Master's degree in mechanical engineering and mechatronic engineering

Course of "Additive Manufacturing Systems and Materials"

Redesign with topology optimization tools of the upright for the Lotus Elise S1

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Sommario

1 Introduction

1.1. Brief explanation

This report presents a topology optimization study of a brake system component, originally designed in aluminium, with the goal of improving structural performance and exploring cost-effective material alternatives suitable for additive manufacturing. The original component under study is a brake calliper bracket, which plays a critical role in transmitting braking forces while ensuring rigidity and safety during operation. The original component under study is a brake calliper bracket, which plays a critical role in transmitting braking forces while ensuring rigidity and safety during operation. It is subject to demanding mechanical loads and must meet strict performance, weight, and manufacturability criteria.

The component is fixed at its mounting points, simulating bolted connections to the chassis or other structural elements. The primary loads applied include braking forces transmitted through the calliper during deceleration, modelled as distributed or point forces depending on contact surfaces. These loads reflect typical operating conditions in automotive braking systems and are essential for capturing realistic stress distributions.

1.2. Load and support conditions

The upright of the front left wheel in the Lotus Elise S1 (1996) is subjected to a combination of dynamic load cases that reflect realistic driving conditions. For the structural optimization process, three primary load scenarios were considered to represent critical functional states of the component:

Longitudinal Braking: this scenario simulates the vehicle decelerating in a straight line with a deceleration of 2G. The forces transmitted from the brake system to the upright generate significant axial loads along the longitudinal axis. The load is primarily distributed through the wheel hub and brake assembly, resulting in compressive forces and bending moments on the upright.

Turn-in Maneuver: the second condition models the vehicle entering a turn, also with a deceleration of 2G. Lateral forces act on the upright due to the inertia, causing shear and torsional stress. These are transferred through the upper and lower control arms, which constrain the upright's movement and introduce reactive forces at the mounting points.

Braking While Turning: the third scenario combines the effects of braking and cornering, with a resultant deceleration of 1.5G. This is considered the most complex load case, as it generates both longitudinal and lateral forces. The superimposed stresses result in a multidirectional loading state, which is critical for evaluating the safety factor and maximum deformation.

These conditions reflect realistic mechanical interactions between the upright and surrounding components, ensuring that the optimization process addresses both performance and safety requirements.

1.3. Analysis of the original component

The original component [Figure 1] was modelled using aluminium alloy Al7075-T6 and it was 2.244 [kg] heavy. This high-strength aluminium alloy offers a good balance of mechanical performance and low weight but is traditionally not optimized for additive manufacturing constraints such as support minimization and material redistribution.

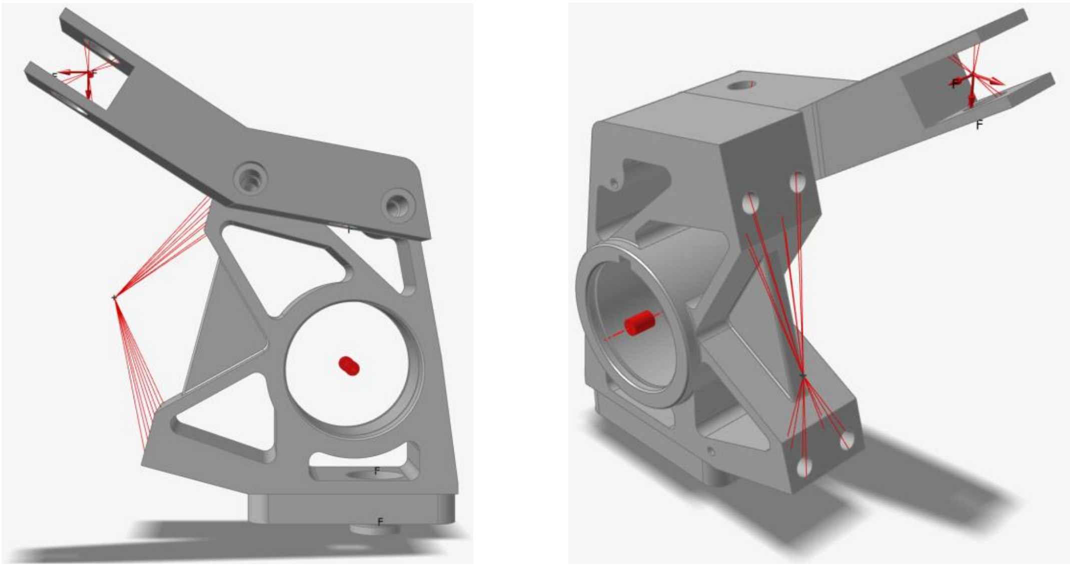


Figure 1: Original component

1.3.1. Longitudinal Braking 2G

As shown in [Figure 2], areas with greater deformation are indicated by darker orange colours. The maximum displacement value of approximately 0.265 [mm] is the lowest among the three analysed load cases, which indicates that the component experiences the least deformation under this specific braking condition. This suggests excellent structural rigidity of the component in this load direction.

Figure 2: Braking 2G displacement analysis

A minimum safety factor of 2.8 [Figure 3] means that the maximum stress in the component is 2.8 times lower than the yield strength of Aluminium (7075-T6), which is 413.7 [MPa]. This value is very good and indicates a high safety margin against material yield failure.
This case, while being a significant load condition, does not appear to be the most critical for the component's design.

Figure 3 : Breaking 2G factor of safety

1.3.2. Turning 2G

Deformation map (Turning 2G) [Figure 4]: the component experiences lateral deformation primarily in areas where the suspension forces are transmitted.
The maximum displacement value of approximately 0.421 mm falls between the maximum displacements observed in the "Braking 2G" (0.265 [mm]) and "Braking while turning 1.5G"

(0.539 [mm]) cases. This indicates that while the component experiences noticeable deformation under turning loads, it is still within a relatively small range, suggesting good structural rigidity. The deformation is mainly in the out of plane direction and follows the expected behavior of a suspension component under cornering forces.

Figure 4 : Turning 2G deformation analysis

A minimum safety factor of 3.2 [Figure 5] is the highest among all three load cases analysed. This means that the maximum stress within the component is 3.2 times lower than the yield strength of the Aluminium (7075-T6). This is an excellent safety margin, indicating that the component is very robust and well-suited to withstand the stresses induced by a 2G turning manoeuvre.

Figure 5 : Turning 2G safety factor

1.3.3. Braking in turn 1.5G

This scenario represents a more complex operating condition, combining braking with a lateral force due to turning. This is reflected in the deformation and safety factor values compared to the other cases.

Deformation map (Braking in turn) [Figure 6]: the component experiences lateral deformation primarily in areas where the suspension forces are transmitted. The maximum displacement is approximately 0.539 [mm]. Although it is the highest maximum deformation of all the cases, it is still a relatively small value, indicating good structural rigidity.

Figure 6 : Braking in turn 1.5G deformation analysis

The safety factor for this load case is the most critical among the three analysed and it's of 2.6 [Figure 7]. This value is generally considered acceptable for most engineering applications, indicating that the component has a good safety margin against yield failure.

However, being the lowest value among the three cases, it confirms that this combination of braking and turning generates the highest stresses in the component (as anticipated by deformation analysis).

Figure 7 : Breaking in turn 1.5G safety factor

2. Description of the redesign process

2.1. Selection of technology and material

For the material selection, materials were identified based on their compatibility with the part, suitability for the working environment, cost-effectiveness, ability to guarantee a minimum safety factor of 2, and compatibility with 3D printing technologies. Within these criteria, the following materials were selected and tested, each compatible with its respective printing technology and any necessary post-processing prior to use [Table 1]:

Properties	AlSi10Mg-T6	AlZnMgCu (7075/50 AM)	Scalmalloy	Ti6Al4V
Density [kg/dm³]	2.68	2.80	2.67	4.43
Young's Modulus [GPa]	70	71	73	113
Yield Strength [MPa]	260–290	450–480	480–520	880–950
Ultimate Strength [MPa]	400-430	510-560	520-570	950-1000
Thermal Cond. [W/m·K]	150–170	130-150	120-130	6-8
α [µm/m·K]	21	21	21	21
Heat Treatment	T6 (required)	T6	Short aging	aging
Compatible AM	SLM/DMLS	SLM	SLM	SLM/EBM
Print Cost [$/kg]	~600–900	~700–1100	~1200–1800	~2800-3500
Post-processing	Needed	Needed	Better	Needed
Printability	Easy	Medium	Good tuning is needed	Difficult

Table 1 : Comparison between compatible materials

After carefully evaluating all the information in the table, the following observations came up:

- **Titanium** may seem attractive at first glance due to its yield strength and fatigue resistance. Unfortunately, the material cost, printing cost, printing difficulties (such as warping tendency), and very poor thermal conductivity make it relatively unsuitable for the intended application.
- The first aluminum alloy **AlSi10Mg** is widely used in the AM (additive manufacturing) field and is relatively inexpensive. However, it has low yield strength, which risks bringing the safety factor below the desired threshold. After several tests confirming this limitation, we decided to discard it.

As final options, it has been chosen to carry out analysis into the last two materials:

- **Scalmalloy** is widely used in aerospace and motorsport sectors, but it comes with a high cost, requires high-precision equipment for printing, and is harder to find on the market compared to its competitor. It outperforms in both yield strength and fatigue resistance.
- **AlZnMgCu** AM is printable but not widely used; it also requires reliable post-production heat treatment.

So, the following comparison table can be made [Table 2]:

Design Objective	Best Material
Minimize weight + maintain high	Scalmalloy (ideal) or AlZnMgCu (Best compromise)
Good strength at reasonable cost	AlZnMgCu (7075 AM)
Cost-driven prototyping	AlSi10Mg
Maximum strength	Ti6Al4V

Table 2 : Comparison table

After a comparative analysis of the materials and production techniques, **AlZnMgCu AM** was identified as the most suitable option. It provides 90–95% of **Scalmalloy**’s structural advantages at approximately 50% of the cost, while offering significantly better performance than **AlSi10Mg**. These characteristics make it an optimal material for a topology-optimized brake system component, where a safety factor greater than 2 can be achieved.

This component, with this tupe of material, will then be printed using **Selective Laser Melting**: also called **SLM,** is an additive manufacturing technology used to produce metal components by selectively melting fine metal powders with a high-powered laser.
It allows for the creation of complex geometries, lightweight structures, and components with excellent mechanical performance.

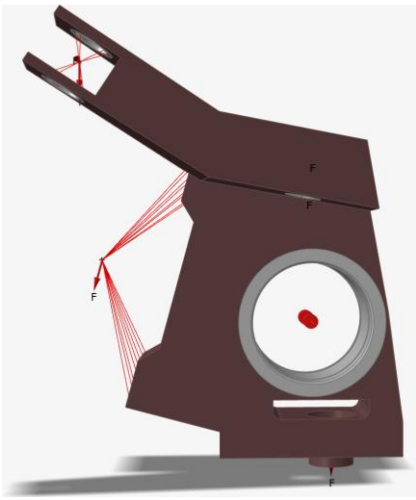
These type of process often re quires post-processing steps such as heat treatment or machining to achieve the desired final properties.

2.2. Preparation of the piece for topology optimization

The design space setup for topology optimization was carried out as follows:

- First, the 6 screw holes present in the original three-piece component were closed.
- Areas deemed suitable for design space were filled, with consideration given to the part's eventual mounting location to ensure compatibility with the overall braking system structure.
- Specific regions were removed from the design space. These exclusions included:
    - Areas designated for load application.
    - Three holes mandated to remain per specifications.
    - The bearing support area.
- The only area that was not completely closed but was still restricted was the one allowing access to the nut in the lowest slot of the part: for obvious reasons, that feature could not be simplified.

Upon completion of these steps, the part, as depicted in [Figure 8], represented the finalized design space.



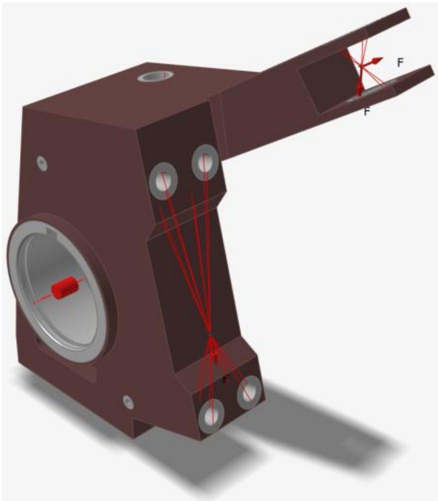


Figure 8 : Piece prepared for optimization

All analyses were conducted using the "Speed/Accuracy: Faster setting" in order to achieve reliable results without excessive computation time.
Initial attempts to run simulations using SimSolid as the solver were unsuccessful due to technical limitations on the available computers. After several days of troubleshooting, the decision was made to switch to OptiStruct. This change not only resolved the issue but also allowed for greater utilization of CPU cores, significantly accelerating the optimization and analysis processes compared to the setups previously used in the laboratory.
Throughout the project, an element size of 2 [mm] was consistently applied in all simulations and topology optimizations were thoroughly explored using various configurations, including maximum stiffness (evaluated both as a function of total mass and as a percentage of the design space volume) and minimum mass scenarios.
As an additional investigation, a single analysis was performed using the More "Accurate setting". This revealed a theoretical point of concern in the pre-optimized component, specifically near the insertion location of the bearing locking tab. At that point, the safety factor was found to be 1.7. However, even with the use of minimum and maximum callouts, the software did not visually highlight the exact location of the issue, leaving a small element of uncertainty. Despite this, the localized stress was calculated to be only 58% of the material's yield strength, indicating that the component remained safely within the linear-elastic range.

2.3. Optimization process

The topology optimization was configured with the following parameters: maximum stiffness and a volume constraint of 30% of the total volume, identified as the most accurate setting after numerous trials. The simulation was executed, and the preferred configuration was selected using the corresponding slider.

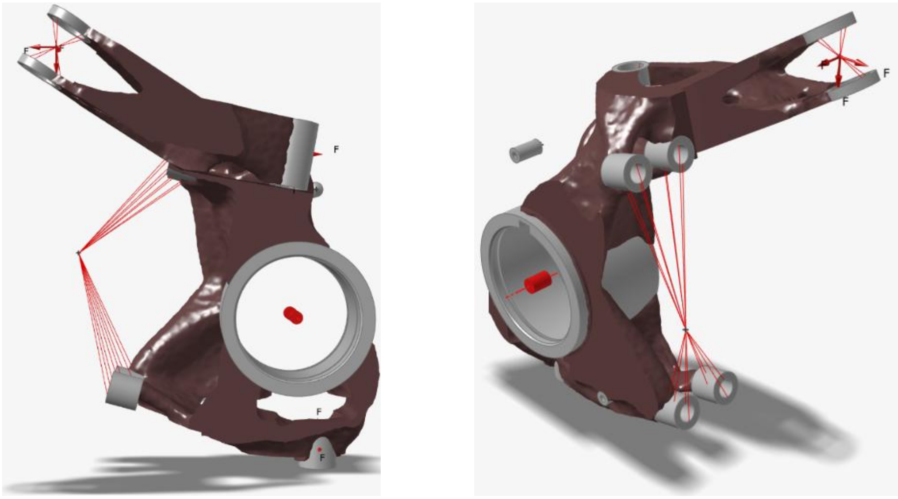


Figure 9 : Optimized piece before the mesh generation

2.4. FEM analysis on the topologically optimized piece

Across all load cases, the displacement results demonstrate that the optimized design performs well under dynamic conditions.

In the braking 2G scenario [Figure 10], which simulates strong deceleration, the component exhibits minimal deformation. This indicates that structural stiffness is sufficient to resist bending or flexing forces effectively, a critical attribute in high-load situations such as emergency stops.

Figure 10 : Braking 2G optimized piece

In the braking while turning at 1.5G case [Figure 11], the component is subjected to a combined load of longitudinal and lateral forces. As expected, the displacement under this condition is slightly more pronounced than in the straight braking case. However, the results still suggest that the structure maintains integrity and does not exhibit any excessive or localized deflection. This confirms the robustness of the design under more complex loading paths.

Figure 11 : Braking while turning 1.5G optimized piece

The turning at 2G case subjects the structure primarily to lateral forces [Figure 12], challenging its torsional rigidity. The displacement here appears to remain within acceptable limits, further reinforcing that the design's stiffness-centric optimization effectively mitigates torsional deformation.

Figure 12 : Turning 2G optimized piece

The factor of safety (FOS) assessments for each load case complements the displacement results. For the braking 2G load case, the FOS distribution is generally favorable. Most regions of the structure maintain a FOS above the critical value of 1.0, indicating that the component can safely withstand the applied loads with some margin.
Under braking while turning, the safety factor may decrease slightly in regions experiencing stress concentrations due to the complexity of the load application. However, the distribution shown in the isometric safety factor views reveals no widespread structural vulnerabilities.
The turning 2G case presents the greatest challenge to lateral and torsional resistance. Yet, the safety factor plots suggest the structure remains within safe operational thresholds.

2.5. Final piece

Subsequently, the PolyNURBS and sketch tools were employed to generate a suitable mesh, ensuring printability, the elimination of ambiguous geometric features, and proper connectivity among all parts. A final simulation was then performed [Figure 13], yielding favorable results compared to the original design. The optimized component weighs 1.23 [kg], representing a 45% reduction in weight relative to the initial model, while still complying with a safety factor of 2.

Figure 13 : Rendering of the final piece

In the braking 2G condition [Figure 14], the structural response is indicative of high rigidity; displacements appear minimal and well-distributed, suggesting that the part resists longitudinal loads without noticeable deformation.

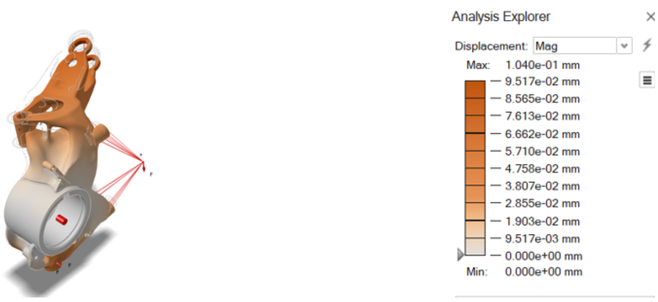


Figure 14 : Braking 2G final piece

Under the more complex braking while turning at 1.5G scenario [Figure 15], where lateral and longitudinal forces act simultaneously, the displacement slightly increases, particularly in areas that experience combined stress effects. Nonetheless, the response remains within acceptable limits, confirming the design's ability to handle multi-directional loading without compromising functionality.

Figure 15 : Braking while turning 1.5G final piece

In the turning 2G case [Figure 16], the structure is primarily subjected to lateral forces. This load case typically poses a greater challenge to the component's torsional stiffness. The observed displacement fields show localized deformation, but the overall stiffness holds. The deformation does not appear excessive, indicating that the part is structurally stable and capable of withstanding high side-loading events, such as aggressive cornering.

Figure 16 : Turning 2G final piece

The factor of safety (FOS) result provides further confidence in the design's robustness. During the braking 2G load case [Figure 17], most of the component maintains safety factors comfortably above 1.0, signifying that the part endures stress without reaching material yield limits. The FOS is well-distributed, indicating an even stress flow throughout the structure.

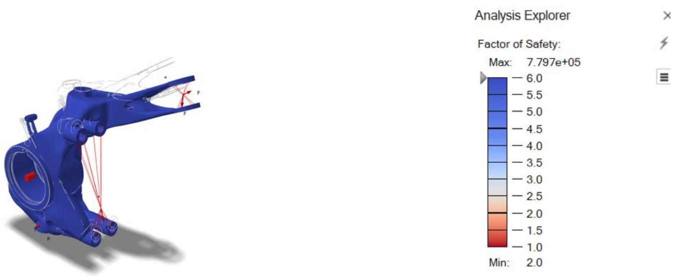


Figure 17 : Braking 2G FOS final piece

In the braking while turning 1.5G scenario [Figure 18], slight reductions in the safety factor are expected due to the complex stress patterns. These are often concentrated at geometrical transitions or connection points. However, the FOS iso view does not reveal any critical failure zones, and even the lower values likely remain above the threshold for structural integrity.

Figure 18 : Braking while turning 1.5G FOS final piece

The turning 2G load case reveals the most demanding conditions [Figure 19], with lateral loads testing the component's torsional capacity. Here, certain areas may experience further safety factor reduction, but again, the minimum values are assumed to stay above 1.0, ensuring the component retains a sufficient safety margin under peak stress.

Figure 19 : Turning 2G FOS final piece

<u>Is the design directly printable and ready to use?</u>
Obviously, the answer is no, but it is not far from the goal. The part results printable with some minor refinements in the structure, and maybe we can decrease the mass in some other point to achieve another 3-5% reduction.

AM parts require post-print heat treatment to ensure the stable properties considered in this case study, so the chosen printing method is feasible on such equipment, although it is not the most used with SLM printing. It's also probably necessary to refine the holes and the bearing attachment once the piece has been printed.

3. Conclusion

After a considerable number of attempts, we managed to achieve a satisfactory result: from the initial study of the component to the creation, modification, and subsequent expansion of the design space (considering the limitations), to the choice of material/printing technique, and finally, to the optimization and actual construction of a printable product. We believe we have reached an acceptable outcome.

The main problems encountered during the project were:

- **Initial material choice:** Initially, we only considered AlSi10Mg, which, although common in SLM printing, did not possess the adequate characteristics for this type of part.
- **Design space setup:** We forgot to include some essential points in the design space for the correct functioning of the part.
- **Optimization times:** Each optimization varied in time between half an hour and two hours, depending on the PC and the solver settings used.
- **Uncooperative polyNURBS:** In several cases, the tool did not work for anomalous reasons. Often, these issues were resolved simply by restarting the PC or the program, but they still caused time loss.
- **Inspire issues:** Problems included memory overflow during PolyNURBS, Simsolid initially working as a solver but then starting to give unclear issues, and sudden crashes even with minimal interaction with Inspire.

4. Bibliography

1- EOS Material Data for AlSi10Mg, AlZnMgCu and Ti6Al4V characteristics [https://www.eos.info]

2- APWORKS -Scalmalloy® Datasheet for characteristics of the material [https://apworks.de]

3- "Fatigue behaviour of AlSi10Mg alloy processed by SLM" – Materials & Design (Elsevier)

4- Additive Manufacturing Technologies -Gibson, Rosen & Stucker for cost of materials, if present

5- Unionfab, Sandvik and 3DHubs for average printing cost and consideration of printability