# Structural Optimization of a Landing Gear

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**Abstract**

This dissertation consists on the process of optimizing the landing gear of an existing Unmanned Aerial Vehicle (UAV). For this purpose, a composite optimization was performed with the main objective of reducing the weight of the structure while maintaining its structural integrity.

The studies were carried out using a finite element structural analysis software coupled with an appropriate optimization algorithm.

Regarding the Finite Element Analysis, the structure was subjected to a load during the most critical flight phase, the landing. In this phase, the landing gear supports the weight corresponding to the rest of the aircraft structure.

In order to write this thesis, a bibliographic research was conducted to better understand the behaviour of composite materials. Also, a research about the optimization method called Direct Multi-Search (DMS) was made.

Secondly, it was necessary to do an initial model of the Landing Gear (LG) with the following steps: choosing the adequate mesh and element types; modelling the initial state of the material composites around the carcass of the LG; modelling the drop and shock tests that correspond to the landing phase; to divide posteriorly, the optimization process into smaller problems with each problem gradually increasing the design space.

Finally, a comparative analysis was done between the final results and the starting point: the primary goal, which was the reduction of the weight of the structure, was achieved. Additionally, it was verified that the structural integrity of the LG was maintained.
**Keywords:** Composite Structure Optimization, Weight Reduction, Direct MultiSearch, Landing

## 1. Introduction

In the times we live, in any kind of industry, the management of fuel and resources and their impact on the environment is of the utmost importance. In this work, we will be talking about an aircraft (such as the UAV presented in figure 1) with a certain long range mission where fuel consumption is crucial. The wider the range of the aircraft is, the more fuel is needed. Therefore, one of the solutions to reduce the fuel needed for a certain range; another solution, in order to increase the range of the aircraft with a specific amount of fuel, is to reduce the weight of the aircraft.

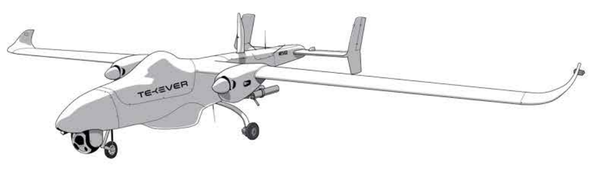


Figure 1: Ilustrative example of an UAV with Landing Gear [1].

The current work will focus on the landing gear of an aircraft developed by the enterprise TEKEVER[1]. The one-part landing gear is intended to support the remaining structure of the aircraft during some of the most crucial phases of flight: taxiing, take-off and landing. Therefore, when reducing the weight of the landing gear, one must make sure that it can uphold the same loads it used to before; in other words, that it can maintain its structural stiffness and strength. This is why it is so important to perform the optimization of the material this part is made of.

Material composites usage has expanded widely due to its well known stiffness-to-weight ratio. How the material composite is stacked-up is crucial for how much material is needed. By finding the optimal composite material composition we can build a much lighter landing gear with an excellent performance, with special attention to the landing phase, where the landing gear has to sustain the aircraft during the impact with the ground.

This work can, therefore, be useful for the mass reduction of other aircraft structures that can be manufactured with composite materials. This way, reducing the aircraft structure's mass would have a significant decrease in the materials costs and an increase in the range the aircraft can fly, leading to a lower fuel consumption and fuel expenses and, consequently, increasing the aircraft's sustainability, economically and environmentally.

The technical goals of this work are the following:

1. To define the critical structural loads to which the landing gear will be subjected;

2. To ensure the compatibility of the landing gear with the company's previous work, using an existing CAD;

3. To define the composite material compositions (both fibers and resins) candidate to be used in the optimization process;

4. To execute simulations of the landing gear during the landing phase of the flight, in order to assess the structural integrity and what solutions can be obtained. These simulations are structural analysis such as static (*Drop Test*) and dynamic non-linear (*Shock Test*);

5. According to the configuration that ensures the best structural integrity, to perform an optimization with reference to the number of layers, layer thickness, fibre orientation and, fibres to be used in order to make significant improvements to the landing gear.

## 2. Background

### 2.1. Basic Composite Concepts and Terminology

One of the most important and studied type of fibre composite materials is the unidirectional composite. An unidirectional (UD) composite is made of parallel fibres arranged in a matrix. This type of material forms the basic configuration of fibre composite materials. These fibres can be arranged in a specific orientation.

Woven fabric (WF) composites represent a class of textile composites where two or more yarn systems are interlaced at a certain angle. WF composites provide more balanced properties in the fabric plane and higher impact resistance than unidirectional composites. As the handling of woven fabrics is easier, fabrication of WF composites becomes less laborious and the manufacturing errors are also reduced. Nonetheless, these advantages are obtained at the cost of in-plane stiffness and strength properties due to the undulation of yarns [6].

A composite is called a laminated composite when it consists of layers of at least two different materials (or the same material with different assemblage) that are bonded together. Lamination is used to combine the best aspects of the constituent layers in order to achieve a more useful material. The ability to structure and orient material layers in a prescribed sequence leads to several particularly significant advantages of composite materials compared with conventional monolithic materials. The most important among these advantages is the ability to tailor or to match the lamina properties and the orientations to the prescribed structural loads. The properties that can be emphasised by lamination are strength, stiffness, corrosion resistance and low weight, for example [8].

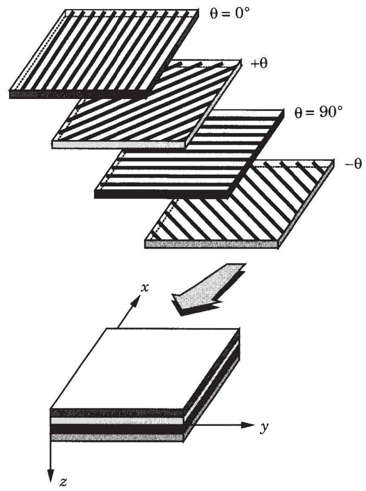


Figure 2: A laminate made with laminae with different fiber orientations [7].

### 2.2. Laminate Theory and Finite Element Analysis

Classical laminate theory defines the response of a laminate with the following assumptions:

- For two-dimensional plane stress analysis, the strain is constant through the thickness.
- For bending, the strain varies linearly through the thickness.
- The laminate is thin compared with its in-plane dimensions.
- Each layer is quasi-homogeneous and orthotropic.
- Displacements are small when compared with the thickness.
- The behaviour remains linear.

With these assumptions satisfied, the laminate theory allows the response of a laminate to be calculated, the engineering constants to be determined and substituted into standard formulas for stresses and deflections, and the material properties of the laminate to be defined, either analytically or using a FE software.

In summary, the finite element method in structural analysis [3] involves dividing the continuum structure into discrete elements. Each panel becomes an assembly of non-overlapping plate or brick elements that are connected at discrete points called nodes. The behaviour of each element is defined by a relation between force and displacement at the nodes that are usually located at the boundaries of the element. The elements are then assembled into a structure by satisfying the equilibrium of the forces. The modelling process involves approximations for geometry and may not reflect the true detail, such as the change of the orientation of fibres during lay-up and cure. The size of a three-dimensional brick element will be governed by the minimum dimension (usually the thickness). As a result, engineers have developed beam, plate, and shell approximations to structural behaviour [2].

### 2.3. Multi-objective optimization problem

In a Multi-Objective Optimization (MOO) problem, two or more objective functions are simultaneously optimized. A MOO problem with inequality constraints can be stated as:

$$\text{Find } \boldsymbol{X} = \begin{Bmatrix} x_1 \\ x_2 \\ \dots \\ x_n \end{Bmatrix} \tag{1}$$

which minimizes simultaneously,

$$f_1(\boldsymbol{X}), f_2(\boldsymbol{X}), ..., f_k(\boldsymbol{X}) \in \boldsymbol{Y} \tag{2}$$

subject to,

$$\begin{gathered} g_i(\boldsymbol{X}) \leq 0, i = 1, 2, ..., m; \\ h_j(\boldsymbol{X}) = 0, j = 1, 2, ..., p; \\ x_l^L \leq x_l \leq x_l^U, \forall l = 1, 2, ..., q. \end{gathered} \tag{3}$$

where $k$ denotes the number of competing objective functions to be minimized, $(m + p + q)$ is the number of constrains and $n$ is the number of design variables. Any or all of the functions $f_k(\boldsymbol{X})$, $g_i(\boldsymbol{X})$ and $h_j(\boldsymbol{X})$ may be non-linear.

The inequality constraints are treated as 'greater-than-equal-to' types, although a 'less-than-equal-to' type inequality constraint is also taken care of in the above formulation. In the latter case, the constraint must be converted into a 'greater-than-equal-to' type constraint by multiplying the constraint function by -1 [5]. In other words, maximizing $f$ is equivalent to minimizing $-f$. Therefore we refer only to minimization.

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### 2.4. Concept of Domination

In general, no solution vector $\boldsymbol{X}$ exists that minimizes all the $k$ objective functions simultaneously. Hence, a concept (of domination), known as the *Pareto optimum solution*, is used in multi-objective optimization problems to compare two solutions. A feasible solution $\boldsymbol{X}$ is called *Pareto optimal* or non-dominated if there is no other feasible solution $\boldsymbol{Y}$ such that $f_i(\boldsymbol{Y}) \leq f_i(\boldsymbol{X})$ for $i = 1, 2, ..., k$ with $f_j(\boldsymbol{Y}) < f_i(\boldsymbol{X})$ for at least one $j$. In other words, a feasible vector $\boldsymbol{X}$ is called non-dominated or *Pareto optimal* if there is no other feasible solution $\boldsymbol{Y}$ that would reduce some objective function without causing a simultaneous increase in at least one other objective function. The family of all non-dominated solutions is denoted as *Pareto-optimal* set (Pareto Set) or *pareto-optimal* front.

### 2.5. Direct MultiSearch

One possible optimization algorithm to be applied in a MOO problem is the Direct MultiSearch Method (DMS), which does not aggregate or define priorities for the several objectives involved. Each iteration of this method is organized around a search step and a poll step. Given a current iterate (a poll centre), the poll step evaluates the objective function at some neighbour points defined by a positive spanning set and a step size parameter. After having chosen one of the non-dominated points (stored in the current iterate list) as the iterate point (or poll centre), each poll step performs a local search around it.

In a MOO problem the acceptance criterion of new iterates changes according to *Pareto* dominance, which then requires the updating of a list of (feasible) non-dominated points. At each iteration, polling is performed at a point selected from this list, and its success is dictated by changes in the list. A search step is done too, whose main purpose is to further disseminate the search process of all of the *Pareto* front. The concept of *Pareto* dominance is used to characterize global and local optimality, by defining a *Pareto* front or frontier as the set of points in $\Omega$ non-dominated by any other one in $\Omega$.

The DMS algorithm can be summed up in the following steps:

- Initialization;
- Selection of an iterate point;
- Search Step;
- Poll Step;
- Step Size Parameter.

In the DMS method, the constraints are handled with an extreme barrier function that is set as shown in equation 4:

$$F_\Omega = \begin{cases} F(x) & \text{if } x \in \Omega \\ (+\infty, ..., +\infty)^T & \text{otherwise} \end{cases} \quad (4)$$

When a point is infeasible, the components of the objective function F are not evaluated, and the values of $F_\Omega$ are set to $+\infty$. This approach allows one to deal with black-boxtype constraints, where only a yes or no answer is returned.

In reference [4] DMS is compared to some of a well known genetic solvers, the NSGA-II (C version), and conclude that DMS has a better performance in terms of efficiency.

Details are omitted in the present work and the reader is referred to [4] for a more complete description of this method.

## 3. Implementation

### 3.1. Model

The CAD of the Landing Gear designed by TEKEVER is one solid piece only. Firstly, in order to model it as a carcass with a composite stack-up, the usage of shell elements is necessary. Therefore, one single change was made to the CAD so it would be a surface object. The object was also moved so its centroid would coincide with the origin of the Cartesian coordinate system. To reduce the computational cost the Landing Gear model was "cut" in half, since we are dealing with a symmetric problem.

Secondly, the *Engineering Data* was defined in the *ANSYS Workbench* environment. There are two possible composite materials that can be used to manufacture the landing gear according to TEKEVER: Epoxy Carbon (Unidirectional) Wet and Epoxy Carbon (Woven) Wet.

Figure 3 shows the mesh convergence analysis which was done in order to chose the most adequate mesh for the static structural analysis (mentioned in section 3.2) that will be done multiple times during the optimization phase. Therefore, it was taken into consideration the computational cost needed.


Figure 3: Mesh Convergence Analysis.

Since this work implies a "shell" type of geometry, the elements are, trivially, shell type elements. The elements used were the **Quad4 Thin Shell** and the **Tri3 Thin Shell**. **Quad4** refers to a **4 Node Linear Quadrilateral Element** and **Tri3** refers to a **3 Node Linear Triangle Element**. Being these elements shell type, each of the nodes has 5 Degrees of Freedom (DOF): translation in X, Y, Z and two in-plane rotation.

Figure 4 shows the mesh obtained with a total of 2371 elements and 2263 nodes.

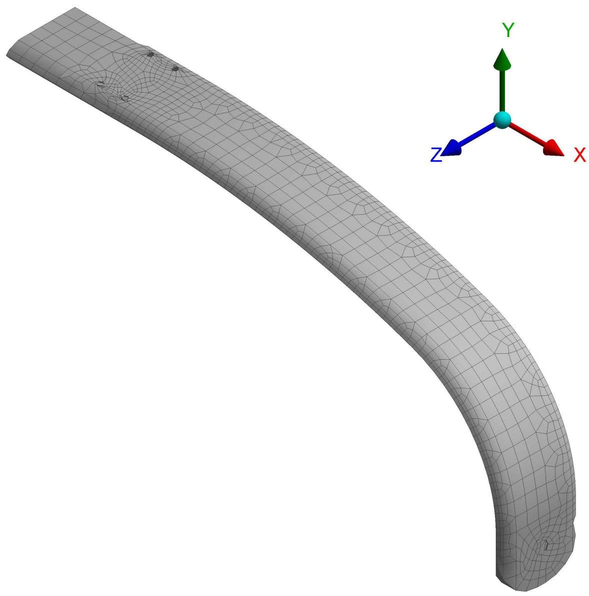


Figure 4: Mesh used for the FEA.

Last, but not least, several *Named Selections* were created according to the sections shown in figure 8, but also, dividing the LG in an upper and lower part.

After the defining the mesh, *ANSYS Composit PrePost* (ACP) tool was used in order to model the composite stack-up around the carcass.

To start, and for further comparison with the optimization results, an initial stack-up was modelled according to the table 1 (with special attention to the fact that it is top-down with no symmetry selected):

Table 1: Initial Stack-up.

| Ply | Material | Thickness [mm] | Orientation [°] |
|---|---|---|---|
| 1 | Epoxy Carbon UD | 0.5 | 0 |
| 2 | Epoxy Carbon UD | 0.5 | 0 |
| 3 | Epoxy Carbon UD | 0.5 | 0 |
| 4 | Epoxy Carbon UD | 0.5 | 0 |
| 5 | Epoxy Carbon UD | 0.5 | 0 |
| 6 | Epoxy Carbon Woven | 0.75 | 45 |
| 7 | Epoxy Carbon Woven | 0.75 | 45 |
| 8 | Epoxy Carbon UD | 0.5 | 0 |
| 9 | Epoxy Carbon UD | 0.5 | 0 |
| 10 | Epoxy Carbon UD | 0.5 | 0 |
| 11 | Epoxy Carbon UD | 0.5 | 0 |
| 12 | Epoxy Carbon Woven | 0.75 | 45 |
| 13 | Epoxy Carbon Woven | 0.75 | 45 |

To model the carcass that was specified on table 1, the ACP tool was used. In order to do this, the rosette, the oriented selection set and the modelling group had to be defined.

Firstly, a single rosette was created with the type *Edge Wise* and with the edge along the LG selected (the named selection that was created before it is used). The origin of the Rosette is the centroid of the LG. Last, but not least, the direction 1 and direction 2 are (1, 0, 0) and (0, 1, 0), respectively in the (x, y, z) axis. These directions represent the 0 fibre alignment and the stack direction.

Secondly, a single Oriented Selection Set was created (the named selection that are used in this correspond to section 4 from figure 8, both upper and lower part of the LG). The chosen point was (0, 0.0534, 0) so it would coincide with the middle bottom of the landing gear. Finally, the chosen direction was (0, 1, 0) and the created Rosette was selected.

Lastly, a single Modelling Group was created with the created stack-up and oriented selection set selected.

3.2. Static Structural Analysis - Drop Test

At this point, half of the LG weights 1.6339 N. Through a static structural analysis, the displacements, stresses, strains, and forces in structures or components caused by loads that do not induce significant inertia and damping effects can be determined assuming steady loading and response conditions.

For all the analysis, the model with the shell elements was imported from the ACP tool. This analysis it is intended to simulate a drop test - the drop of the landing gear at a height of 0.5 m with a deceleration of 0.1 s. Like any FEA, boundary conditions and solutions have to be defined.

### 3.2.1 Boundary Conditions

- The nodes that are on the symmetry plane of the landing gear have a fixed support;
- Springs (*body-ground* type) are attached to the landing gear where the wheels are supposed to be; These springs have a longitudinal stiffness of 83.025 N/mm;
- A remote force is applied where the wheels are supposed to be. This force has a positive sign in the y axis and is equal to 2817.5 N.

### 3.2.2 Solutions

For the optimization process, only the maximum total deformation value is needed from this analysis, but, for the purpose of results comparison, the following solutions are defined.

- Total Deformation;
- Equivalent Elastic Strain;
- Equivalent Stress.

Also, using the Tsai-Hill failure criteria, the Composite Failure Tool available on ANSYS WB was used and the following solutions where defined:

- Safety Factor (SF);
- Inverse Reserve Factor (IRF);
- Saftey Margin (SM).

These results are shown in table 2 and will be compared with the final results.

Figure 5 shows the Total Deformation solution after the analysis of the initial stack-up. It can be seen that the part of the LG that experiences the most deformation is the part that is connected to the wheels - thus, it is the part that is more exposed to the impact. Also, it can be recognized that the upper part of the LG is subjected to compressive forces and the lower part, on the other hand, is subjected to tensile forces.

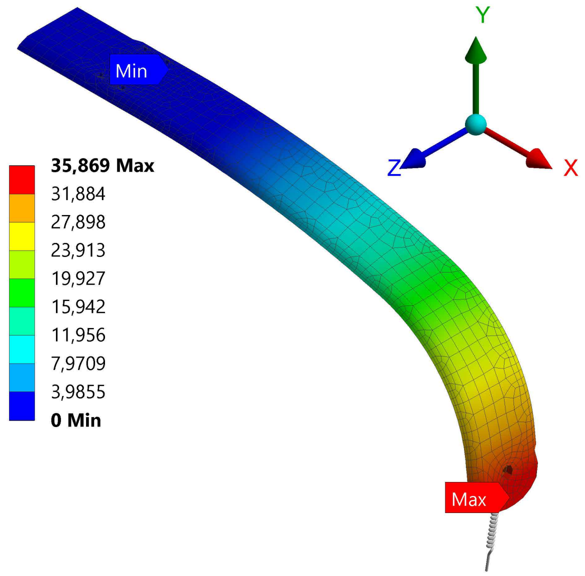


Figure 5: Total Deformation solution of the Static Structural Analysis.

Table 2: Drop Test Simulation for the Initial Stack-up

| | **Maximum** | **Minimum** |
|---|---|---|
| Total Deformation [mm] | 35.87 | 0 |
| Equivalent Elastic Strain [mm/mm] | $8.47\times10^{-3}$ | $\approx 0$ |
| Equvalent Stress (Von-Mises) [MPa] | 511.76 | 0.55 |
| Inverse Reverse Factor | 1.42 | 0.02 |
| Safety Factor | 58.60 | 0.70 |
| Safety Margin | 57.60 | -0.30 |

3.3. Transient Structural Analysis - Shock Test

A transient analysis, by definition, involves loads that are a function of time. Since the tires are modelled with a spring that has a damping factor, it is essential to make this analysis. Once again, there is the need to define the boundary conditions and what solutions are necessary, but, most importantly, the analysis settings are also required.

In the **Analysis Settings** field, the time step that is used for the analysis is defined. This value can be found by obtaining the first non zero natural frequency of the structure (the lowest frequency).

### 3.3.1 Boundary Conditions

- The nodes that are on the symmetry plane of the landing gear have zero displacement on the x and y axis;
- Springs (*body-ground* type) are attached to the landing gear where the wheels are supposed to be. These springs have a longitudinal stiffness of 83.025 N/mm;
- *Standard Earth Gravity* is applied on the -y axis;
- An initial velocity of 3.13 m/s is applied.

### 3.3.2 Solutions

- Total Deformation;
- Equivalent Elastic Strain;
- Equivalent Stress;
- Inverse Reserve Factor;
- Safety Factor;
- Saftey Margin.

These results are shown in table 3 and will be compared with the final results.

Table 3: Shock Test Simulation for the Initial Stack-up

| | **Maximum** | **Minimum** |
|---|---|---|
| Total Deformation [mm] | 202.38 | 162.98 |
| Equivalent Elastic Strain [mm/mm] | $1.82\times10^{-3}$ | $\approx 0$ |
| Equvalent Stress (Von-Mises) [MPa] | 674.87 | 0.18 |
| Inverse Reverse Factor | 3.55 | 0.02 |
| Safety Factor | 59.55 | 0.28 |
| Safety Margin | 58.55 | -0.72 |

3.4. Optimization of the composite material

In this work, the DMS method was employed, starting with the reference stack-up as its first poll centre and, therefore, start searching locally around that point with a small design space. Later on, after having some initial solutions, it was intended to gradually expand the design space in order to "guide" the optimization process.

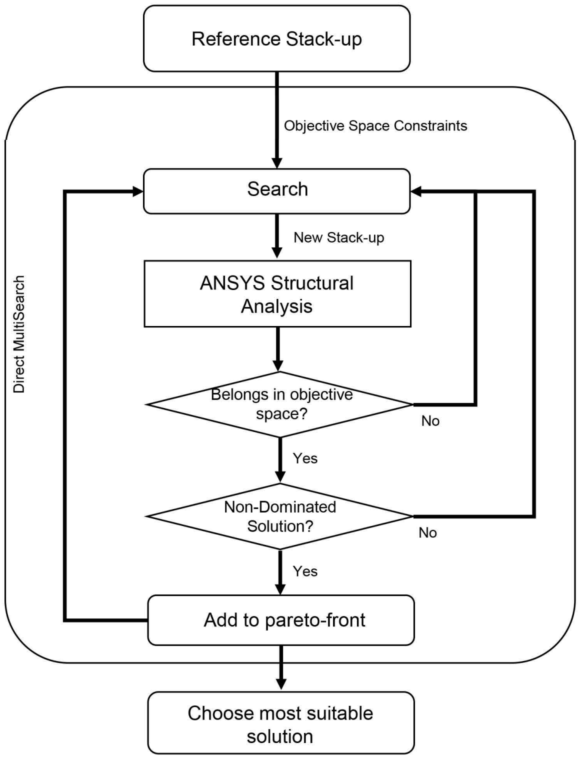


Figure 6: Schematic of the optimization process.

The algorithm is adequate to deal with black-box type of analysis and figure 6 shows how the *ANSYS WB* software was used as the black-box from this optimization process. Therefore, the static structural analysis will be returning to the algorithm two values, the **Maximum Displacement Over Time** and the **Weight** of the structure, as it is shown in the schematic from figure 7.

The connection between the DMS algorithm coded in *MatLab* and the *ANSYS* software is done when *MatLab* executes an operating system command requesting *ANSYS WB* to run a python script. This script opens the project of the Landing Gear, updates the model with the new stack-up, requests a new static structural analysis and saves the values to be returned to the DMS algorithm.

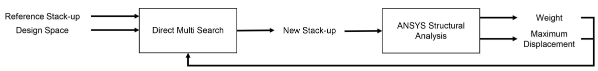


Figure 7: Schematic of the DMS and ANSYS WB interaction.

In order to ANSYS be able to update the model, it is necessary, beforehand, to redo the modelling procedure explained before, but, this time, adapted to the new solution found by the algorithm. This is done by editing a python script where the ACP tool, from *ANSYS WB*, saves the modelling of the composite materials. It is found in a file named *ACP-Pre.acp* in the Landing Gear project files. Therefore, this script is coded through strings of characters that *MatLab* writes on the files, according to the stack-up indicated and to the specified procedure.

Consider that, taking reference [4] into account the algorithm is for continuous variables. Since this optimization problem has discrete variables, one modification had to be made: when the algorithm indicates a set of data to be analysed by *ANSYS*, the data values are approximated to their nearest integer.

#### 3.4.1 Objective Space

It was necessary to define the objective space so the extreme barrier function (equation 4) could be set. Since the only solutions of interest were solutions that were better than the reference stack-up, and considering the extreme barrier function, (equation 4) the objective space was defined as:

$$x \in \Omega \text{ if } F(x) < F(\text{Reference}) \tag{5}$$

where

$$\begin{cases} F(x) = \{ \text{ Weight ; Maximum Displacement } \} \\ F(\text{Reference}) = \{1.653 \text{ [N] }; 35.869 \text{ [mm] } \} \end{cases} \tag{6}$$

These values from equation 6 were outputs from the ACP tool and the static structural analysis (see section 3.2).

#### 3.4.2 Design Space

The most appropriate approach regarding the design space was to perform several optimization runs and with each run slightly expand the design space. There were several variables that make the design space to be considered in this optimization problem:

- **Thickness** ($t_i$)- The thickness of each ply ($i$) can be either a discreet or a continuous variable, but, due to manufacturing considerations, it was be considered as a discreet variable.
- **Orientation** ($\alpha_i$) - The orientation of the fibres in each ply has to vary between 0 and 45. It can either be a discreet or continuous variable, but, for the reason mentioned above, it was considered as a discreet variable.
- **Material** ($M_i$) - The material in each ply can either be UD Carbon fibre epoxy or the Woven Carbon fibre.
- **Number of plys** ($n_{top}$ and $n_{bottom}$) - This discreet variable can vary between 5 plys to a maximum of 13 plys in either the upper or lower part of the landing gear.

- **Length** ($l_i$) - The composite material is supposed to go from the centre of the landing gear until a specific section of the piece. Four sections of the landing gear were defined and are shown in figure 8. The composite can go from the mid-plane to one of these sections in either the upper or lower part of the landing gear. These sections are defined in the Finite Element Software as Named Selections.

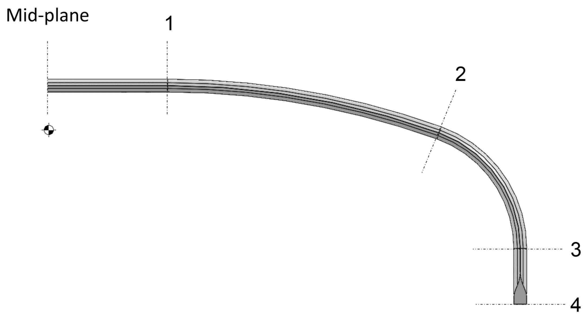


Figure 8: Section division of half of the Landing Gear.

## 4. Results

As mentioned before, the optimization process was divided into smaller problems, in which the design space progressively increased. This allowed the algorithm to look for solutions in the vicinity of the solutions found in previous stages and, therefore, to increase its performance. The complete design space where the algorithm searched was the following:

### 4.1. Design Space

- $t_i \in \{0.5; 0.75\}$ (mm);

- $n_{top}, n_{bottom} \in \{5; 6; 7; 8; 9; 10; 11; 12; 13\}$;

- $\alpha_i \in \{0; 5; 10; 15; 20; 25; 30; 35; 40; 45\}$ (°);

- $M_i \in \{0; 1\}$ being 0 the composite with UD fibres and 1 with the woven fibres;

- $l_i \in \{1; 2; 3; 4\}$;

After the five stages of the optimization process the pareto-front in figure 9 was obtained. Each point in the figure represents a unique stack for the Landing Gear and it can be observed that all the points dominate the original stack and are also non-dominated.

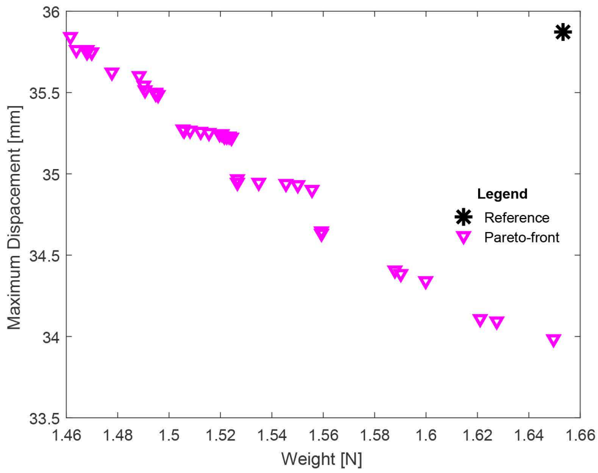


Figure 9: Resulting Pareto-front of the optimization process

Since the main goal is the reduction of the weight of the structure, the solution with most interest in figure 9 is the point that is at the left of all the remaining points. The stack-up for this solution is presented in tables 4 and 5.

Table 4: Upper Part of the Landing Gear Final Stack-up

| Ply Number | Material | Thickness [mm] | Orientation [°] | Length |
|---|---|---|---|---|
| **1** | Carbon UD | 0.5 | 0 | 4 |
| **2** | Carbon UD | 0.5 | 0 | 4 |
| **3** | Carbon UD | 0.5 | 0 | 4 |
| **4** | Carbon UD | 0.5 | 0 | 4 |
| **5** | Carbon Woven | 0.5 | 0 | 4 |
| **6** | Carbon Woven | 0.5 | 0 | 4 |
| **7** | Carbon UD | 0.5 | 0 | 4 |
| **8** | Carbon UD | 0.5 | 10 | 4 |
| **9** | Carbon UD | 0.5 | 0 | 4 |
| **10** | Carbon UD | 0.5 | 0 | 4 |
| **11** | Carbon Woven | 0.5 | 0 | 4 |
| **12** | Carbon Woven | 0.5 | 45 | 4 |

Table 5: Lower Part of the Landing Gear Final Stack-up

| Ply Number | Material | Thickness [mm] | Orientation [°] | Length |
|---|---|---|---|---|
| **1** | Carbon UD | 0.5 | 0 | 4 |
| **2** | Carbon UD | 0.75 | 0 | 3 |
| **3** | Carbon UD | 0.5 | 0 | 4 |
| **4** | Carbon UD | 0.5 | 0 | 4 |
| **5** | Carbon UD | 0.5 | 0 | 4 |
| **6** | Carbon UD | 0.5 | 0 | 4 |
| **7** | Carbon UD | 0.75 | 0 | 4 |
| **8** | Carbon UD | 0.5 | 25 | 4 |
| **9** | Carbon UD | 0.75 | 0 | 4 |
| **10** | Carbon UD | 0.75 | 0 | 4 |
| **11** | Carbon UD | 0.5 | 0 | 4 |
| **12** | Carbon UD | 0.5 | 0 | 4 |
| **13** | Carbon Woven | 0.5 | 45 | 4 |

Table 6 compares the result of the minimization of both objective functions. The maximum displacement slightly decreased and, on the other hand, the weight of the structure decreased in 11.57%.

Table 6: Improvements in relation to weight and maximum displacement.

| Weight [N] | Displacement [mm] | Maximum Displacement Variation [%] | Weight Reduction [%] |
|---|---|---|---|
| 1.461688 | 35.841986 | -0.12% | 11.57% |

## 5. Conclusions

### 5.1. Achievements

The main objective of this thesis was to optimize the composite material from an existing Landing Gear and find a considerably lighter version comparing to the initial Landing Gear, maintaining its structural integrity, thus, being able to withstand the landing phase of a flight. The final composite design is approximately 11.57% lighter than the initial version of the LG. According to the initial simulations, the structure had a total weight of 3.306 N (considering the whole LG and not just half). After the optimization, the structure has 2.923 N. This difference can revert to higher fuel weight or a longer distance can be achieved by the aircraft. Additionally, taking into account the static structural simulation, the maximum total deformation reduced 0.12% which means the structural integrity was maintained. On the other hand, both the maximum values of equivalent elastic strain and equivalent stress increased, but they were still very similair to the initial values.

Table 7: Drop Test Simulation for the Final Stack-up

| | Maximum | Minimum |
|---|---|---|
| Total Deformation [mm] | 35.83 | 0 |
| Equivalent Elastic Strain [mm/mm] | $9.95 \times 10^{-3}$ | $\approx 0$ |
| Equvalent Stress (Von-Mises) [MPa] | 524.42 | 0.37 |
| Inverse Reverse Factor | 1.31 | 0.02 |
| Safety Factor | 46.96 | 0.76 |
| Safety Margin | 45.96 | -0.24 |

Table 8: Shock Test Simulation for the Final Stack-up

| | Maximum | Minimum |
|---|---|---|
| Total Deformation [mm] | 179.81 | 156.91 |
| Equivalent Elastic Strain [mm/mm] | $1.82 \times 10^{-3}$ | $\approx 0$ |
| Equvalent Stress (Von-Mises) [MPa] | 698.18 | 0.65 |
| Inverse Reverse Factor | 3.24 | 0.02 |
| Safety Factor | 59.10 | 0.31 |
| Safety Margin | 58.10 | -0.69 |

In table 2 and according to section 3.2, the composite failure tools indicate failure on the static and transient structural analysis on both the initial configuration and final solution. It is concluded that there is a discrepancy from reality. Consulting the IRF maximum values for the static and transient structural simulations, it is seen that it was reduced after the optimization, being, therefore, closer to the non-critical values. This means that the relative amount that the applied load can be increased before reaching the failure load is now higher.

### 5.2. Future Work Recommendations

Due to time versus computational cost, a more complete design space was not explored. Either using a machine with more computational power or spending more time, fibre orientations and ply thickness with a larger domain could be explored. Moreover, the Static Structural Analysis was performed during the optimization runs even though an impact situation was being dealt with and that a Transient Structural Analysis would give better results. This, once again, was a compromise due to computational costs, since doing each optimization iteration with a transient analysis would take a much more extensive period of time. Using a supercomputer it might be possible to do this kind of optimization within an acceptable period of time.

Secondly, the option of including variability on the mesh during the optimization could be explored in order to have a more efficient analysis. Also, using the yield limit as a criterion, instead of the maximum displacement, could be an option.

Some material testing could be done in order to evaluate different composite materials. This way, finding the orthotropic properties of each candidate composite material and using them on the finite element software could bring more realistic results.

Last, but not least, a deeper study on the manufacturability should be done so the implementation of the algorithms can be adapted to make sure it is possible to fabricate the LG with the obtained results. Also, a more extensive study could be done about how to include the wheel damping during the impact.

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