0.033	0.342	1.408

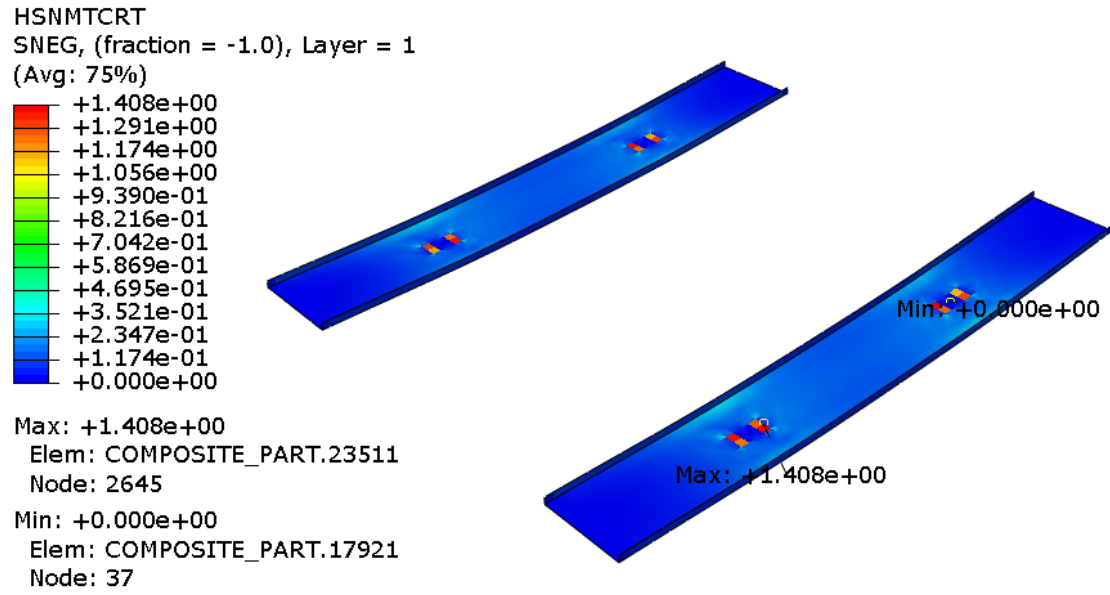


Figure 6.9: Hashin's Matrix Tensile failure criteria for sections 3 and 4.

As it is seen in Table 6.5 and Figure 6.9, the structure provides good results in terms of the failure of the fiber, but in sections 3 and 4 there is failure of the matrix, and this can be justified by the number of samples not being high enough for the optimization tool to provide an optimal results. However, as previously mentioned, the tool should be viewed as a support in the decision making so, this way, based on the results provided by the genetic algorithm, a modification was applied to the composite layups of sections 3 and 4: the addition of an extra layer in the $\pm 45^\circ$ direction, in order to strengthen the structure in this areas.

Therefore, creating the composite layups as in Table 6.6, the results are presented in Table 6.7.

Table 6.6: Optimized Layup with additional ply in critical sections.

	0°	$\pm 45^\circ$	90°
	Number of Plies	Number of Plies	Number of Plies
Section 1	1	1	0
Section 2	2	1	1
Section 3	1	2	3
Section 4	1	2	3

Table 6.7: Obtained results regarding Hashin's failure criteria for the final structure.

	Fiber Compressive	Fiber Tensile	Matrix Compressive	Matrix Tensile
Section 1	0.0028	0.025	0.001	0.015
Section 2	0.002	0.228	0.041	0.235
Section 3	0.132	0.026	0.106	0.714
Section 4	0.128	0.025	0.108	0.750

6.3. Results

From the results in the Tables above and Figure 6.10, it is seen that, with the introduction of a single ply of $\pm 45^\circ$ in the critical sections 3 and 4, the composite does not present a risk of failure and is well within the failure limits for all 4 failure indexes of Hashin's damage initiation failure criteria

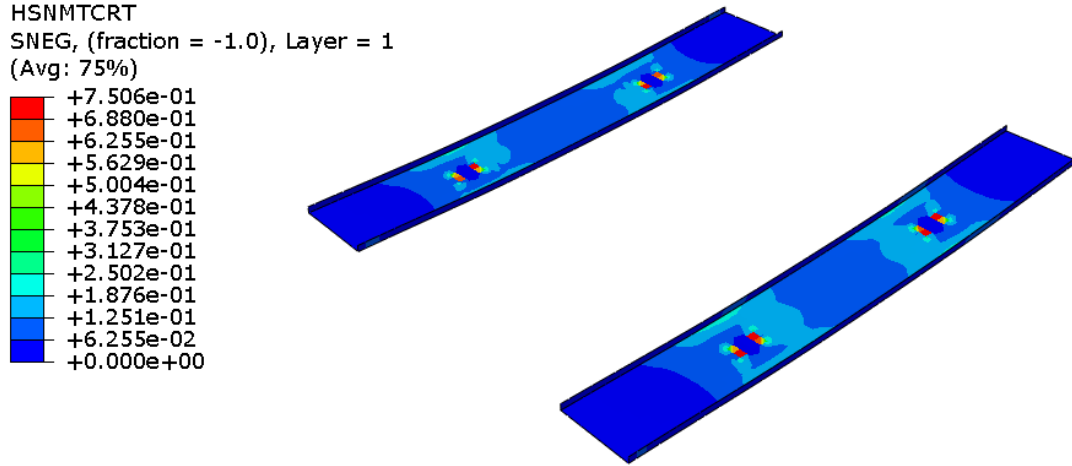


Figure 6.10: Hashin's Matrix Tensile failure criteria for sections 3 and 4 in the reinforced structure.

Performing a final analysis on the obtained results, it becomes evident that the optimization tool has provided coherent and expected outcomes for Sections 1 and 2. In Section 1, which constitutes the upper composite layer, the results align well with the initial expectations, as since no significant load is applied to this section, it was anticipated that it would not require many plies to guarantee that it would not fail. The final result indicating that just one ply in the 0° direction is sufficient to withstand the loads confirms this prediction, demonstrating that the section is adequately reinforced. In Section 2, the lower composite layer, the results are also consistent with expectations, as this section experiences higher loads than Section 1, particularly in areas near the stringers where high-stress concentrations occur. Consequently, the addition of one ply in each direction compared to Section 1 is appropriate and expected. This reinforcement ensures that the lower composite layer can handle the stresses without risk of failure, and the results indicate that this section is adequately protected and shows no signs of failure under the applied loads.

However, Sections 3 and 4, which correspond to the left and right stringers respectively, presented different results than anticipated. These sections are subjected to concentrated loads, creating high-stress zones near the points of load application, thus increasing the risk of failure significantly. Upon detailed analysis in ABAQUS, it was observed that these two regions fail under one of the Hashin's failure criteria, specifically the matrix tensile criterion. Given this information, and considering that the optimization tool is intended to aid the engineer's decision-making process, it was decided to reinforce Sections 3 and 4 with an additional ply in the $\pm 45^\circ$ direction. This strategic reinforcement addresses the high-stress concentrations effectively, as subsequent analysis confirmed that this adjustment brought the stress values within the failure envelope for all four Hashin's criteria. This proactive measure ensures that the sections can withstand the applied loads without failing, thereby validating the effectiveness of the optimization tool in guiding engineering decisions and reinforcing critical structural areas.

6.3.2 Weight Optimization

For a comprehensive final analysis, it is essential to evaluate the weight difference between the initial modeled structure, the structure subjected to optimization in the code, and the final optimized structure based on the results obtained from the optimization tool. Initially, the structure was modeled without any optimization considerations, resulting in a configuration that, while functional, was not weight-efficient. Subsequently, the structure was subjected to an optimization process aimed at reducing its weight by optimizing the number of plies and their orientations in each section, and the final optimized structure reflects the improvements suggested by the optimization tool, incorporating the most effective ply configurations for each section.

Table 6.8 presents the evolution of the structure's weight across each section for the different stages of analysis: the first structure with stringers, the following with thicker stringers, and the final optimized structure.

Table 6.8: Weight comparison on the different structures pre and post-optimization.

	Section 1 [kg]	Section 2 [kg]	Section 3 [kg]	Section 4 [kg]	Total Weight [kg]
Sandwich Panel with Two Stringers	2.790	2.260	0.284	0.302	6.020
Sandwich Panel with Two Thicker Stringers	2.790	2.260	0.299	0.318	6.090
Final Optimized Structure	0.698	1.131	0.224	0.239	2.740

Analyzing the results presented in Table 6.8, we can observe significant differences in weight across the different stages of structural optimization. In the initial stage, the structure, which included a sandwich panel with two stringers, had a total weight of 6.02 kg. This configuration, while functional, was not optimized for weight efficiency, as section 1 (the upper composite layer) weighed 2.79 kg, Section 2 (the lower composite layer) weighed 2.26 kg, and Sections 3 and 4 (the left and right stringers) weighed 0.284 kg and 0.302 kg, respectively. In the second stage, the structure was modified to include thicker stringers. This change resulted in a slight increase in the overall weight to 6.09 kg, as while Sections 1 and 2 remained the same in weight, Sections 3 and 4 experienced slight increases to 0.299 kg and 0.318 kg, respectively, due to the additional material required for the thicker stringers, as well as the increased volume of foam needed to accommodate the larger stringer profiles. The total weight also considers the foam, which is relevant in distinguishing the first case from the second one.

Finally, the optimized structure, as suggested by the optimization tool, showed a significant reduction in total weight to 2.74 kg, and this substantial decrease is attributed to the optimized number of plies and their orientations in each section. In Section 1, the weight dropped drastically to 0.698 kg, which can be explained by the minimal loading on the upper composite layer, requiring fewer plies for adequate reinforcement. Section 2, experiencing higher loads, was reduced to 1.131 kg due to an optimized ply configuration that still meets the structural requirements. Sections 3 and 4, which are critical due to the concentrated loads and high-stress areas near the stringers, saw their weights reduced to 0.224 kg and 0.239 kg, respectively. These reductions were achieved while ensuring that the regions remain within the failure envelope for all four Hashin's criteria,

6.3. Results

and the additional ply in the $\pm 45^\circ$ direction, applied as a precaution, ensured that these sections were sufficiently reinforced without adding excessive weight.

In conclusion, the weight optimization process has led to substantial reductions in the overall weight of the structure, as comparing the initial model (sandwich panel with two stringers) to the final optimized structure, we observe the following weight reductions in each section: Section 1 experienced a decrease from 2.79 kg to 0.698 kg, representing a 75% reduction, and section 2 saw a reduction from 2.26 kg to 1.131 kg, amounting to a 50% decrease. Sections 3 and 4, the left and right stringers, respectively, were reduced from 0.284 kg to 0.224 kg (21% reduction) and from 0.302 kg to 0.239 kg (21% reduction). Overall, the total weight of the structure decreased from 6.02 kg in the initial model to 2.74 kg in the optimized structure, resulting in a global weight reduction of approximately 54%. This significant reduction highlights the effectiveness of the optimization tool in enhancing the design for weight efficiency while maintaining the necessary structural integrity, and these results demonstrate the value of the optimization process in achieving a lightweight and robust structure, which is crucial for the performance and efficiency of the designed component.

Chapter 7

Conclusion and Future Works

This thesis presented a comprehensive approach to the design, structural analysis, and optimization of a cargo compartment for an unmanned aerial vehicle (UAV), and the primary focus was on developing a robust and lightweight composite structure capable of meeting the stringent requirements of UAV operations (namely the ASTM F3116 requirements), particularly for Tekever's ARX drone. This study successfully integrated advanced composite materials, finite element analysis (FEA), and genetic algorithms to optimize the ply configurations and enhance the structural performance of the cargo compartment.

The research began with a detailed review of UAV technologies, composite materials, and failure criteria, establishing a solid foundation for the design and analysis phases. The initial design of the cargo compartment included considerations for connections to the fuselage, extraction mechanisms, and actuation systems for the trapdoor, and structural analysis were performed to evaluate the response of the compartment under critical loading conditions, ensuring compliance with safety and performance standards. It was concluded that a lateral opening is the best option for the extraction of the cargo compartment, preferably with a sliding rail system, that provides a simple and reliable design, offering a smooth and controlled lateral movement for the cargo compartment, providing an easier loading and unloading of the cargo. Regarding the actuation mechanism of the trapdoors, different options were considered, and the preferred solution is the use of linear actuators, as its combination of moderate precision, high force output and reliability is the most suitable for the intended functioning. Finally, an electric strike lock mechanism emerges as the recommended choice for securing the UAV trapdoors, as its combination of fail-safe operation, reliability, precision control, and moderate cost makes it well-suited to meet the project's needs.

One of the significant contributions of this work was the improvement and application of an optimization tool tailored for composite structures that, by employing a genetic algorithm, the tool optimized the number of plies and their orientations in different sections of the cargo compartment, aiming to minimize weight while maintaining structural integrity. Improvements and modifications were made in different aspects of the tool, as adjustments in the number of analyzed sections were performed, requiring the transformation of certain variables to ensure the tool could retrieve and process the failure values for each of the newly defined sections. The introduction of Hashin's failure criteria into the optimization process provided a more accurate assessment of the composite material's performance under stress, leading to a more reliable design, and in efforts to reduce computational time and resources as much as possible, the code was adapted to import CAE files, therefore not needing to directly model the geometry of the structure and instead import it from

an already existing file.

The results demonstrated substantial weight savings and improved structural performance, as the optimized structure exhibited a significant reduction in total weight compared to the initial design, with a global weight reduction of approximately 54%. This achievement underscores the effectiveness of the optimization tool and the potential benefits of using advanced algorithms and FEA in the aeronautical field. While the optimization tool proved to be a valuable asset, it is important to recognize its role as a supplementary tool for engineers, as the results obtained should be carefully analyzed and validated through additional simulations and testing.

As final remarks, it is relevant to note that this thesis is in between the conceptual and preliminary stages of the development of the ARX, therefore, the theoretical study performed on the connection of the compartment to the fuselage, the possibilities of extraction of the cargo compartment, the actuation mechanism of the trapdoors and the locking mechanism to ensure a fail-safe structure should serve as a baseline for the continuous development of the ARX. Similarly, the design and modeling of the sandwich structure provided insights on how the structure reacts to the different modes of the load application and considered boundary conditions, and the optimization tool allowed to study the principal failures modes of each section and to obtain a significant weight reduction without compromising the structural integrity of the cargo compartment.

For future works, there are several paths that could be followed to continue the work performed on this thesis. Firstly, the current optimization process could be further refined by exploring alternative algorithms, such as memetic algorithms, which combine global and local search techniques to enhance optimization efficiency. Additionally, performing the same analysis with even more detailed sections and a higher number of samples would be interesting to further optimize the structure in critical areas and obtain even more precise results. For this, the optimization tool should be further improved in order to reduce computational time, as this would take weeks to complete. Moreover, the theoretical approach performed on the extraction of the cargo compartment and the actuation mechanism should be experimentally validated and studied in a more advanced phase of the project, as physical testing of prototypes would ensure that the theoretical benefits observed in the research translate into real-world performance gains. Finally, a trajectory analysis of the cargo deployment would be the next suggested course of action, as this analysis would ensure that the deployment mechanisms and the cargo's descent are thoroughly understood and optimized, minimizing the risk of collision or damage during release for both the cargo and the UAV itself.

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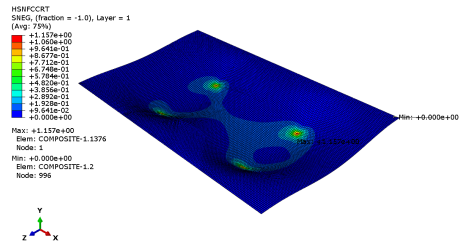
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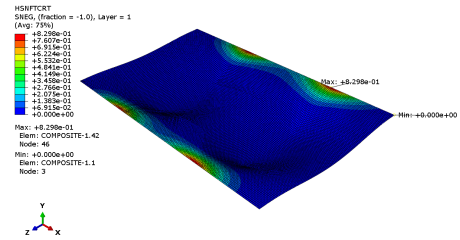
Appendices

Appendix A

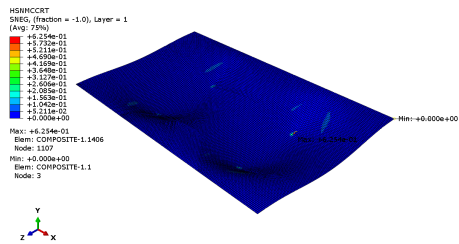
Hashin's values for all of the analyzed cases



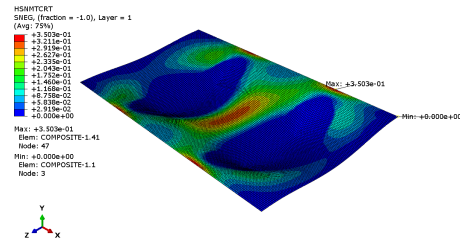
(a) Fiber compressive initiation criterion.



(b) Fiber tensile initiation criterion.

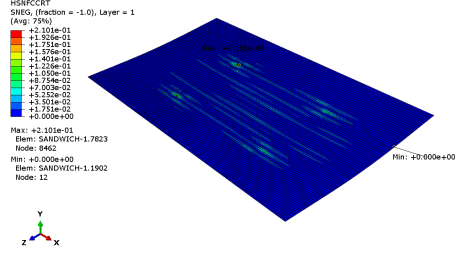


(c) Matrix compressive initiation criterion

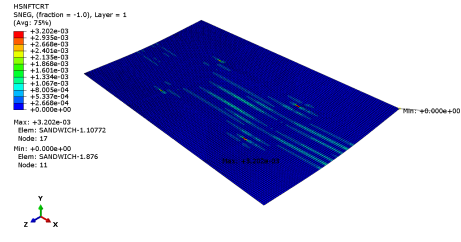


(d) Matrix tensile initiation criterion.

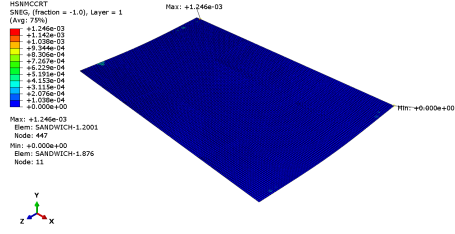
Figure A.1: Hashin's damage initiation criterion for analysis 1.



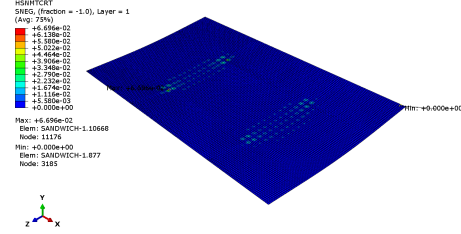
(a) Fiber compressive initiation criterion.



(b) Fiber tensile initiation criterion.

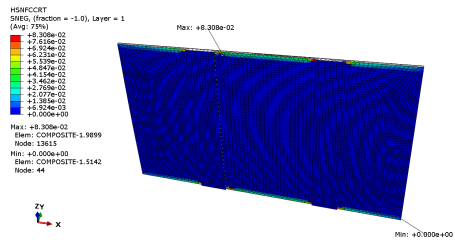


(c) Matrix compressive initiation criterion

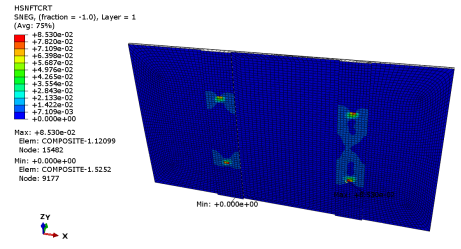


(d) Matrix tensile initiation criterion.

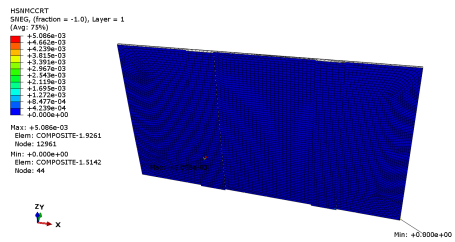
Figure A.2: Hashin's damage initiation criterion for analysis 2.



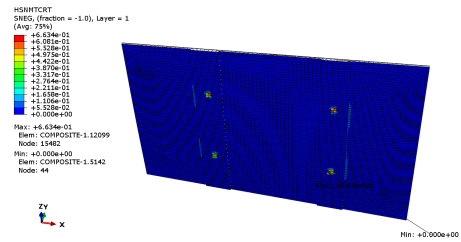
(a) Fiber compressive initiation criterion.



(b) Fiber tensile initiation criterion.

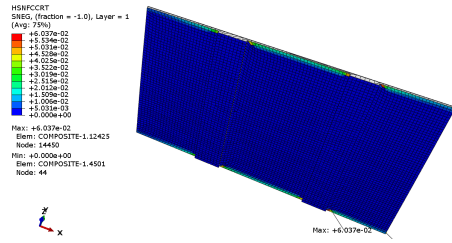


(c) Matrix compressive initiation criterion

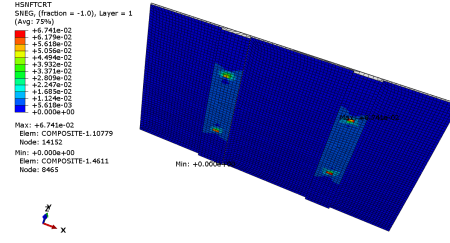


(d) Matrix tensile initiation criterion.

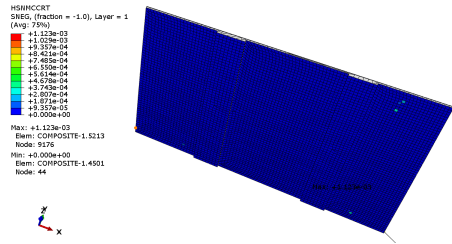
Figure A.3: Hashin's damage initiation criterion for analysis 3.



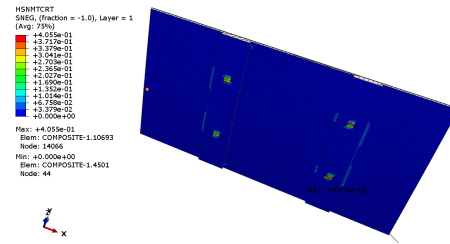
(a) Fiber compressive initiation criterion.



(b) Fiber tensile initiation criterion.



(c) Matrix compressive initiation criterion

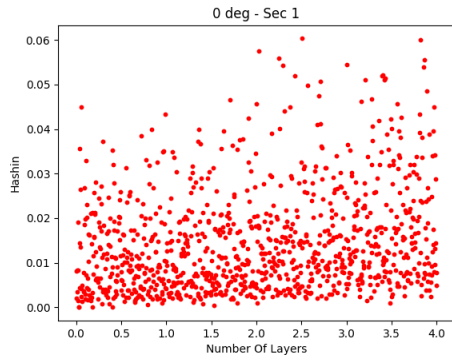


(d) Matrix tensile initiation criterion.

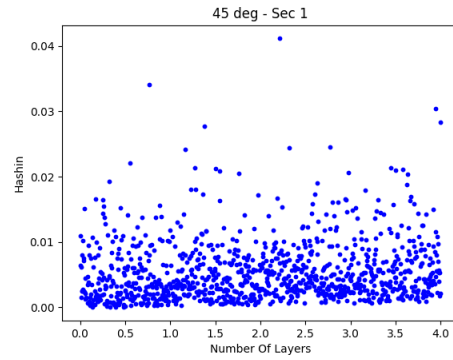
Figure A.4: Hashin's damage initiation criterion for analysis 4.

Appendix B

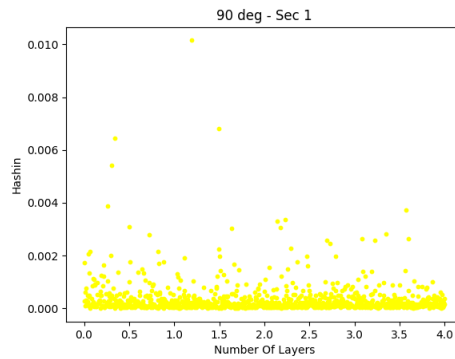
Hashin's values x Number of Layers for each Direction in each Section



(a) Hashin's Values x Number of Layers for 0 degrees in Section 1.

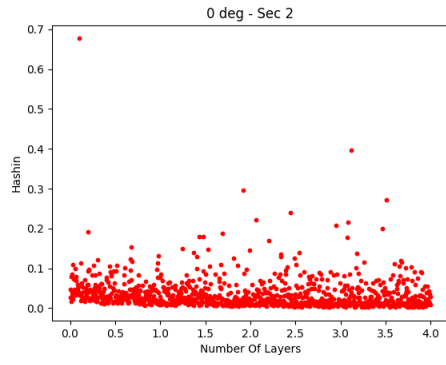


(b) Hashin's Values x Number of Layers for 45 degrees in Section 1.

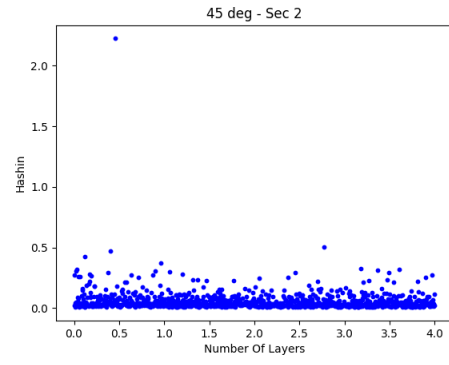


(c) Hashin's Values x Number of Layers for 90 degrees in Section 1.

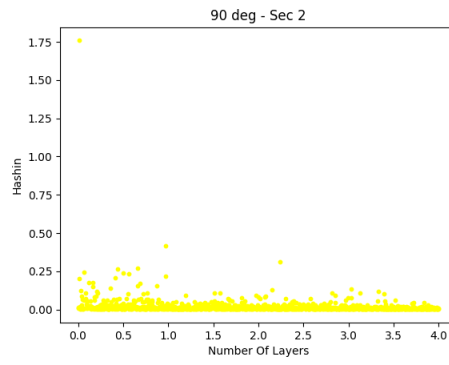
Figure B.1: Hashin's values for each direction in Section 1.



(a) Hashin's Values x Number of Layers for 0 degrees in Section 2.



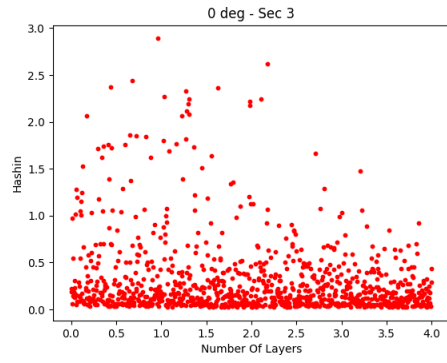
(b) Hashin's Values x Number of Layers for 45 degrees in Section 2.



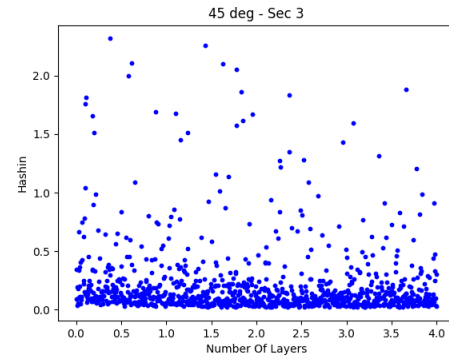
(c) Hashin's Values x Number of Layers for 90 degrees in Section 2.

Figure B.2: Hashin's values for each direction in Section 2.

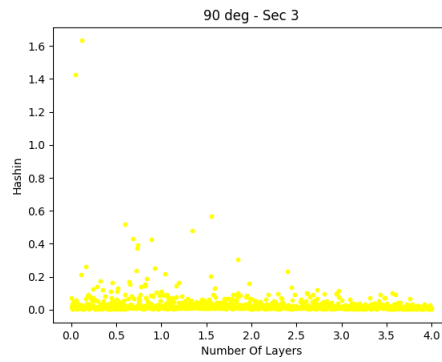
Chapter B. Hashin's values x Number of Layers for each Direction in each Section



(a) Hashin's Values x Number of Layers for 0 degrees in Section 3.

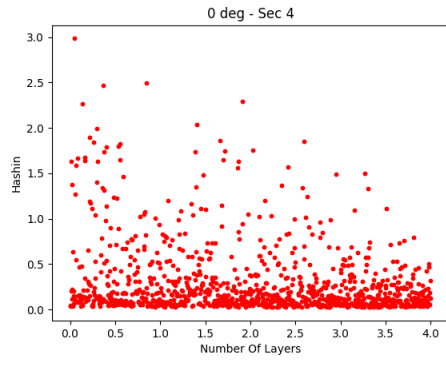


(b) Hashin's Values x Number of Layers for 45 degrees in Section 3.

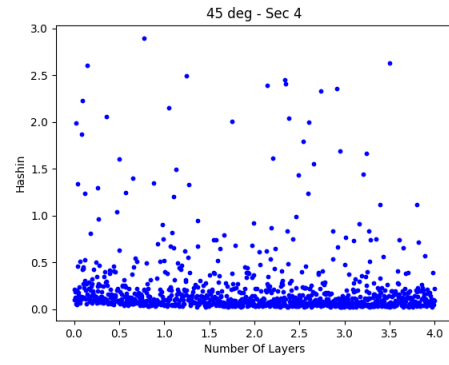


(c) Hashin's Values x Number of Layers for 90 degrees in Section 3.

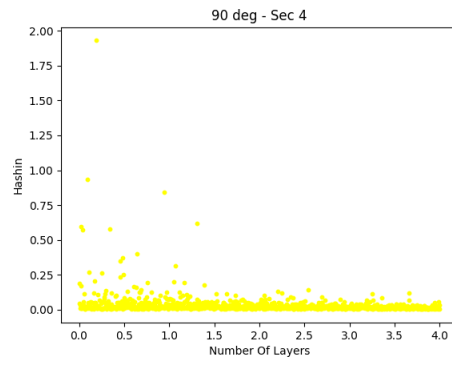
Figure B.3: Hashin's values for each direction in Section 3.



(a) Hashin's Values x Number of Layers for 0 degrees in Section 4.



(b) Hashin's Values x Number of Layers for 45 degrees in Section 4.



(c) Hashin's Values x Number of Layers for 90 degrees in Section 4.

Figure B.4: Hashin's values for each direction in Section 4.