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# Reverse Engineering of Brake Calliper Design via Integration of Topology Optimisation and Lattice Structure for Additive Manufacturing

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ABSTRACT

*The emergence of additive manufacturing has enabled design improvements for automotive industry components, such as reducing weight and enhancing performance. However, the application of lightweight designs for automotive components is yet to be fully explored. Previous studies have explored the different types of lattice structures and topology optimized parts, but have yet to explore its application in a brake calliper. This paper focuses on the design improvement of brake calliper for the automotive industry. The methodology consists of reverse engineering of an actual Volkswagen Golf Mk6 brake calliper and redesigning using topology optimisation and lattice structures. The new brake calliper design is then compared to the existing model in terms of weight reduction. The results show that through topology optimisation, it is possible to achieve weight reduction of brake calliper, while maintaining the part requirements. In conclusion, brake calliper designs can be improved using topology optimisation and lattice structures to achieve weight reduction. This research contributes to sustainability and reduces fuel consumption of cars through the decrease in part weight of automotive components, which is important in this era to comply with the environmental regulations and sustainability, in accordance with the UNESCO Sustainable Development Goals.*

*Keywords: Lattice structure, brake calliper, reverse engineering, topology optimization*

## INTRODUCTION

Additive manufacturing, also known as 3D printing, is a layer-by-layer manufacturing process. This approach makes it possible to manufacture complex forms, which were previously difficult to obtain using conventional manufacturing processes such as die-casting or machining. These processes are also not cost-effective or time-effective for manufacturing. With the breakthrough in additive manufacturing, complex parts such as lattice structures can be easily manufactured. However, the use of additive manufacturing methods is primarily constrained by the size of the production product and the complexity of its geometry (Jiménez et al., 2019). Lattice structures are architectured materials which are lightweight compared to initial solid design parts. Lattice structure is a type of architecture consisting of various periodic spatial unit cells with edges and faces. Two and three-dimensional lattice structures exist, and they are often connected to solid lattices (Zadpoor, 2019). Another example of complex form is topology-optimised parts, where weight reduction is achieved by designing and locating material only where is required to meet the part's requirements.

Additive manufacturing can be used in various industries, such as the automotive, aerospace and biomedical industries. Thirty years ago, 3D printing was primarily used for prototyping purposes. However, with the advancements and improvements in metal 3D printing, it can now be considered as a manufacturing process; hence, the term additive manufacturing is introduced. It is now possible to not only produce prototypes but also to produce final end-user parts which have mechanical properties that are equal to those obtained by conventional manufacturing processes. Additive manufacturing has many potential applications in the automotive sector. New part designs with mechanical properties comparable to those obtained using traditional manufacturing can be produced (Thakar et al., 2022).

The versatility of additive manufacturing is vital in saving time and cost, process efficiency and enabling high-speed production for mass customisation (Butt, 2020). Thanks to the many advantages of additive manufacturing, it has received high interest among researchers and engineers compared to traditional manufacturing methods (Jiang & Xu, 2018).

The main benefit of additive manufacturing is the design flexibility of parts that can be manufactured. Complex parts can be made using AM that were previously difficult to obtain with traditional manufacturing methods (Yusoh et al. 2020). It can also allow the design of new and better components with fewer parts and weight reduction, which, according to Alogla et al. (2021), can bring better performance. However, the application of lattice structures and topology optimisation in additive manufacturing part for the automotive industry for commercial cars is yet to be widely used (Seharing et al. 2019). This can be attributed to cost and a lack of understanding in designing and integrating lattice structures and topology-optimised parts in automotive components, as shown in Figure 1. Therefore, in this paper, a case study was conducted to redesign an existing brake calliper and improve the design by integrating lattice structures and topology optimisation.

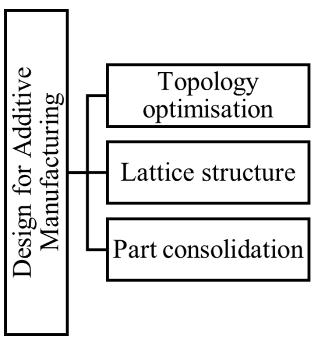


FIGURE 1. Design for additive manufacturing possibilities through lattice structure, topology optimisation and part consolidation.

A brake calliper reduces the velocity of a car by creating friction with the brake rotor. Brake callipers function like clamps on a wheel rotor to stop the wheel from spinning during braking (Lie et al., 2018). Inside each calliper is a pair of metal plates known as brake pads, as shown in Figure 1. During braking, the brake fluid applies pressure to the piston in the brake calliper, forcing the pad against the brake rotor and slowing the car. Brake calliper designs can be improved by reducing its weight and improving its cooling performance. This can be achieved using lattice structures and topology optimised parts manufactured using additive manufacturing. A lattice structure is a type of architecture that consists of multiple periodic unit cells of space with edges and faces. Two and three-dimensional lattice structures exist and are connected to a lattice solid (Zadpoor, 2019). Lattice structures can be considered as a monolithic material with a set of properties that is effective on its own.

FIGURE 2. Example of a brake system including the brake calliper and brake disc

## METHODOLOGY

The first step is to identify the boundary condition, load and material, then redesign the brake calliper through reverse engineering process while maintaining the part's mechanical requirements. Reverse engineering can be performed by using a 3D scanner to obtain the exact CAD model of the existing brake calliper. This increases model accuracy and reduces time (Fu, 2007). After obtaining the brake calliper geometry from the 3D scanning process, the design of the brake calliper was then modelled using Autodest inventor 2021 software to produce a 3D CAD file (Szilvási-Nagy & Mátyási, 2003). Reverse engineering uses a 3D scanner to capture 3D geometric data and specialised software to manipulate and interpret the data into cloud points (Buonamici et al., 2018). This information can be used to create 3D models that were inaccesible.

Once the brake calliper CAD model is obtained from the 3D scanning results, structural analysis was performed to identify the areas that can be optimised and integrate lattice structures and topology optimisation in order acheive weight reduction. Next, lattice structures was also integrated in the topology optimised sections. The strength of the lattice structure was identified by observing the displacement and the maximum and minimum lattice diameter values that have low safety factor values. The generation of this lattice structure was obtained by using Altair Inspire software. This software allows the optimal lattice structure to be generated and analysed through the topology optimisation and lattice structure creation feature.

FIGURE 3. Freescan-UE11 3D Scanner for reverse engineering of the brake calliper

The scanning was conducted using the Freescan-UE11 3D scanner, as shown in Figure 3. The surface of the brake calliper geometry is scanned and converted into a 3-dimensional form. This Freescan UE-11 3D scanner uses a blue laser beam for optimal results since the surface of the brake calliper is reflective, which makes this equipment suitable for use (Abid et al., 2022).

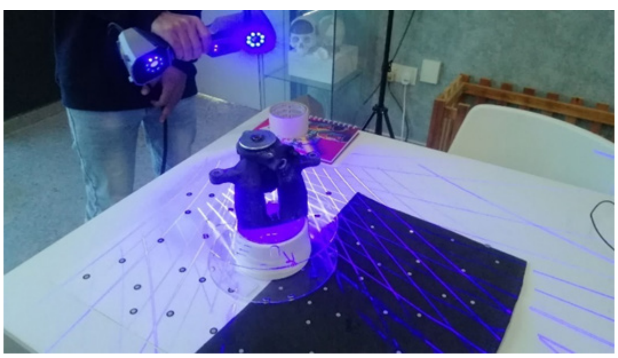

FIGURE 4. 3D scanning process of the brake calliper

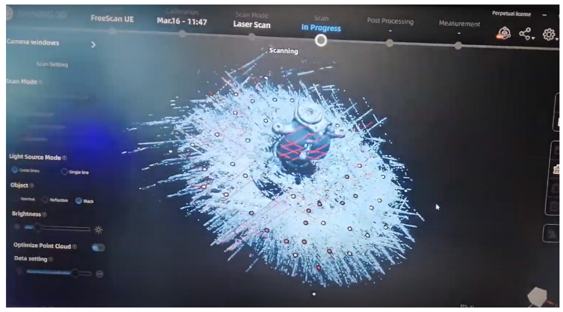

FIGURE 5. Cloud points generated from the 3D scanning process

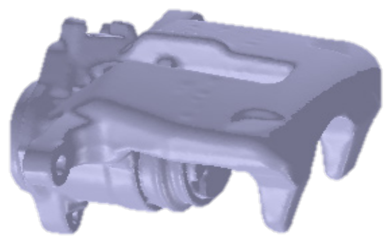

FIGURE 6. STL 3D CAD model obtained from the Freescan-UE11 3D scanner of the brake calliper

The result of the scanned brake calliper was converted to a Stereolithography (STL) file that only has the geometry of the shape. To obtain a unified design, the STL file was imported in the Autodesk Inventor 2021 software as a reference model to recreate an accurate 3D CAD model in native Autodesk Inventor file format. The original weight of the brake calliper was 2.5 kg, and the CAD model weighs 2.42 kg. Figure 6 shows the result of the 3D CAD model of the brake calliper produced from the software used. The brake calliper is a floating-type brake calliper used by Volkswagen Golf Mk6.

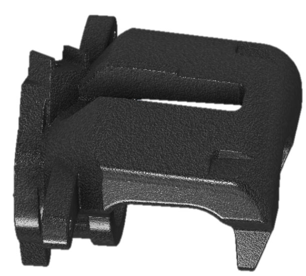

FIGURE 7. Brake calliper generated from the cloud points

Next, the STEP file is imported into the Altair software to undergo a structural analysis process to verify the stress and strain. The forces applied in the analysis of the structure are pressure, heat, and push force. For the applied force of 2000N which is often applied by the brake calliper, 5 MPa of pressure resulting from the piston has pushed the brake pad to stop the vehicle. The resulting heat is 5 to 10 percent absorbed by the brake calliper. The boundary conditions and design space are chosen based on the literature for the floating brake calliper. Figure 8 shows the boundary conditions and the design space that have been set.

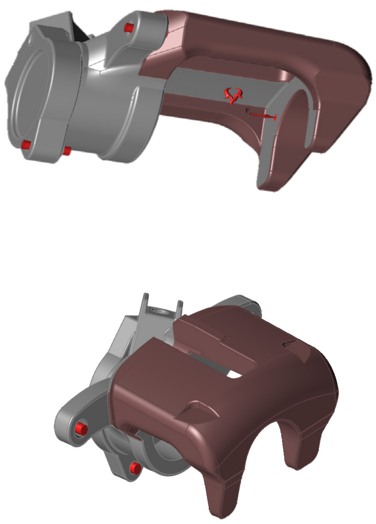

FIGURE 8. Boundary conditions and design space of the brake calliper

The brown volume indicates the design space has been chosen. After determining the boundary space, the topology optimisation process is performed to obtain a lightweight and optimal design. This optimisation can also be adjusted to obtain a better design and simplify the process of PolyNURBS. Weight reduction has also been set to not exceed 40% of the original weight of the brake calliper. The generation of PolyNURBS is the result of re-designing the framework that has been optimised as suggested. The result of this optimisation is also significant in obtaining low values of spacing and pressure after the analysis.

The optimisation process using PolyNURBS follows the shape that has been adjusted so that it can be aligned with the design that was set. Figure 9 shows the final result that was been achieved by using the PolyNURBS method to create a new model. This topology optimisation model will be reanalyzed to get good results. If this analysis finds that the results obtained are not good; redesigning the parts with high pressure values should be done. This is because maintaining the mechanical strength properties is important.

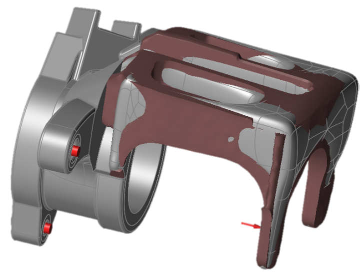

FIGURE 9. Resulting PolyNURBS from the optimisation process

The lattice structure optimisation was performed by generating the lattice structure in the brake calliper model that was optimised. This lattice structure will be generated by changing the displacement length, maximum and minimum diameter values. Before generating the lattice structure, the design space needs to be defined. The specified design space should be constructed by drawing on the center of the brake calliper. Figure 7 shows the design space created to generate the lattice structure in it. The design space for this lattice structure has become a new model, which makes it a lattice structure model. This lattice structure model is generated in the middle part because the spacing applied in that part is low and suitable for generating a more optimal lattice structure.

Finite element analysis will be carried out on the composition of the brake calliper model in order to integrate the topological structure and lattice into it. This analysis is carried out using Altair Inspire 2021 to determine the solid area of the brake calliper model that can be optimised and needs to be filled with structure lattice.

FIGURE 10. Design space for the lattice structure in the brake calliper

## RESULTS AND ANALYSIS

This section presents the results obtained from the finite-element analysis of each CAD model. The analysis and redesign models are based on the forces and boundary conditions that are applied on the brake calliper. To obtain accurate results, it is important to use the correct material and boundary conditions. This brake calliper consists of cast iron material as the main material in this component. Table 1 shows the mechanical properties of cast iron. The selection value of this material is taken from the CES Edupack software reference.

TABLE 1. Mechanical properties of cast iron

| Parameter | Value |
|---|---|
| Density (g/mm^3) | 0.007 |
| Tensile Strength (MPa) | 444 |
| Yield Strength (MPa) | 375 |
| Young Modulus (GPa) | 148 |
| Heat conductivity (W/mm*K) | 0.261 |
| Thermal expansion coefficient (/K) | 10.4 |

Figure 11 is the result of the structural analysis performed in the Altair Inspire 2021 software to obtain the maximum von Mises value, safety factor, and principal strain. From the results obtained, it can be observed that the distribution of the stress on the brake calliper and the areas which have lower stresses and areas which have higher stresses. In the areas with higher stresses, it is suitable for design improvements and certain volume can be removed to reduce mass, while at the same time maintaining the strength of the part and meeting the part's requirements.

Three CAD models were used for the simulation: the initial brake calliper design, the topology optimized model, and the third model is the recreation of the brake calliper after the topology optimized results, using PolyNURBS function, which has smoother surface and better aesthetics in terms for forms and design. Table 2 shows the results of the initial solid model and topology optimised model of the brake calliper. The results in Table 2 show that the percentage of mass decreased by 36.37 % for the topology optimised model, and for the polynubrs model, the the mass decreased by 31%. An increase can be seen in the safety factor found of the optimal model, whereas in the PolyNURBS model, the safety factor and the maximum von Mises value are less than the topology optimised model.

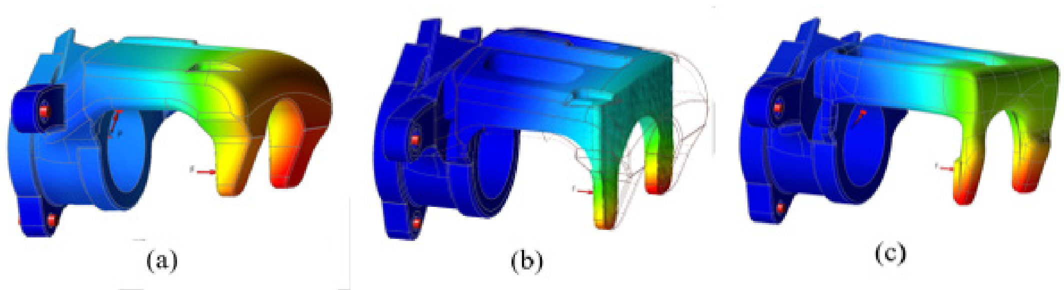


FIGURE 11. Results from the simulation for (a) initial brake calliper design, (b) topology optimised model, and (c) final optimised model using PolyNURBS

TABLE 2. Topology optimisation (TO) results

| Model | Mass (Kg) | Mass reduction (%) | Displacement (mm) | Safety factor | Maximum Von Mises (Mpa) | Principal Strain (Mpa) |
|---|---|---|---|---|---|---|
| Solid | 2.426 | - | 0.036 | 3 | 139.8 | 0.0004 |
| TO model | 1.536 | 36.67 | 0.944 | 4.42 | 182.1 | 0.0011 |
| PolyNURBS model | 1.660 | 31.57 | 0.180 | 2.72 | 141.8 | 0.0008 |

Heat resistance is an important aspect of brake calliper design in a braking system. The heat generated by the braking system is caused by the brake discs spinning very fast and the brake pads will reduce the speed of that rotation to stop the vehicle and high heat is generated on the brake disc. Therefore, in this study, a thermal stress analysis was also performed, which aims to understand the level of heat resistance by the brake calliper model. Figure 12 shows the heat transfer simulation, with a heat parameter of 600 ℃ which was set in this analysis. This heat transfer analysis is only performed by solid brake calliper models, and the optimized PolyNURBS brake calliper model.

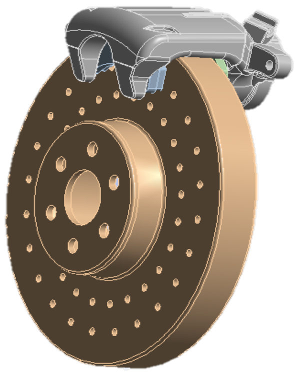

FIGURE 12. Car braking system and heat generated due to the friction between the brake disc, brake pad and brake calliper

A heat transfer analysis was generated and the result is presented in Table 3. This analysis compared the initial brake calliper design, which is fully solid, with the topology optimization model.

TABLE 3 Heat transfer simulation results

| Model | Temperature (C) | Thermal increment (c/mm) | Heat flux (W/mm^2) |
|---|---|---|---|
| Solid | 60.052 | 0.024 | 0.0140 |
| Topology Optimization | 82.012 | 0.052 | 0.030 |

Next, to further improve the brake calliper design, lattice structures were generated to further enhance the strength and performance of the lattice structure. The generation of the lattice structure is made by using the Altair Inspire lattice generation feature.

TABLE 4. Values for the targeted length displacement, maximum and minimum diameter Parameters for lattice structure generation

| Model | Targeted length (mm) | Minimum Diameter (mm) | Maximum Diameter (mm) |
|---|---|---|---|
| | 5 | 0.8 | 1.6 |
| | 2 | 0.8 | 1.6 |
| | 3 | 0.8 | 1.6 |
| | 5 | 0.2 | 4 |
| Final model | 3 | 1.4 | 2.8 |
| | 3 | 0.3 | 0.6 |
| | 3 | 0.6 | 1.2 |
| | 3 | 1 | 2 |
| | 3 | 0.75 | 1.5 |

To generate the lattice structures, three parameters must be chosen, which are the targeted length, minimum diameter, and maximum diameter. The values chosen for these parameters are shown in Table 4.

The models were analysed using the Altair Inspire 2021 software to generate the optimisation of the lattice structure and perform the finite element analysis. Figure 9 shows the 3D CAD model of the lattice structure generation produced by the software. Structural analysis will be carried out on each model. The following are the results that have been analysed for all lattice fractions, as shown in Table 5.

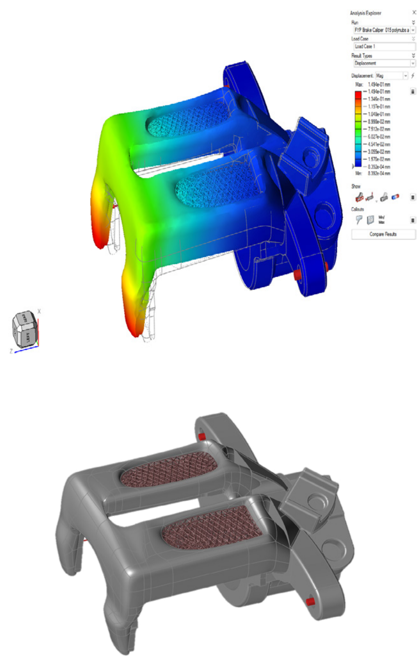

FIGURE 13. Lattice structure generated in the middle section of the final model.

TABLE 5. Results of structure analysis for the final model

| Model No. | Targeted length (mm) | Minimum Diameter (mm) | Maximum Diameter (mm) | Mass (kg) | Mass reduction (%) | Spacing (mm) | Safety factor | Von Mises Maximum (MPa) | Maximum lattice structure diameter (mm) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 5 | 0.8 | 1.6 | 1.660 | 31.58 | 0.137 | 8.4 | 51.1 | 1.024 |
| 2 | 2 | 0.8 | 1.6 | 1.683 | 30.64 | 0.145 | 4.4 | 95.93 | 0.800 |
| 3 | 3 | 0.8 | 1.6 | 1.713 | 29.37 | 0.149 | 5.5 | 77.16 | 0.800 |
| 4 | 5 | 0.2 | 4 | 1.643 | 32.27 | 0.139 | 6.3 | 67.26 | 1.217 |
| 5 | 3 | 1.4 | 2.8 | 1.737 | 28.41 | 0.138 | 4.4 | 95.93 | 1.400 |
| 6 | 3 | 0.3 | 0.6 | 1.645 | 32.19 | 0.149 | 4.4 | 95.94 | 0.600 |
| 7 | 3 | 0.6 | 1.2 | 1.665 | 31.39 | 0.147 | 4.4 | 95.93 | 0.6144 |
| 8 | 3 | 1 | 2 | 1.702 | 29.84 | 0.143 | 4.4 | 95.93 | 1.000 |
| 9 | 3 | 0.75 | 1.5 | 1.678 | 30.83 | 0.142 | 4.4 | 95.93 | 0.7804 |

Based on the results obtained, for each model, there is a variation of the safety factor, with the minimum safety factor of 4.4 is obtained. The minimum safety factor is also compared with the maximum von Mises disaster resulting from a model that has a 4.4 safety factor value. It can be discussed that a high safety factor does not necessarily mean it is good, since it can cause over dimensioning of the part. It is important to verify the safety factor and mass to choose the suitable design. In this result, there are 2 optimal lattice models, which have a weight of 1.683kg (model number 2) and 1.713kg (model number 3), for the optimal lattice structure diameter value. The maximum von Mises stress is lower than the yield stress of the material which is 375 MPa.

## CONCLUSION

This study aims to improve the design of automotive components using additive manufacturing. A brake calliper was chosen in this study, and reverse engineering method was used to obtain the CAD model. Topology optimisation and lattice structures were used to generate new designs. The aim is to produce more optimal and lightweight automotive components by using additive manufacturing. A heavy component of the vehicle can affect fuel consumption. In order to reduce fuel consumption, it is important to reduce the mass of automotive components. The component part chosen as the main subject of this study is the brake calliper and lattice structure is created to replace certain volumes of the brake calliper. A lattice structure is an architectured material formed by an arrangement of unit cell spaces with ordered edges and faces that has a porous design structure. It is commonly used in the field of 3D and additive printing to reduce the weight of a model and achieve different strength resistance.

Among the lattice structures used in this study is the random lattice structure optimization. Structural analysis has been carried out after the formation of the lattice structure optimisation in the brake calliper. The data found that model number 2 with the weight of 1.683kg has an optimal lattice structure diameter. In conclusion, based on the data obtained and recorded after the simulation was performed on all 11 calliper brake models including the full volume model and the topology optimisation model, the results show that it meets all the conditions that have been set in this study. Therefore, it can be concluded that weight reduction for brake callipers has been achieved through the use of topology optimisation and lattice structure integration.

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## DECLARATION OF COMPETING INTEREST

All authors declare that they have no conflicts of interest.

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