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TOPOLOGY AND LATTICE OPTIMIZATION: DESIGN OF WING-FUSELAGE ATTACHMENT COMPONENT FOR AN AERODESIGN AIRCRAFT

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Abstract. *This work aims to design the wing-fuselage attachment component of an AeroDesign aircraft using topology and Lattice optimizations in order to increase the structural efficiency of the aircraft. For the execution of the work, the maximum loads on the component were calculated, and then the optimizations were carried out individually. At the end, the values of tension, weight, displacement, safety factor and natural frequencies were compared. Finally, it is concluded that for the proposed case the Lattice optimization presents more attractive results, despite having a more complex manufacturing method.*

Keywords: *Topology optimization. Lattice Structure. Structural Efficiency. AeroDesign.*

1. INTRODUCTION

The aeronautical industry is characterized as one of the most dynamic society's economic sectors. Through it, one of humanity's greatest technological leaps was provided, accelerating social relations in all areas. Facing a constant need to renew itself, associated with the need to reduce weight, the aeronautical industry has always sought solutions to increase the efficiency of its projects. With that said, there are several areas where alternatives can be proposed to increase structural and energy efficiencies.

Meanwhile, in the academic world, projects like AeroDesign, Formula SAE and Baja encourage students to think about innovative solutions, inserting them in a highly competitive and educating environment. Such projects enable students to develop important knowledge related to the mobility industry.

In this context, especially AeroDesign faces a major challenge related with optimizing the weight of radio controlled aircraft developed by students. In order to obtain a competitive aircraft, load studies, material selection and structural optimizations must be developed. The methodologies used in the project are very similar to the stages experienced in the industry, and therefore such projects are of great importance for the student's education.

This work proposes the application of two different approaches for the optimization of one of the AeroDesign aircraft most important structural parts: The wing-fuselage attachment component.

The first approach proposed is called topology optimization. Starting from a pre-defined shape, usually called by Design Space, topology optimization consists to remove as much material as possible, maximizing the stiffness of the part. An example of topology optimization can be seen in Fig. 1(a).

The second optimization technique applied is the Lattice optimization. According to Maconachie *et al.* (2019), Lattice structures can be defined as topologically ordered, three dimensional open-celled structures, with strut elements connecting themselves through cell nodes, usually repeated in a specific pattern, allowed to be manufactured normally through additive manufacturing. An example of an aeronautical bracket made with lattice can be seen in Fig1(b).

On one hand, lattice structures can be analyzed using classical solid mechanics theory, as a domain composed of nodes and trusses. On the other hand, it should also be considered as a meta-material, with is own properties, given the profound changes on mechanical, thermal and electrical behavior it brings. This interpretation allows a direct comparison between Lattice structures and common materials to be made (Ashby, 2006).

Optimization regarding Lattice is given by the correct distribution of cell positioning, length, minimal and maximal truss diameter for a given design space. To deal with lattice structures in a design perspective, one should be aware that they can be divided into two main groups: stretch- and bending-dominated structures. They differentiate themselves, being more adequate to distinct applications (Ashby, 2006).

Both Lattice and topology optimizations were realized on the aircraft attachment component with common objectives: maximize stiffness, maximize modal frequencies and minimize mass.

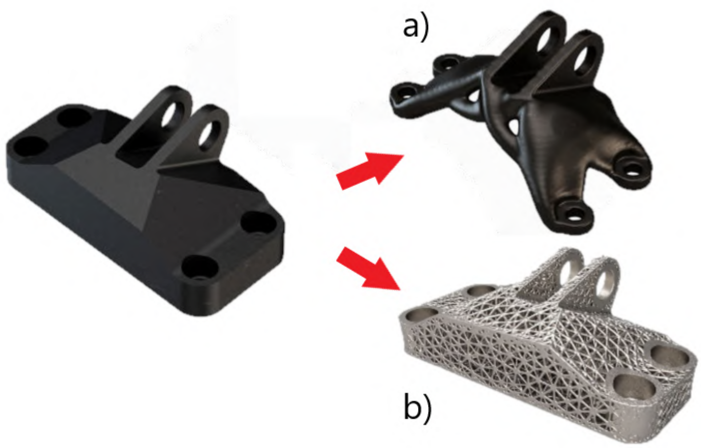

Figure 1. Topology(a) and Lattice (b) optimization of an aeronautical bracket (3D Systems (a) e Food4Rhino (b)

Finally, the results were analyzed and parameters such as mass, tension, displacement, natural frequencies and safety factor were compared between the original part and the topology and lattice optimized designs.

This work provides an overview analysis and comparison between two distinct, thus very useful optimization techniques. Although the current work is applied to an AeroDesign project, the results shown can be extended and applied to a variety of cases due to the high value that both optimization techniques brings to any project seeking high performance, less amount of material waste and innovative solutions.

2. GENERAL OPTIMIZATION CONCEPTS

Practical problems of structural optimization began to be studied around the 60s in the aeronautical environment, aided by the emergence of computers as well as by the development of finite element analysis. When seeking to minimize or maximize an objective function from a variation of parameters such that the imposed restrictions are respected, a general optimization problem is defined. In a general form, according to Larsson (2016), for an optimization problem to be executed the following items must be present:

- Design Variables, also known as Optimization variables, denoted as a vector **x**
- Objective or Cost Function, denoted as $f(x)$
- Equality or inequality constraints, denoted as $g_i(x)$ or $h_k(x)$

Each of these items represents a major role for an optimization to occur, therefore a short explanation of them is made.

2.1 Design Variables

The Design variables are the numerical or geometrical inputs that the optimizer algorithm is allowed to change in order to realize the optimization. They can be divided in two groups: Discrete and Continuous variables:

- **Continuous Variables**: The variables can be represented by a continuous function, which means that it can assume any value respecting the optimization restrictions.
- **Discrete Variables**: The variables are represented by a discrete function, and therefore they can only assume predetermined values.Ex:. Number of bolts, material selection, commercial beam cross sections.

According to Arora (2007) an important factor when designing an optimization problem is the fact that usually problems with discrete variables tend to have considerably higher computational costs when compared to problems with continuous variables, even though the number of feasible solutions for a discrete problem is finite, while being infinite for continuous problems.

2.2 Objective Functions

A normal approach when designing an engineering problem is to find an adequate solution that satisfies the functional requirements of the problem. It is though very common to find more then one acceptable design that suits the requirements. The purpose of optimizing is in fact, to find the best values among the ones analyzed. Thus, a criterion must be chosen in order to compare all the given acceptable alternatives. This criteria in respect to which direction the design variable is optimized is know as objective or cost function. The direction that this criteria is set is governed by the nature of the problem (Rao, 2019).

In aerospace structural design problems, usually the objective functions are set to minimize the weight of the aircraft. On another hand, on civil engineering usually the objective function is related to the minimization of the overall structure cost.

2.3 Constraints

In many optimization problems, the design variables cannot be chosen arbitrarily. According to Silva and Martins (2003), usually they have to satisfy specific conditions and requirements. The conditions that must be satisfied in order to make the project feasible are called Design constraints which can be three types:

- Lateral

$$x_{min_i} \leq x_i \leq x_{max_i}, i = 1, ...n \tag{1}$$

- Inequality

$$g_j(x) \geq 0, j = 1, ...n_g \tag{2}$$

- Equality

$$h_k(x) = 0, k = 1, ...n_e \tag{3}$$

Despite this , they can also be classified as local or global constraints. Local constraints refer to a local point on a domain, like tension on a determined design area. Global constraints are usually related to the whole domain, and can be exemplified as volume, maximum displacement or resonance frequency.

Therefore, in a generic optimization model where x is the design variable, $f(x)$ is the objective function and $h_k(x)$ and $g_j(x)$ are respectively, constraints of equality and inequality, an optimization problem can be defined as the following formulation:

$$Minimize/Maximize \quad f(x) \tag{4}$$
$$So\,that \quad g_j(x) \geq 0; j = 1, ...n_g; \tag{5}$$
$$h_k(x) = 0; k = 1, ...n_e \tag{6}$$

3. TOPOLOGY OPTIMIZATION

The concept of a topology optimization can be explained as: Given a specific volume of a part, usually pre-defined in the preliminary stages of the project, find the optimal distribution of material within this volume, given the boundary conditions and loading for a given situation.

Through this distribution, you can have an overview of which regions of the part in question are essential, and which can be discarded. Naturally, this effect not only causes a significant weight reduction, but also changes the stiffness and the final volume of the part.

In mathematical terms, a topology optimization creates an optimized sub domain $\Omega_{opt} \subset \Omega$ where Ω is the domain of total material available. The domain is divided into discrete elements and the importance of each element in the structural response is assessed by a density value ρ_e. This is incorporated in the stiffness properties of the structure by defining a Young modulus for each element, which is dependent of the density value. This procedure is represented in Eq. 7 and 8, where E_0 represents the Young Modulus of the material and the density value can assume the value of unity (in the optimized domain) or zero (in the empty domain). The equation 9 indicates a volumetric constraint, that is, the final volume of the optimized domain must be less than or equal to the initial volume V (Larsson, 2016). One can observe what has been described through Fig.2.

$$E(\rho_e) = \rho_e E_0; \tag{7}$$

$$\rho_e = \begin{Bmatrix} 1 & if & e \in \Omega_{opt} \\ 0 & if & e \in \Omega \setminus \Omega_{opt} \end{Bmatrix} \tag{8}$$

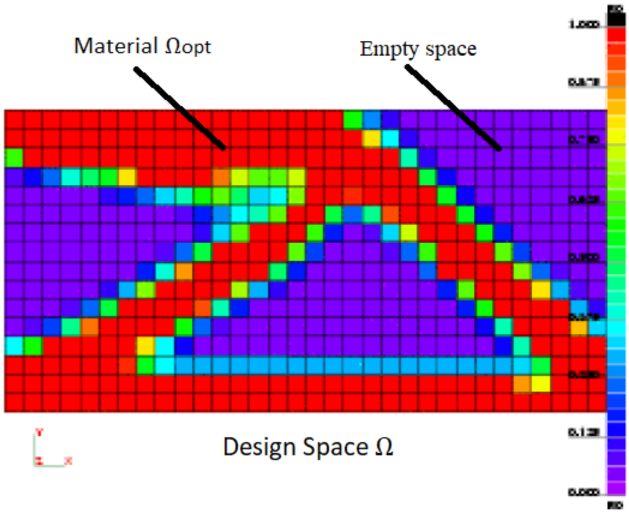

Figure 2. Optimized Design Space representation - Adapted (Roos and Will, 2001)

$$\int_{\Omega} \rho d\Omega = Vol(\Omega_{opt}) \leq V \tag{9}$$

According to Altair (2018), it is necessary that some mathematical tools are introduced to the software algorithm so that these elements of intermediate density can be penalized. The method utilized to do that is called SIMP (Solid Isotropic Material Penalization). Its effect is to transform the equation 8 into a continuous function, allowing the density to assume intermediate values between 0 and 1. The penalty tool used in the SIMP method can be represented mathematically as:

$$E(\rho_e) = \rho_e^p E_0 \tag{10}$$
$$\rho_e \in [\rho_{min}, 1],\ p > 1 \tag{11}$$

The effect SIMP method causes to the relative Young modulus ratio can be seen in Fig.3

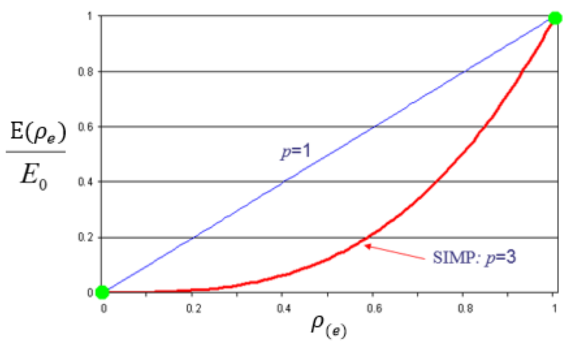

Figure 3. SIMP Effect on Young Modulus Ratio (DassaultSystemes, 2020)

3.1 The checkerboard effect

The checkerboard effect is a problem related to bad parameter settings when realizing topology optimization. It can be described as an inaccurate, bad element densities distribution. This distribution tends to form a checkerboard pattern seen in Fig.4.In 2001 Sigmund (2001) developed a simple but efficient algorithm capable of realizing a two dimensional topology optimization with MATLAB for educational purposes. When changing its available parameters (Volume fraction, filter radius min. size and penalization factor) it is possible to see what influence each parameter has to the final result. This experiment was made and is illustrated in Fig.4

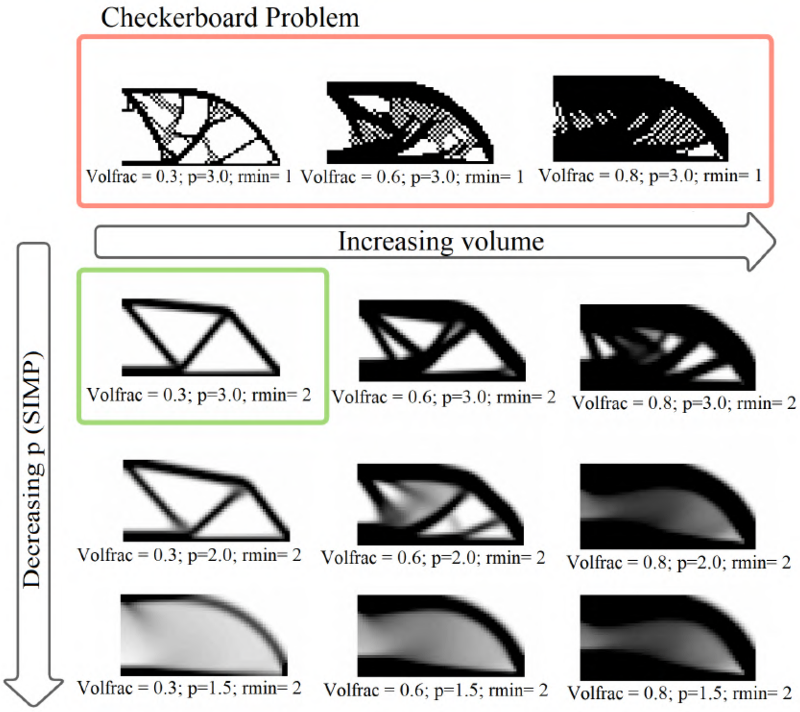

Figure 4. Parameters influence on topology optimization

3.2 General formulation

With all the previous concepts made clear, it is possible to define the solution to a topology optimization as:

Minimize	$C(\rho)$
Subject to	State Function constraint (Directional displacement);
	Manufacturing Constraints (Simmetry, Directional extrusion, Etc.)

Where $C(\rho)$ means a compliance objective function , which in another words means that the objective function seeks to minimize the strain energy, which is the same as maximizing the stiffness.

4. LATTICE STRUCTURES

The development of increasingly lighter structures, associated with advances in additive manufacturing methods, currently allows for almost infinite design freedom, usually limited by the designer's creativity. This has been explored not only through topology optimizations, but also through the creation of reticular structures known as Lattice, which replace a solid body causing profound changes in the mechanical characteristics of a part.

Studies regarding the behavior of this type of structure began to emerge in the early 1960s with the work of Gent and Thomas in 1959, and Patel and Finnie in 1970 (Ashby, 2006). Since then more studies have emerged making this topic more and more widespread, being accelerated mainly from the 90s with the expansion of additive manufacturing technology.

The structures are formed by trusses connected through nodes that are repeated in a certain pattern of organization. The figure 5 illustrates how this type of structure is configured.

Lattice geometries are divided into two behavior categories: Stretch- and Bending-dominated structures. This division is given by Maxwell equations for three dimensional Lattices:

$$M = b - 3j + 6 = s - m \tag{12}$$

Where M is Maxwell's number, b is the number of struts, j is the number of frictionless joints, s is the number of self stress states and m the number of mechanisms. The Lattice structures can therefore be defined by Maxwell's number: For $M < 0$ the structure is either a mechanism or a bending-dominated lattice, depending whether the joints are locked or

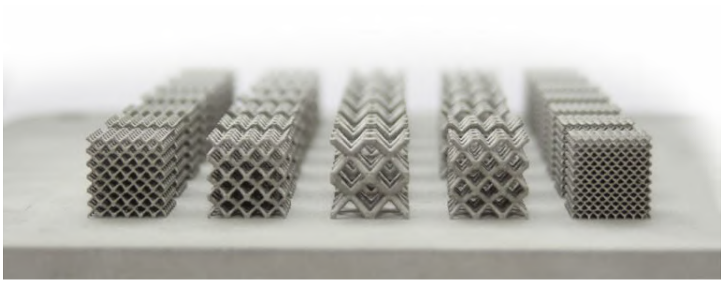

Figure 5. Multiple Lattice geometries (3DPrinting, 2019)

not. For $M = 0$ it is considered to be a stretch-dominated lattice, and finally for $M > 0$ the structure is considered to be in a state of self-stress.

Their use vary according to the type of application. The bending dominated structures are indicated to applications that require energy absorption, such as impacts cases. On the other hand, stretch-dominated structures are more indicated for light weight structural applications (Ashby, 2006). This comparison can be made when observing the tension-yield curve on Fig 6.

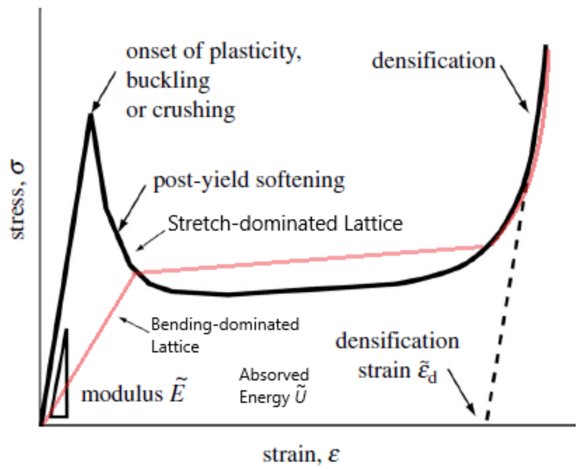

Figure 6. Stress-Strain curve for Stretch- and bending-dominated structures (Ashby, 2006)

Lattice are organized in the form of a crystalline structure, such as Cubic structures with centered bodies (CBC), Cubic with centered faces (CFC), and their variants with transverse Z trusses (Maconachie *et al.*, 2019). The behaviour of a Lattice can be determined by three main characteristics: Material, Cell geometry and relative density $\frac{\tilde{\rho}}{\rho_e}$, where $\tilde{\rho}$ is the lattice density, and ρ_e is the material density. These correlations can be seen on Fig7.

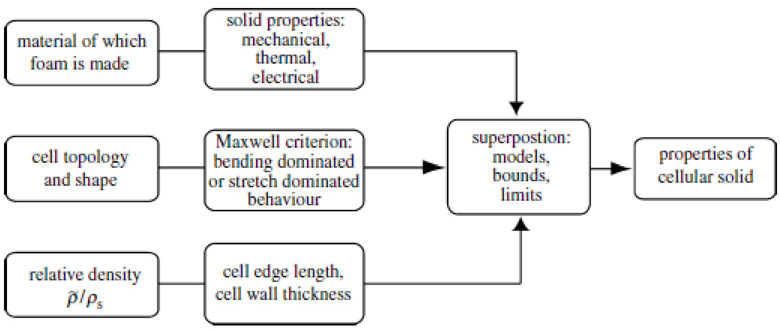

Figure 7. Lattice design variables (Ashby, 2006)

5. CASE STUDY

This work seeks to optimize a wing-fuselage attachment component manufactured through stereolithography (SLA), an Additive Manufacturing (AM) technique that allows high level of precision and good surface finish, as well as the use of resins that simulate high hardness ABS, with elevated Young Modulus and an acceptable density for an AeroDesign project. The material properties can be seen in Tab.1,

The boundary conditions were set as two completely fixed pins (C1 and C2) and one translation constraint (C3) locked in Z for the surface in contact with the round tube section spar of the wing. This last constraint was used to guarantee there wouldn't be any relative displacement between the spar and the wing-fuselage attachment. The aircraft with the non-optimized wing-fuselage attachment detail is shown in Fig.8.

Two additional manufacture constraints were set: The first on is a symmetry plane displayed in red, and the other one is a split draw direction to guaratee the topology result would be possible to be constructed not only with A.M but also with laser cut or water jet technologies.

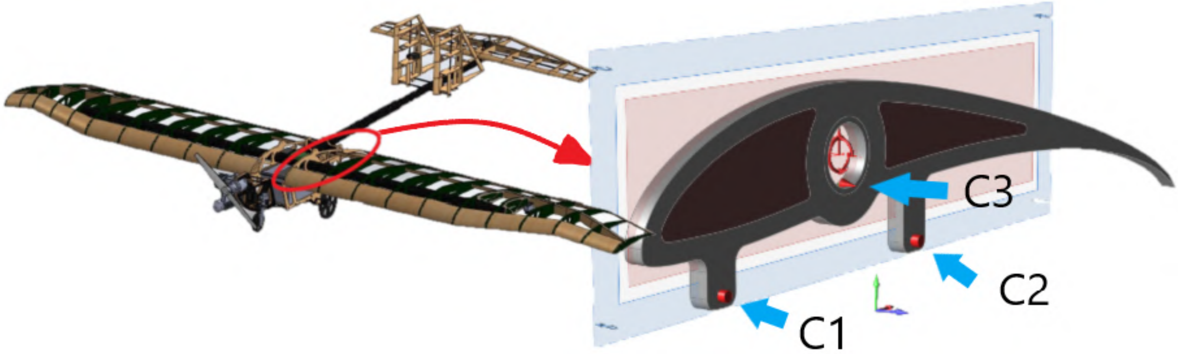

Figure 8. Aircraft and Design Space with boundary conditions and applied loads (Author)

Table 1. Material Properties (Proto3000, 2020)

Material	3D Systems Accura 55 Resin
Failure Criteria	Von Mises
Density (Kg/m^3)	1200
Young Modulus E (MPa)	3200
Poisson	0.35
Yield Strength (MPa)	63,4

The loads were determined by following the methodology applied by Barros (2001), where the load distribution throughout the aircraft wingspan is calculated by utilizing the principles of *Stender* approximation. This method assumes that the load distribution along span is proporitonal to the geometric chord mean of the actual wing and an elliptical wing with same area and wing span.

The shear force, bending moment and torsion moment acting along the wing half-span are shown in Fig.9. The load values acting on the attachment component were assumed at x = 0 position and are given in Tab. 2.

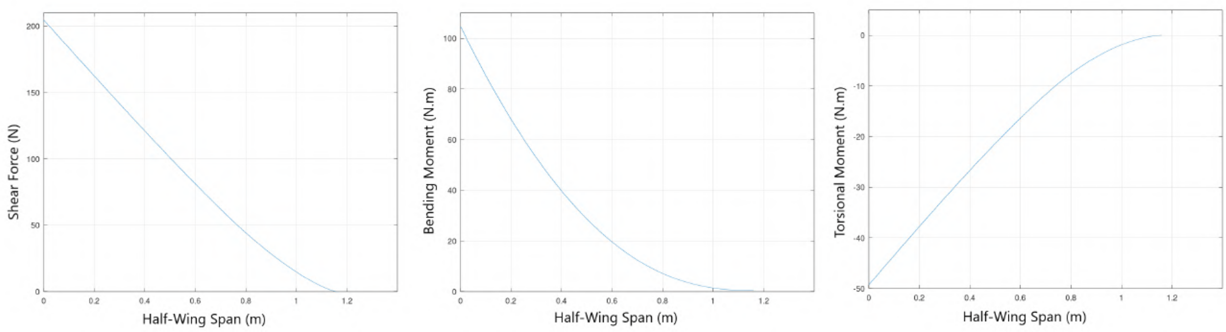

Figure 9. Wing Loads

Table 2. Applied Loads

Shear Force	210 N
Bending Moment	104 N.m
Torsional Moment	-49 N.m

6. RESULTS

The topology and Lattice optimizations were run with OptiStruct through the software *Inspire* using the setup displayed in Fig.10. Both optimizations had objectives such as maximizing the stiffness and natural frequencies while the mass was minimized.

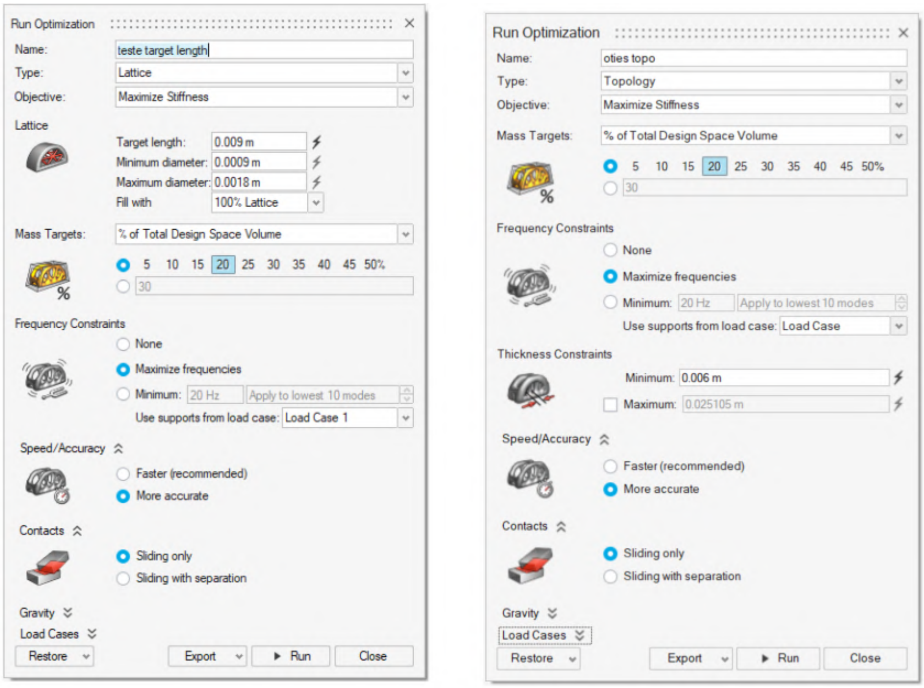

Figure 10. Topology (Left) and Lattice (Right) optimization setups

The following parameters were compared: Mass, Max. Displacement, Von Mises stress, natural frequencies and safety factor. A review of the computational specs used for the analysis can be seen in Tab. 3. The geometry results are displayed in Fig. 11 and 12. The numerical results comparison are displayed in Tab. 4. A modal optimization was run in order maximize the frequencies to evaluate the modal behavior from both structures. The results of natural frequencies are shown in Tab.5 and the corresponding mode shapes in Fig.13.

Table 3. Computational Resources

CPU	GPU	RAM	Average Opt. Time
Intel Core i7-9750H - 2.6Ghz	NVIDIA GeForce GTX 1660 Ti	16 Gb	10 min.

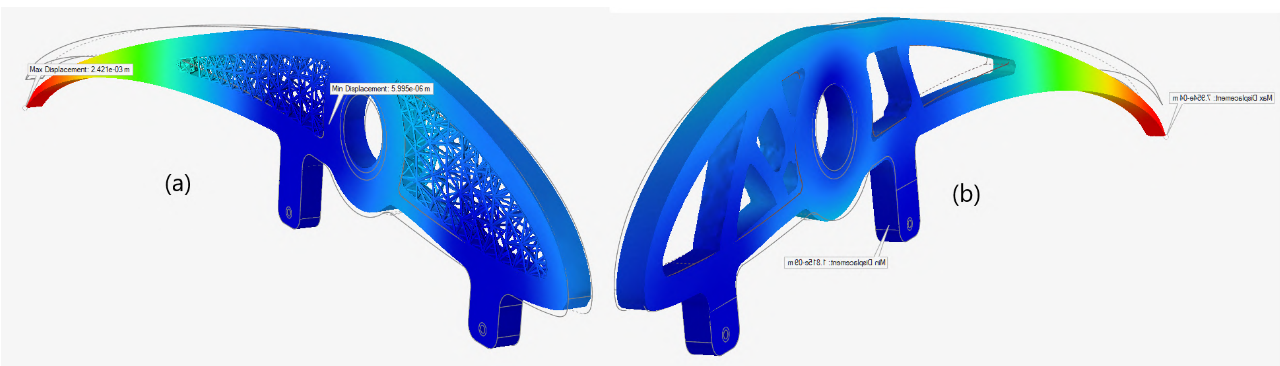

Figure 11. Maximum displacement - (a) Lattice and (b) Topology

It is noted that the two optimization methods showed benefits in relation to the original part, with the exception of the maximum displacement, which the original part kept the lowest value. The Lattice has an equivalent mass 4% lighter than the topology design. In addition, the stresses obtained in the *Lattice* represent a value 23% smaller than that found in the

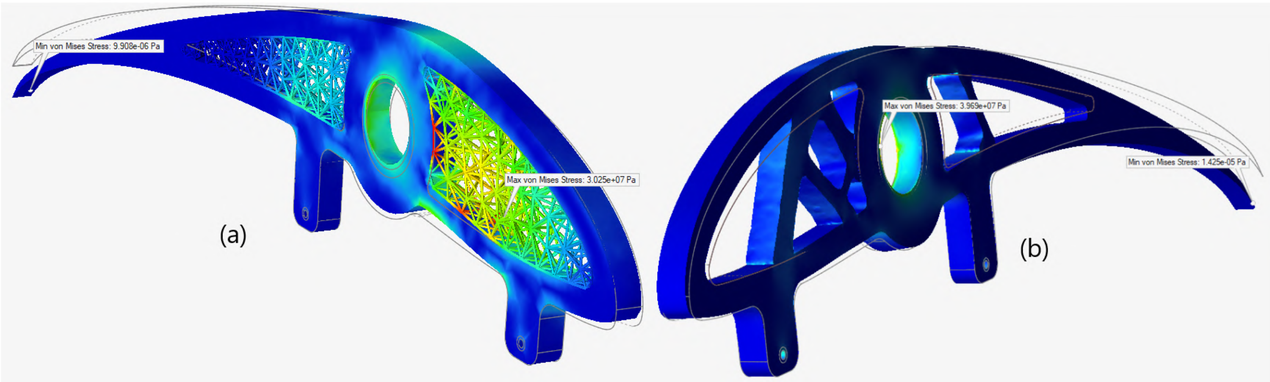

Figure 12. Von Mises Stresses - (a) Lattice and (b) Topology

Table 4. Numerical results and comparison between the optimizations and non optimized design.

Model	Non-optimized	Topology	(%)	Lattice	(%)	$\frac{Lattice}{Topo.} - 1$ (%)
Mass (g)	219,0	158,4	-28,7%	151,6	-30,8%	-4%
Máx. Displ. (mm)	0,3	0,9	179,8%	2,4	667,1%	163%
Von Mises (MPa)	35,0	39,6	13,2%	30,3	-13,4%	-23%
Safety Factor	1.8	1,6	-11%	2,1	16,7%	31%

Table 5. Natural frequencies - Original component, Topology and Lattice Optimized.

Natural Frequencies						
Vibration Modes	Non Optimized	Topology	Var(%)	*Lattice*	Var(%)	$\frac{Lattice}{Topo} - 1$ (%)
1	51,8	40,0	-22,7%	41,2	-20,8%	1,9%
2	152,2	142,4	-6,4%	138,1	-9,2%	-3,0%
3	181,2	174,4	-3,7%	178,4	-1,5%	2,2%
4	348,7	268,6	-23,0%	308,8	-11,5%	11,5%
5	406,1	413,8	1,9%	420,2	3,5%	1,6%
6	417,8	426,7	2,1%	431,4	3,2%	1,1%

topology, causing the safety factor to be 31% higher. In contrast, the displacement value in the *Lattice* represents 163% of the value found with the topology.

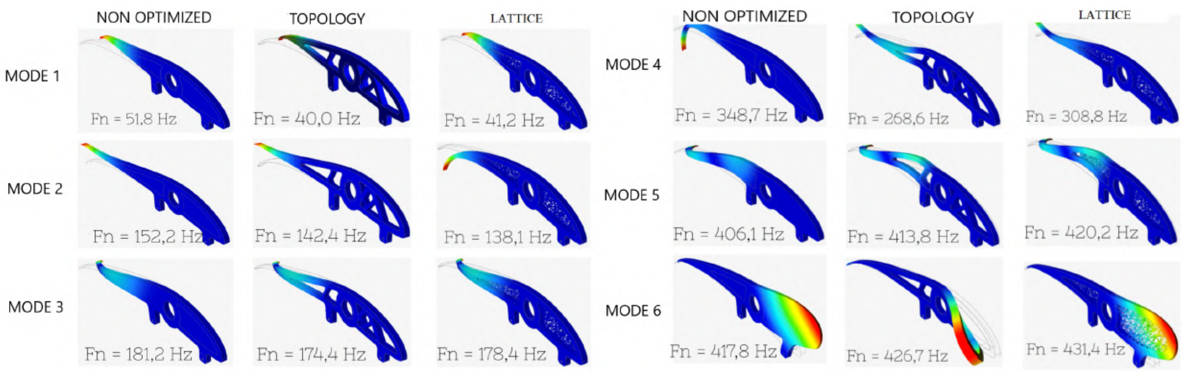

Figure 13. First 6 vibration modes - Non optimized, topology and Lattice design

Regarding the natural frequencies comparison, it can be noted that the Lattice design achieves higher natural frequency values then the topology design for almost all modes analyzed, with a maximum disparity of 11% on the 4th mode , except for the second mode, where lattice values is 2.8% lower than the topology value.

In addition to the frequency values, the comparison of mode shapes among the non optimized and optimized structures shows that the main characteristics of the modes are preserved.

7. CONCLUSION

The results obtained for the two types of optimizations proved to be efficient for the objectives outlined in an AeroDesign project. By directly comparing two types of optimizations it was possible to explore a wide range of benefits gained from exploring this field in an engineering project.

At the end of the work, it can be concluded that the two optimizations promoted greater performance without compromising the safety of the project. It was possible to reduce up to 31% of mass, decrease the stresses acting on the component and consequently increase the safety factor of the project.

The displacement observed for the two optimizations was not taken into account as a prohibitive factor, however it must kept in mind that very high displacements can compromise the mechanical and aerodynamic behavior of the part in question. For the correct evaluation of the influence that this factor has on the project as a whole, it would be necessary to carry out coupled analysis connecting the structural model to the aerodynamic model, which is not the objective of this work.

It has been shown that Lattice structures have a promising potential to further leverage the gains made with structural optimizations. The lattice optimization provided a mass reduction of 4% in comparison with the topology optimization, for the same maximum volume of material removed. In addition, the natural frequencies of Lattice design reached higher values than the topology ones in most of the analyzed modes, which not necessarily poses as an advantage for this study, but rather as a behavior to be kept in mind when using such structures.

Finally, the benefits brought by either type of optimization, whether topology or Lattice, are evident. Therefore, regardless of the method chosen, a high degree of commitment to all possible applications to which the part will be subjected is necessary so that there is no inconsistencies, thus ensuring the high performance and safety of the project. .

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9. RESPONSIBILITIES FOR THE INFORMATION

The authors are the only ones resposible for the information included in this work