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Lightweight Design and Finite Element Analysis of Brake Lever for Motorcycle Application

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Abstract **-** A lightweight component design contributes to the overall optimization of a system to be more effective and efficient. Then, it can lead to the contribution of a carbon footprint reduction. The research aimed to propose a novel lightweight brake lever design for motorcycle applications and numerically investigate its performance by comparing the proposed design with different utilized materials. The subject of the research was an optimized brake lever for motorcycle application. The materials used were aluminum alloy, structural steel, and titanium alloy. A Finite Element Method (FEM) analysis was employed to investigate the proposed brake lever design. Three proposed designs were introduced with the mass reduction in each optimization up to 50,9% of reduced mass. Maximum stress was observed on the most optimized design with a value of 297 MPa. The strain and total deformation were also investigated among the components. In the result, the stress-strain graph shows that the most optimized brake lever experiences the highest stress with the highest strain value. Furthermore, the highest safety factor is achieved with the utilization of titanium alloy, reaching the value of 6,28 for preliminary design and 3,1 for the most optimized component. However, the lightest component can be obtained using aluminum alloy.

Keywords: lightweight design, finite element, brake lever, motorcycle

I. INTRODUCTION

The endeavor in the engineering sector to have a lightweight design in automotive components is proven useful in reducing overall component weight. Then, it can lead to the reduction of fuel consumption (Koffler & Rohde-Brandenburger, 2010) for both internal combustion engines (Bian et al., 2015) and electrified vehicles (Burd, Moore, Ezzat, Kirchain, & Roth, 2021; Carlstedt & Asp, 2020). This action is obviously supporting the movement on the reduction of carbon footprint issues (Hoffmann, Haag, & Müssig, 2021). There are many methods to have a lighter component yet maintain still its mechanical property benefits, such as the use of lightweight material (Gonçalves, Monteiro, & Iten, 2022), forming methodology (Rosenthal et al., 2020), and mass optimization (Chen, Shen, Zhang, & Gao, 2020). Additionally, the other issues in reducing the overall mass of the component are related to the manufacturing process of the component (Zhu et al., 2021). Therefore, those mentioned factors in achieving a lightweight component need to consider the use of materials, optimization method, and the liability of the manufacturing process. Undoubtedly, all those factors will lead to the cost issue (Kamps, Lutter-Guenther, Seidel, Gutowski, & Reinhart, 2018).

A lightweight component design has been considerable attention in research progress nowadays. A previous study has been carried out to understand the relevance and impact of sustainable lightweight design. It shows that the lightweight design is closely related to the entire value chain of the production process (Kaspar & Vielhaber, 2017). Furthermore, lightweight design and activities also highly contribute to the overall reduction of carbon emissions across industries (Albers, Holoch, Revfi, & Spadinger, 2021; Yudianto, Kurniadi, Adiyasa, & Arifin, 2019). In terms of the automotive and mechanical engineering sector, a lightweight design of a component has also been a main research activity, such as the weight reduction of front suspension upright (Li, Tan, & Dong, 2020), axle hub (Zhang et al., 2020), electric bus roof structure (Jung, Lim, Kim, & Min, 2020), vehicle chassis structure (Xia et al., 2021), motorcycle clutch lever (Kholis, Achmad, Yudianto, Adiyasa, & Solikin, 2020), and cutting head tools (Yudianto,

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2019). All mentioned previous studies are carried out mainly to optimize the component weight while maintaining the functionality and the benefits of its mechanical properties.

The use of the Finite Element Method (FEM) in engineering research. It is a numerical technique discretizing a model into small elements and reconnects the elements at points called nodes. It has also been widely employed to investigate various problems in mechanical engineering (Karthikeyan, Rajkumar, Bensingh, Kader, & Nayak, 2020; Yudianto, Ghafari, Huet, & Wakid, 2019), medical devices (Barkaoui, Ait Oumghar, & Ben Kahla, 2021), biomedical engineering (Lisiak-Myszke et al., 2020), safety engineering (Yudianto, Prasetyono, Adiyasa, Purnomo, & Fauzi, 2020), and civil engineering (Pelekis, McKenna, Madabhushi, & DeJong, 2021; Ren, Fan, Li, & Chen, 2019). The use of finite element analysis has also been firmly validated, leading to the proof that the methodology has been used and applicable for engineering research and acceptable in various cases of engineering (Bola, Simões, & Ramos, 2021; López-Campos et al., 2020). The mentioned research on engineering proves that using finite element analysis provides a realistic result compared to the real world.

In terms of the brake lever, this automotive component is generally commercially available in the market with various designs and structures. However, due to the commercial purpose of the component, there are still limited academic research and publications that clearly explain the design and mechanical properties of the component. The research aims to propose a novel lightweight design for motorcycle brake lever and investigate the mechanical characteristic of the component due to the proposed mass optimization considering the different materials used to manufacture the component. The proposed hand lever design is categorized as a light design if the average weight is below the ones distributed on the market. Having a lightweight design of a component contributes to the overall weight reduction of the motorcycle, which leads to reduced carbon emissions of the motorcycle.

II. METHODS

The research starts with performing a literature review, including a need to study the topic (Saurabh & Yadav, 2016). This stage identifies the research gap and the state of the art of the topic under investigation. Then, the designing and modeling of motorcycle brake levers are performed by proposing three stages of lightweight design optimization. The model is modeled using computer-aided design to create a 3D model of the brake lever. Moreover, FEM simulation requires a mesh generation to numerically model the brake lever after the data are selected and inputted to the solver. At the next stage, the loading and boundary conditions are needed to be defined before the FEM is performed. The obtained results are verified to ensure the generated results from the FEM method. The overall research flowchart is portrayed in Figure 1.

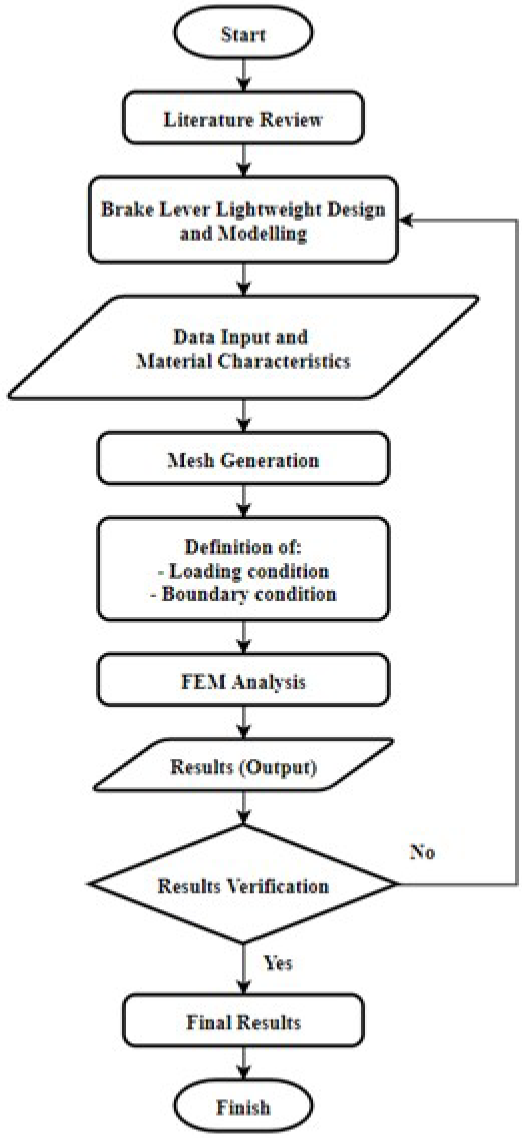


Figure 1 Research Flowchart

III. RESULTS AND DISCUSSIONS

The proposed design of the brake lever is 170 mm in length, 40,50 mm in width, and 11,85 mm in thickness. This dimension has agreed with the standard dimension for certain available motorcycle specifications in the market. Therefore, it is ensured to fit on the motorcycle application. However, the model's thickness varies after the first and second mass reductions are performed. The brake lever is intended to be installed at the right hand of the motorcycle steering system. It consists of a pivot bolt attachment that is 8 mm in diameter. The brake lever is utilized to push the master cylinder to give the necessary fluid pressure to perform a braking force on the motorcycle.

The tipping point to which the part of the brake lever pushes the master cylinder is displayed in Figure 2. Since the brake lever is for the right-hand side of the brake, the hand grip is attached to the part where the force is applied, as described in Figure 2. At the other end of the brake lever, there is a necessary extruded shape functioning to push the brake switch on the motorcycle.

Then, an iterative design process is performed to finalize the lightweight design of the motorcycle lever brake (Feng, Lu, & Jiang, 2022). Figure 3 shows the proposed brake lever design starting from a preliminary design, the first optimized weight, and the final optimization. The initial design of the brake lever only considers the functionality of the lever without mass reduction. It is completely solid and apart from the pivot bolt attachment point. The hand grip area of the initial design is completely straight and has a squared cross-section, as shown in Figure 3(a).

The first optimized design in Figure 3(b) introduces a more ergonomic handgrip by making a curvy shape by reshaping the hand attachment point. It reduces some material in the area nearby the pivot bolt attachment. A subtracted area is also noticed at the end point of the handgrip area. Some material is also removed at the attachment point to the master cylinder.

The second design optimization in Figure 3(c) greatly reduces the mass in many points of the brake lever. Some penetrated subtractions are performed at the handgrip area and nearby the pivot bolt attachment. Some cylindrical holes are also introduced to reduce some mass at some locations at the lever. However, the extruded shape at the end of the lever is not changed since it is necessary to have this shape for pushing the brake switch. Moreover, the total length of the lever, the diameter of the pivot bolt attachment, and the location of the master cylinder push point are also not changed to ensure the functionality of the brake lever from the changes made.

Three types of materials are used to analyze the lightweight design of the brake lever mechanically. The materials are aluminum alloy, structural steel, and titanium alloy. The primary analysis applies aluminum alloy as the main material of the component considering the most common material used (Deshpande, Badadhe, & Khan, 2021). Later, three different types of materials

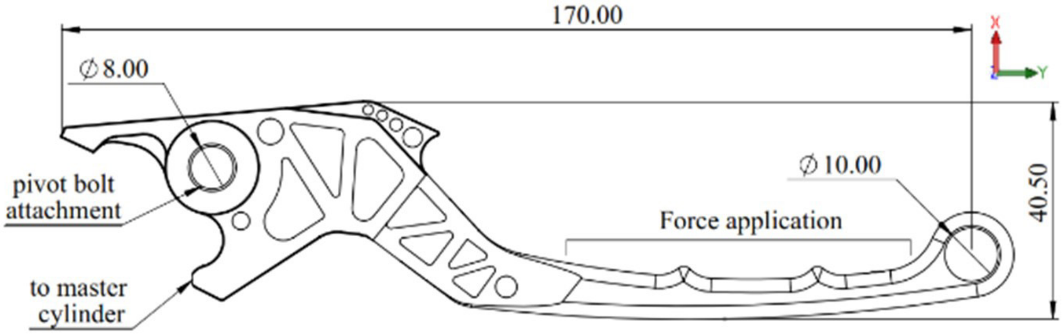
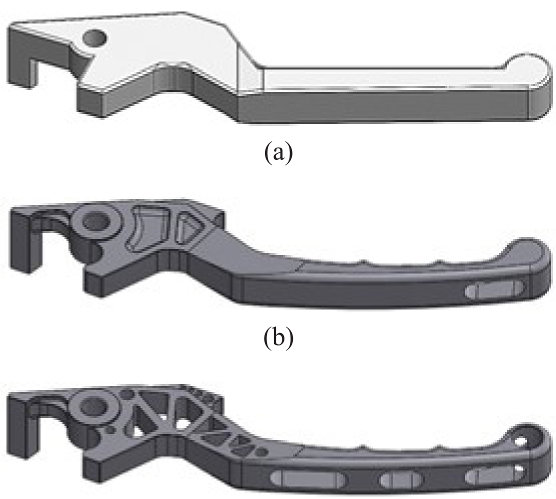


Figure 2 Right-Hand Brake Lever Design



(a)

(b)

(c)

Figure 3 Proposed Brake Lever Design for (a) Preliminary Design, (b) First Optimization, and (c) Second Optimization are applied to identify the effect of material changes on weight reduction and safety factors. The property of used materials can be observed in Table 1.

Table 1 Material Properties of Aluminium Alloy (Al), Structural steel (St), and Titanium Alloy (Ti)

Property	Al	St	Ti
Density	2.770 kg/m^3	7.850 kg/m^3	4.620 kg/m^3
Young's modulus	71.000 Mpa	200.000 MPa	96.000 MPa
Poisson's ratio	0,33	0,30	0,36
Yield strength	280 MPa	250 MPa	930 MPa
Ultimate strength	310 MPa	460 MPa	1,070 MPa

Tetrahedron mesh is chosen in the mesh generation. It can be seen in Figure 4 that the mesh element is representative of generating the initial shape of the brake lever. The element size is 2 mm with a fine set of span angle centers. Then, a medium smoothing is chosen to ensure the smoothness of the generated mesh. The mesh generates 64.138 nodes and 36.804 elements altogether to construct the brake lever model. In general, the mesh setting is great enough to shape the model representative of the brake lever. Figure 4 also shows the detailed mesh overview at the pivot bolt attachment hole and the end of the handgrip area. A similar setting is also performed by previous researchers (Kholis et al., 2020).

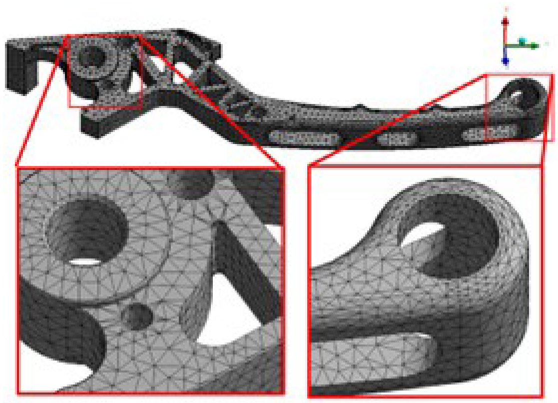


Figure 4 Resulting Mesh of the Component

The simulation considers the worst-case scenario of loading conditions. It applies 30 steps of loading condition with a linear increment from 0 N to 624 N of maximum handgrip force at the direction of -X, referring to Figure 2. Therefore, it is possible to observe the changes in the stress over the strain or the changes in the displacement with respect to the increment of the force applied. The maximum imposed force considers the average value of how much a person can grip the brake lever (Deshpande et al., 2021; Triyono, Kaleg, & Adyono, 2019). The force is imposed at the handgrip surface. Additionally, cylindrical support is applied to the hole in which the pivot bolt is attached. This setting enables to simulate of the capability of the handgrip brake lever to rotate

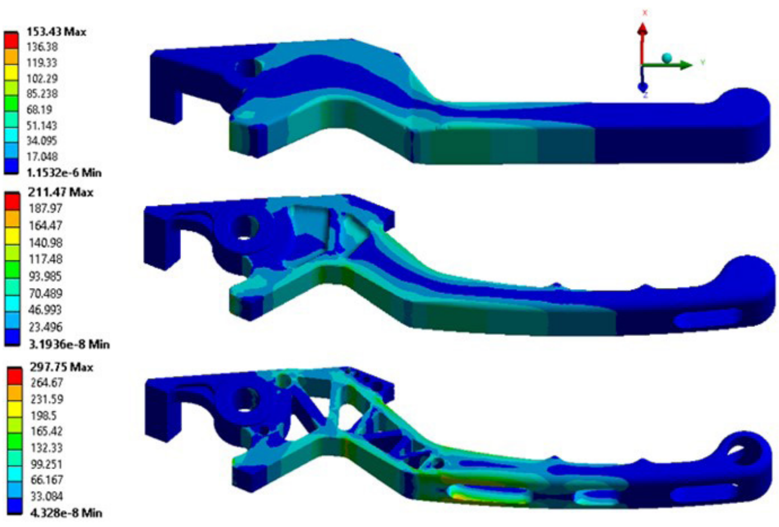


Figure 5 Stress Distributions of the Preliminary Design (Top), First Optimization (Middle), and Second Optimization (Bottom)

at the axis of the hole. Fixed support is set at the point where the brake lever pushes the brake master cylinder. Therefore, it is assumed that the master cylinder is pushed at the maximum point until it is unable to push the master cylinder further.

Figure 5 compares the resulting stress experienced by the three proposed models with the aluminum alloy material. The second optimization undergoes the highest stress value with the same force application. The maximum stress on the preliminary design is 153,43 MPa. It occurs mainly in the area between the handgrip and the pushing tip of the lever to the master cylinder. However, most of the stress is between 51 to 85 MPa, represented by the green color of the results.

However, the first optimized design has a much higher stress value compared to the preliminary design reaching the value of 211 MPa. With some material removal undergone by the first optimization lever, it is clear that higher stress is occurring in the same area of the preliminary design. Moreover, on the second optimization, the maximum stress occurs on the middle part of the lever reaching the value of 297 MPa. However, this value is slightly higher than the yield strength of the material. It can also be observed that the stress hardly occurs at both ends of the lever. It shows that the stress value is nearly zero for the preliminary design and the first and second optimized designs. Therefore, it can be derived that removing materials from the brake lever causes an increment in the component stress distribution.

Figures 6 to 8 (see Appendices) compare the stress changes with respect to the strain when the component is imposed force from 0 to 624 N. The higher slope of the trend is observed on the second optimization compared to the preliminary design. The initial design is capable of experiencing about 153 MPa of stress at the maximum force with the maximum strain of about 0,003 mm/mm. For the first optimization brake lever design, it can hold a maximum of 211 MPa with a strain elongation of slightly more than 0,0035 mm/mm. Instead, the second optimized brake lever reaches nearly 300 MPa of stress at the strain value of 0,0043 mm/mm.

All three trends are in the linear line so that it can be observed that even the second optimization component is on the plastic deformation of the material. Moreover, it can be said that the weight reduction on the brake lever component causes higher strain with a higher peak of stress compared to the preliminary design of the brake lever. This finding is similar to what has been investigated by previous researchers on similar objects (Deshpande et al., 2021; Triyono et al., 2019).

Figure 9 (see Appendices) compares and contrasts the deformation of the preliminary design of the brake lever and the first and the second optimizations of the component as the same given force of 624 N. The maximum deformation occurs on the end of the clutch lever of all three components. The preliminary design reaches a maximum deformation of 0,87 mm. The first design optimization experiences 1,53 mm of maximum deformation. Meanwhile, the second optimization component undergoes 2,94 mm of deformation. The more material is removed, the higher deformation occurs on the component with the same force level.

In contrast, nearly zero deformation occurs on the other end of the clutch lever. Figures 10 to 12 (see Appendices) give a comparison of the force-displacement graph of three components made from aluminum alloy. The force of 624 N applied to the preliminary design only gives a displacement of about 0,87 mm. Instead, for the first optimized design, the maximum force imposed on the component results in a displacement of 1,54 mm. It is almost 3 mm for the second optimized design. All three trends of the force-displacement graph are linear, with the highest slope in the preliminary design and the lowest slope for the second optimized design. The force-displacement graphs give information on how much displacement occurs to the component with the given force from 0 to 624 N.

The weight reduction by optimizing the shape of the component needs to consider the safety factor of the proposed component. It gives the assessment of how safe the component is to be used with the mentioned case of loading conditions (Triyono et al., 2019). Figure 13 (see Appendices) depicts the comparison of the safety factor of the proposed models made from aluminum alloy material. The minimum safety factor of the preliminary design of the component reaches about 1,82. However, this value occurs only in a small area of the clutch lever at the base of the handle grip area. The other area shows a relatively higher value, which is about 5 to 10. The range of value is considered highly safe. Instead, the first optimized design of the clutch lever results in the safety factors of only 1,32, and the area of the minimum value of the safety factor is much wider than the preliminary design. Nonetheless, the second optimized component has merely a 0,94 value of safety factor, which is the lowest value among others. The area of the lowest safety factor value occurs mainly in the middle part of the component.

Next, it is about the effects of material changes on the weight reduction achieved by the components. Three different materials are applied to the component, and the mass is estimated. The components made of structural steel can reach the heaviest mass compared to other materials. The preliminary design made by structural steel is estimated to have 0,328 kg of mass. It is followed by titanium, having a mass of 0,193 kg and aluminum alloy, with 0,116 kg. The first optimized design made from structural steel has 0,219 kg of mass. Meanwhile, titanium alloy has 0,129 kg, and aluminum alloy shows 0,077 kg. The lightest component is the second optimization made from aluminum alloy, and the heaviest second optimization component is made of structural steel. The first optimized design can achieve approximately 33% mass reduction instead of the preliminary design. Meanwhile, the second optimization component can reach a much higher mass reduction value of slightly more than 50%. There are still more possibilities for a much higher mass reduction for advanced manufacturing technology, such as using additive manufacturing technology (Blakey-Milner et al., 2021; Ingarao, Priarone, Deng, & Paraskevas, 2018). The detail of the comparison can be observed in Tables 2−4. Then, it is graphically compared in Figure 14 (see Appendices).

Table 2 Weight Reduction for Aluminium Alloy Material

Proposed Design	**Mass (kg)**	**Mass Reduction (%)**
Preliminary Design	0,116	-
First Optimization	0,077	-33,6%
Second Optimization	0,057	-50,9%

Table 3 Weight Reduction for Structural Steel Material

Proposed Design	**Mass (kg)**	**Mass Reduction (%)**
Preliminary Design	0,328	-
First Optimization	0,219	-33,2%
Second Optimization	0,162	-50,6%

Table 4 Weight Reduction for Titanium Alloy Material

Proposed Design	**Mass (kg)**	**Mass Reduction (%)**
Preliminary Design	0,193	-
First Optimization	0,129	-33,2%
Second Optimization	0,095	-50,8%

Different materials results in different safety factor value for the same component. Figure 15 describes the changes in the safety factor value of three components due to the changes in materials. It is noticeable that the use of titanium alloy yields the highest value of safety factor among other materials. The result is in line with the previous researchers (Pavlenko, Dvirnyk, & Przysowa, 2021; Salins, Mohan, & Stephen, 2021). The preliminary design made by titanium alloy has 6,28 of a safety factor value. It is followed by aluminum alloy with 1,85 and structural steel with 1,57. In this case, the value is almost triple when the titanium alloy is used.

As seen in Figure 15 (see Appendices), the first optimization design made by titanium has 4,52 of a safety factor value. It is also almost three times higher than the ones made from structural steel and aluminum alloy. However, the lightest design fabricated by titanium alloy is estimated to have a safety factor of 3,1. Meanwhile, the second optimized design made from aluminum alloy has merely 0,94 of safety factor and 0,85 of structural steel. In this case, the use of titanium alloy brings benefits in a higher value of safety factor regardless of the cost of the material and manufacturing itself.

The proposed brake lever design in the research implies that the brake lever product on the market has the potential to be reduced in terms of weight. However, it still manages the safety aspect of the product. Therefore, the results can give a reference for automotive manufacturers to modify their brake lever product to support the green movement with the use of light material for automotive components while the safety factor is still the highest consideration.

IV. CONCLUSIONS

The research investigates the proposed lightweight brake lever design for motorcycle application and the mechanical performance through finite element analysis. The comparison of three different designs with the effects of material substitution is also studied. The highest material stress is undergone by the component with the lightest mass, in this case, the one with 50% mass reduction. A directional deformation observes the highest value at the end of the brake lever since it is the largest distance from the pivot bolt attachment and nearby the application of the hand grip force. The safety factor of titanium alloy has the highest value compared to other materials, reaching the value of 6,28. However, the use of aluminum alloy as the brake lever material contributes to the lightest mass compared to the other designs and material utilizations.

The research results contribute to the possibility of reducing the weight of the brake lever handle. Therefore, it supports the use of the most effective material utilized but keeps maintaining its safety consideration. In addition, the weight reduction of the component impacts the overall effectiveness of the system in terms of energy used and contributes to environmental sustainability. The research limitation lies in the requirement to validate and compare the results with the actual model cases, which will be the next activity following the research.

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APPENDICES

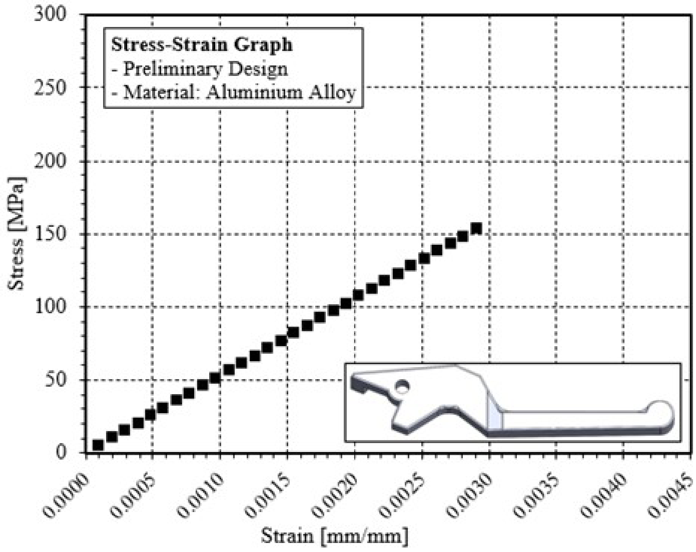

Figure 6 Stress-Strain Graph for Preliminary Design at Given Force

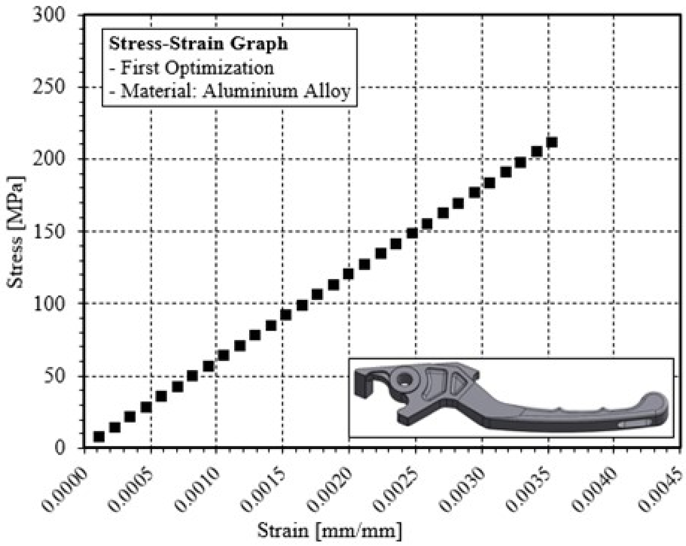

Figure 7 Stress-Strain Graph for the First Optimized Design at Given Force

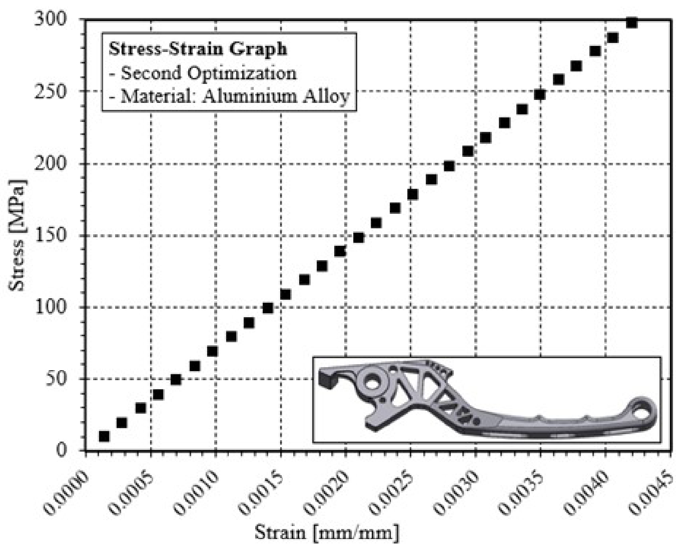

Figure 8 Stress-Strain Graph for the Second Optimized Design at Given Force

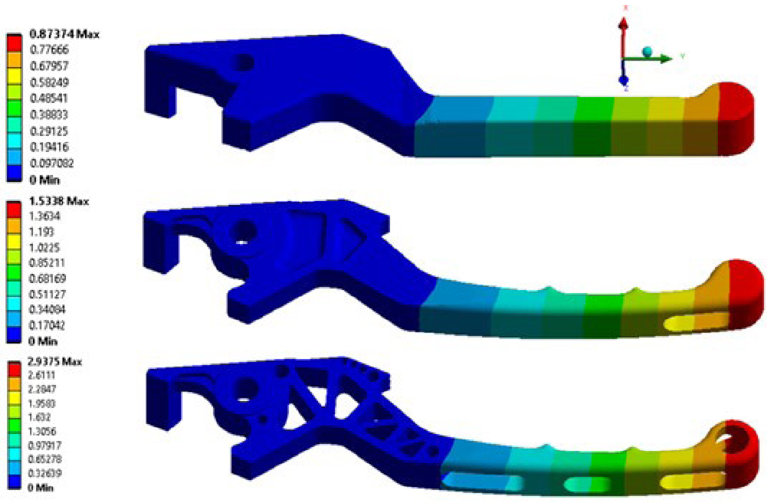

Figure 9 Deformation of the Preliminary Design (Top), First Optimization (Middle), and Second Optimization (Bottom)

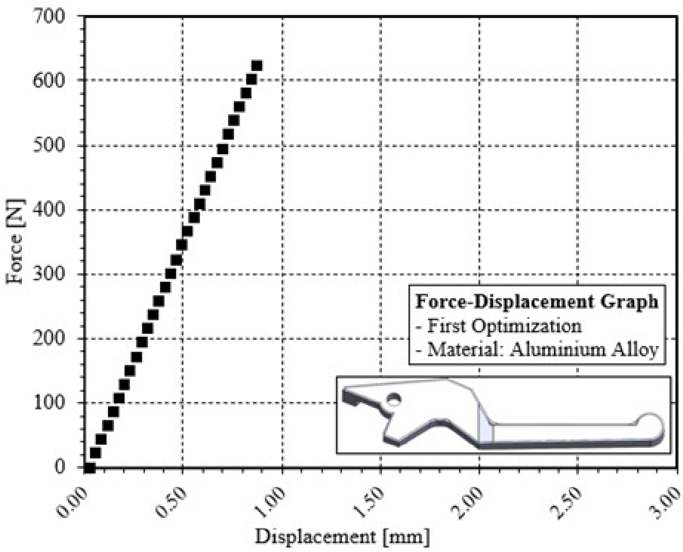

Figure 10 Force-Displacement Graph of The Preliminary Design of Brake Lever

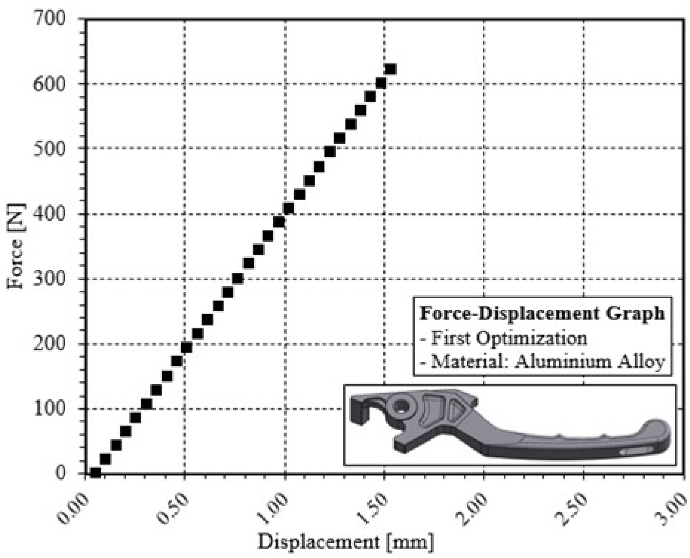

Figure 11 Force-Displacement Graph of the First Optimized Design of Brake Lever

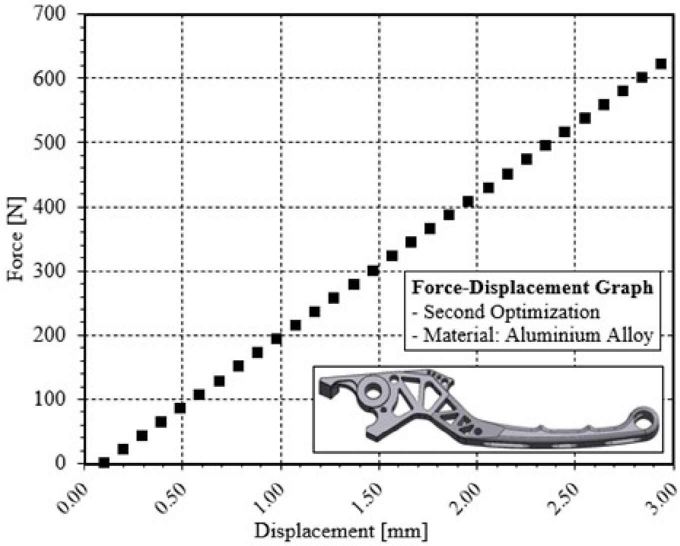

Figure 12 Force-Displacement Graph of the Second Optimized Design of Brake Lever

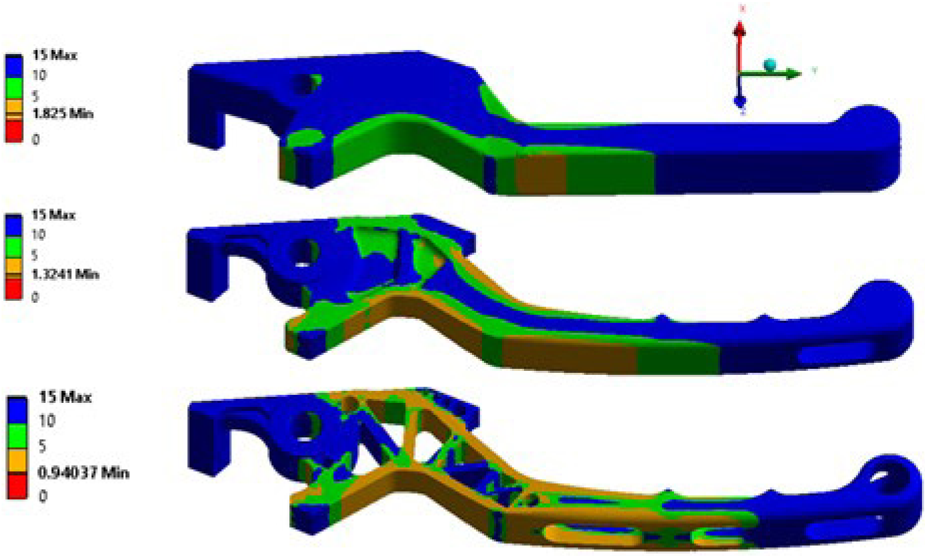

Figure 13 Factor of Safety of the Preliminary Design (Top), First Optimization (Middle), and Second Optimization (Bottom)

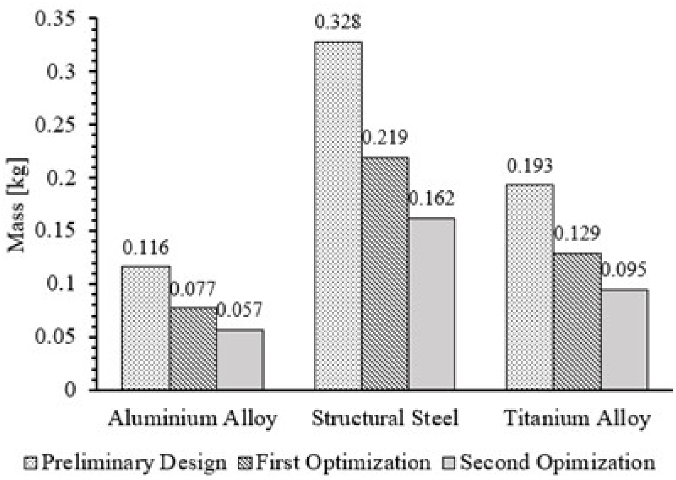

Figure 14 Mass Comparison of the Components Made from Aluminium Alloy, Structural Steel and Titanium Alloy

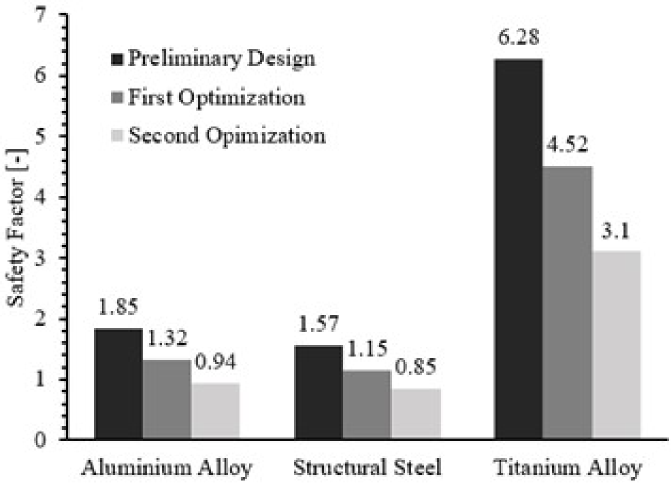

Figure 15 Safety Factor Value for Three Different Components with Three Different Materials