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Design And Analysis of Front Lower Control Arm Using Lattice Structure Optimization Process

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Bachelor of Mechanical Engineering Technology (Automotive Technology) with Honours

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A thesis submitted
In fulfilment of the requirements for the degree of
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DECLARATION

I declare that this "Design and Analysis of Front Lower Control Arm Using Lattice Structure Optimization Process" is the result of my own research except as cited in the references. "Design And Analysis of Front Lower Control Arm Using Lattice Structure Optimization Process" has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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APPROVAL

I hereby declare that I have checked this thesis, and, in my opinion, this thesis is adequate in terms of scope and quality for the award of the Bachelor of Mechanical Engineering Technology (Automotive Technology) with Honours.

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Supervisor Name : Ts. Mohd Hafizi bin Abdul Rahman

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DEDICATION

This thesis is dedicated to all the individuals that have provided unwavering support and encouragement throughout my degree academic journey.

To my parents, who constantly give endless love, support, and believing in my potential to further my study. Your guidance and wisdom have been priceless and has given me the strength to persevere every challenge.

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To my fiancée, for giving me a lot of confidence on my work, repairing my language in the report. Your dedication and patience to stay and support during my lowest cannot be repay. Your efforts can’t be described by words.

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Finally, to all those who have believed in me and supported me in the making of this thesis, thank you for being a part of my wavy journey. This thesis stands as a statement to your faith and encouragement.

ABSRACT

The purpose of this study is to analysis and optimise a new concept design of vehicle lower control arm (LCA) using. This research addressing the problem of automotive manufacturer to build a light-weight vehicle. This is because vehicle's weight affects the fuel efficiency of the vehicle itself. A mixed method of optimizations will be employed such as topology and lattice structure optimization with the help of Finite Element Analysis in between all the optimization process. But all of that will be started with selection of base design. In this first part of the thesis, a clear result from four (4) load cases has been gathered from analysing the base design. The load cases are 20,321N, -12,133N, 21,883N and -16,000N with different directions of axis applied. The base design passed all of it without exceeding the yield strength of the material, steel which is 205 MPa. Topology optimization removed the low-stress areas and reduced the mass of the base design from 34.057 kg to 12.761 kg, while maintaining a good structural integrity. Lattice Structure Optimization (LSO) further reduced the material from the optimized design. Yet, after the analysis, there is still more room for optimization. Thus, final design iterations have been done and one of it has been selected to be the final design. The final design has two area that has been optimized using LSO which is top and the bottom. The left and right side of the LCA have been reduces its thickness to also reduce the mass. The final design has an outstanding mass of 8.129kg which is a total of 76% of the mass has been reduced. This was achieved while still maintaining a minimum of Factor of Safety (FoS) of 1.3 under the most critical loading conditions. The results show that by combining topology and LSO can effectively reduce the material usage while meeting performance standards. This research opens a new path for designing automotive components to achieve the light-weight vehicle. Future improvements include exploring alternative materials, conducting a real-world dynamic test, and verifying the industry capability of producing the design.

ABSTRAK

Tujuan kajian ini adalah untuk menganalisis dan mengoptimumkan reka bentuk konsep baharu penggunaan lengan kawalan bawah kenderaan (LCA). Penyelidikan ini menangani masalah pengeluar automotif untuk membina kenderaan ringan. Ini kerana berat kenderaan mempengaruhi kecekapan bahan api kenderaan itu sendiri. Kaedah gabungan dua pengoptimuman akan digunakan seperti topologi dan pengoptimuman struktur kekisi dengan bantuan Analisis Elemen Terhad di antara semua proses pengoptimuman. Tetapi semua itu akan dimulakan dengan pemilihan reka bentuk asas. Dalam bahagian pertama tesis ini, hasil yang jelas daripada empat (4) kes beban telah dikumpulkan daripada menganalisis reka bentuk asas. Kes beban ialah 20,321N, -12,133N, 21,883N dan -16,000N dengan arah paksi yang berbeza digunakan. Reka bentuk asas melepasi kesemuanya kes beban tanpa melebihi kekuatan hasil bahan, keluli iaitu 205 MPa. Pengoptimuman topologi menghilangkan kawasan tekanan rendah dan mengurangkan jisim reka bentuk asas daripada 34.057 kg kepada 12.761 kg, sambil mengekalkan integriti struktur yang baik. Pengoptimuman Struktur Kekisi (LSO) mengurangkan lagi bahan daripada reka bentuk yang dioptimumkan. Namun, selepas analisis, masih terdapat banyak ruang untuk pengoptimuman. Oleh itu, lelaran reka bentuk akhir telah dilakukan dan salah satu daripadanya telah dipilih untuk menjadi reka bentuk akhir. Reka bentuk akhir mempunyai dua kawasan yang telah dioptimumkan menggunakan LSO iaitu bahagian atas dan bawah. Bahagian kiri dan kanan LCA telah dikurangkan ketebalannya untuk turut mengurangkan jisim. Reka bentuk akhir mempunyai jisim sebanyak 8.129kg iaitu sejumlah 76% daripada jisim reka bentuk asas telah dikurangkan. Ini telah dicapai sambil mengekalkan sekurang-kurangnya Faktor Keselamatan 1.3 pada keadaan pemuatan beban paling kritikal. Keputusan menunjukkan bahawa dengan menggabungkan topologi dan pengoptimuman struktur kekisi boleh mengurangkan penggunaan bahan secara berkesan sambil memenuhi piawaian prestasi. Penyelidikan ini membuka laluan baharu untuk mereka bentuk komponen automotif untuk mencapai kenderaan ringan. Penambahbaikan masa hadapan termasuk meneroka bahan alternatif, menjalankan ujian dinamik dunia sebenar dan mengesahkan keupayaan industri menghasilkan reka bentuk tersebut.

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LIST OF ABBREVEATIONS

CAD	Computer Aided Design
FEA	Finite Element Analysis
FoS	Factor of Safety
LCA	Lower Control Arm
LSO	Lattice Structure Optimization
QFD	Quality Function Deployment

CHAPTER 1

INTRODUCTION

1.1 Background

Automotive manufacturers all over the world are studying and developing lighter weight vehicles. This is because there is a significant relationship between vehicle mass and fuel consumption. There was a study by Massachusetts Institute of Technology, and they found out that 35% reduction of vehicle weight can save fuel consumption between 10 to 20% (Refiadi et al., 2019).

As the effort to reduce vehicle weight, all angles are being experimented including testing ferrous, non-ferrous, and polymeric composite metals as the material for the vehicle parts (Refiadi et al., 2019) and designing new vehicle concept design but keeping the performance, and comfort (Wadas & Tisza, 2020). Many new concept designs from existing parts have been made to tackle this challenge. Although changing one part of the vehicle design will not reduce much from the vehicle weight, if it is being done cumulatively for multiple parts or on a single massive part of the vehicle, it will reduce the vehicle weight.

In the process of designing new vehicle concept design, optimization process is important by reducing the most volume of materials but keeping the sturdiness and strength of the parts. Software like Altair Inspire and Solidthinking are some of many 3D software than can assist designers and CAE engineers to optimize 3D parts of vehicles.

1.2 Problem Statement

Weight reduction is one of the goals in designing and manufacturing automative vehicles. It will help to have a smoother ride, reducing faulty or wear to mechanical parts. Abu et al., (2020) shows that loading more loads in the vehicle will increase fuel consumption compared to loading less. Thus, by keeping the external loads constant, reducing the weight of the car can reduce fuel consumption.

Efforts to improve fuel efficiency in the automotive industry have been essential nowadays. Increasing fuel efficiency is not only benefits for the consumers, but also for the environment by reducing greenhouse gas emissions. Furthermore, Refiadi et al., (2019) states that in previous research, a lighter vehicle can be more fuel efficient then a heavy vehicle because almost 70% of fuel consumption is used by the weight of the vehicle itself.

In previous studies of optimization lower control arm (LCA), most authors experimented with topology process but not many used lattices structure process. Thus, new angles can be tackled and experiment by using the lattice structure process alongside the topology process

1.3 Research Objective

The main of this research is to design and analysis a new concept design of vehicle frontal LCA. Specifically, the objectives are as follows.

a) To produce an optimized design of front vehicle LCA using Topology and LSO.

b) To evaluate the structural strength of the optimized front vehicle LCA

1.4 Scope of Research

The scope of this research are as follows:

a) Focusing on A-shape frontal lower control arm design.
b) Designing new concept design of front vehicle LCA using Catia V5 software.
c) The design undergoes Topology Optimization using Ansys software.
d) Optimized design undergoes LSO using Altair Inspire software.
e) Analysing linear static structural performance of the optimized design using Altair Inspire software.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In the automotive industry, the competition among manufacturers to make the best products or parts are very furious. Some will compete to be make the most comfortable, luxurious, fastest vehicles, but some will compete to make light-weight vehicles that can reduce fuel consumption. To achieve a light-weight vehicle, they can decrease the amount of material used to manufacture or choose a lighter material. In some cases, optimization can be done to reduce vehicle parts' weight. This chapter will cover on topics that related to optimization and analysis of vehicle LCA.

2.2 Suspension System

The suspension system is one of the main parts of a vehicle, which is responsible for steering ride quality. Suspension system is a combination of spring and damper arrangement in which the negative force transmission is eliminated by arranging the spring stiffness to be in series (Muzakkir Ahamed & Natrayan, 2022). It also prevents vibration or shock due to bad road surface channel into the cabin of the vehicle. A good suspension system can ensure the best experience for the passenger on a short or a long ride. Previous study had considered to reduce unwanted car vibrations during car vibration modelling with mathematical models (Yaghoubi & Ghanbarzadeh, 2024). Figure 2.1 shows the mechanical components of suspension system of an automobile (Rudra, 2022).

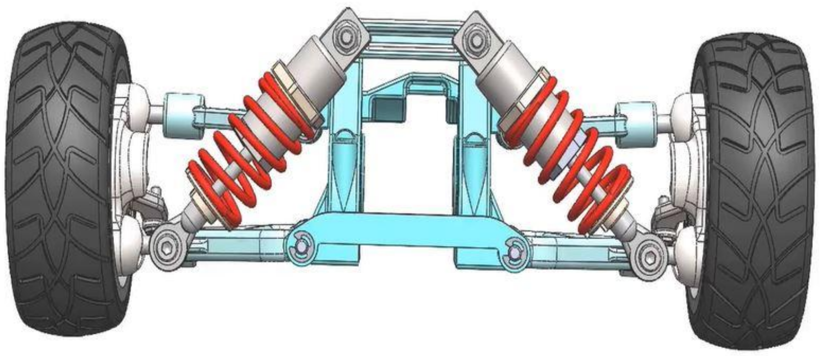

Figure 2.1 Suspension System of an Automobile (Rudra, 2022)

2.3 Vehicle LCA

LCA is a part of suspension system that helps to absorb shocks and impacts from rough surface of the road. Control arm controls the position of the tyre end in a single degree of freedom (Pachapuri et al., 2021). It is consisting of bushings, spherical hinges and control arm which will transfer the force and moment that is acting on the wheel to the body of the vehicle (Zhao et al., 2020). It connects the wheel hub and steering knuckle to the frame of the vehicle. Without a good and sturdy LCA, it will lead to handling issue such as unstable steering and can also lead to uneven tire wear.

2.3.1 Double Wishbone or A-Shaped LCA

A double wishbone suspension consists of two, upper and LCAs attached to the wheel hub and the vehicle's body. The shape of the control arm resembles of the letter "A" or a wishbone, thus the name applied. This design has been made such a way the roll centre is close to the centre of the gravity and near to the ground (Vignesh et al., 2019). A-shaped LCA usually can be seen in sports or luxury cars due to its performance and it can give more advanced driving dynamics. Figure 2.2 shows an example of A-shaped LCA with bushings.

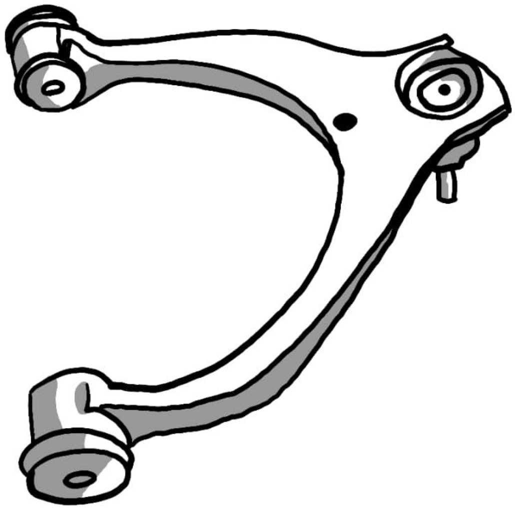

Figure 2.2 Wishbone LCA

2.3.2 L-Shaped LCA

L-shaped control arms are usually consisting of singular arm that attached to the wheel hub at one end and to the vehicle's body at the other end. It also usually on economy and compact cars due to its simplicity and cost-effectiveness. L-shaped LCA is the best choice for daily vehicle use. Figure 2.3 shows the typical L-shaped lower control arm with its bushings.

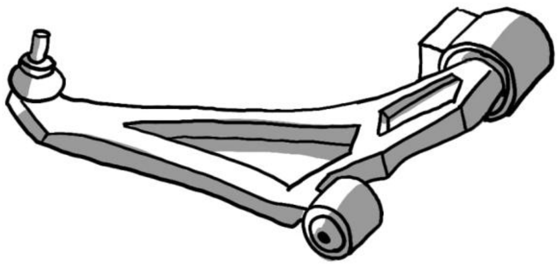

Figure 2.3 L-Shaped LCA

2.3.3 Materials used for LCA

Throughout the decade, manufacturers had done many experiments and used variety of materials to mass produce LCA. All materials have its own advantages and disadvantages thus, manufacturer need to decide on which material that they will pick and consider the consequences of it. For instance, LCA usually made from stamped steel, cast iron or aluminium alloy. In previous study, application of aluminium alloy has increased in the range of 2019 to 2021 but comparing to high-strength steel, high strength steel was one of the best options at the time considering cost and performance factors (Song et al., 2022). Table 2.1 shows the material properties for LCA's common material used (Ashby, 2021).

Table 2.1 Material Properties for LCA (Ashby, 2021)

Material	Density (kg/m^3)	Yield Strength (MPa)	Young's modulus (GPa)
Stainless Steel	7,600 - 8,100	170 - 100	190 - 210
Cast Iron	7,100 - 7,300	140 - 420	80 - 140
Aluminium Alloy	2,500 - 2,900	30 - 500	68-82

2.4 Engineering Process Design

Engineering process design is a linear step that engineers follow and refer to come up with a solution to a problem (What Is the Engineering Design Process? A Complete Guide - TWI, n.d.). There are many versions of engineering design process, but it follows the same concept and adding one or multiples steps in between of the process based on the industry or project. By using the engineering process design, the design process will go smoothly and cover all the important aspects of designing a part or product.

2.4.1 Benchmark

Benchmark is one of the steps in engineering process design and it fall under the testing process. Benchmark is a process of measuring the product's performance, quality, and innovation with the other competitors' product. It helps to overcome weaknesses and improve the product. It also a few steps process that needed to be followed to fully implement the improvements starting from identifying areas for benchmarking until monitoring and reviewing the performance applied.

2.4.2 Quality Function Deployment (QFD)

QFD is a process and a set of tools that can helps defining customer requirements and convert it into an engineering standard specification. Although QFD was developed for manufacturing industry, services industry found applications for it. QFD works by reducing the startup costs and development time while increasing the quality of new product (Erdil & Arani, 2019). This will help the manufacturer to speed up the process time of a new product's development. A few benefits of QFD are the organizations will be able to gain a better understanding of their customers and act with or without the customers instructions, utilizing customer feedback by gathering previous customer feedback and use it for further performance metrics and establishing a better structure of requirements that will minimizes unnecessary risks and bottlenecks (QFD: A Guide to Quality Function Deployment | SafetyCulture, 2023).

2.5 Optimization

Optimization means the action of making the best or most effective use of a situation or resources. In this case study, optimization means redesigning a part to a reduce material usage to build while keeping the strength and sturdiness of the part (Wu, 2022.). In traditional way, manufacturer will spend a lot of their project budget for mock-ups and testing to do optimization. But now, with the help of technology, several software have been created to that. In manufacturing industry, there is a lot of software that can ease the process of optimizing by using multiple methods such as topology and LSO which are considered as mathematical optimization. By using the software, the optimization process time and cost can decrease a lot instead of doing manual calculations and physical prototyping to optimize.

2.5.1 Topology Optimization

Topology optimization is referred to as layout optimization and have been around since 19th century where Maxwell, had performed a simple topological analysis for a minimum weight truss structure with stress constraint (Wu, 2022.). Topology optimization will generate the optimal shape of a mechanical structure after running some stress analysis and will remove low stress area on the design. Users need to predefine the 2D and 3D boundaries area that can and cannot be optimized. After following the steps, an optimized design from the original design will be created.

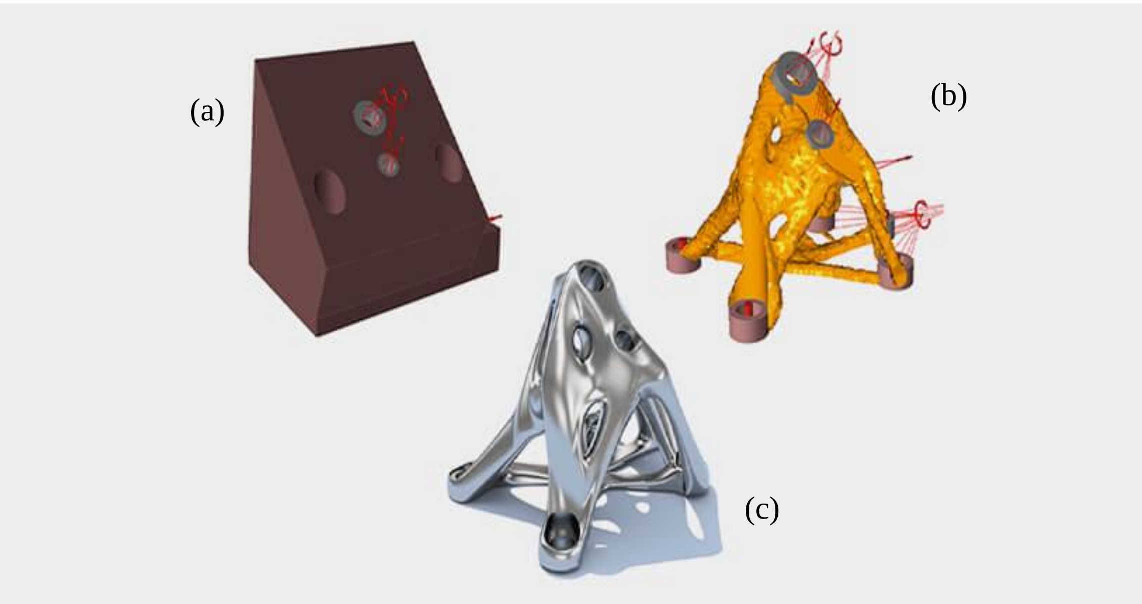

Figure 2.4 Topology Optimization Process (Topology Optimization Software | Altair, n.d.)

Figure 2.4 shows the topology optimization process in Altair Inspire software. Figure (4a) is the base design with a few load cases have been applied to it. Figure (4b) is the optimized design that has been generated from the software. Figure (4c) is the final design that has been redesigned and smoothed after the optimization.

2.5.2 Lattice Structure Optimization

LSO refers to the process of designing and optimizing a lattice structure to achieve a high-performance structure while minimizing material usage. Unlike topology optimization, lattice structure will not remove the material completely, but it will make a porous design that interconnects with a beam or flat surface which makes it sturdier. This structure has a high strength-to-weight ratio and great absorbing energy efficiently. There are three common types of lattice structures which are surface-based lattices, strut lattices, and planar-based lattices. Figure 2.5 shows all three types of lattice structures mentioned above respectively.

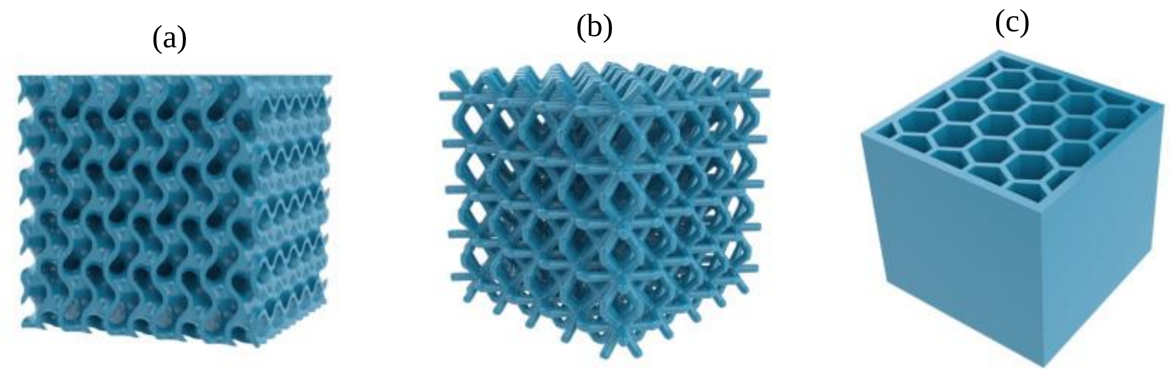

Figure 2.5 (a) Surface Based Lattice, (b) Strut-Based Lattice, (c) Planar Lattice (Types of Lattices for Additive Manufacturing – Terms Engineers Need to Know, 2022)

2.6 Analysis

From Oxford Dictionary, analysis means the detailed study or examination of something to understand more about it. For this research, the analysis that is been focused on is Finite Element Analysis (FEA). FEA is a computerized method or simulation for predicting how a real-world object will react to forces, heat, and other factors in terms of whether it will function as theorized. FEA also helps to reduce the number of physical prototyping and experimenting like optimization does (What Is FEA | Finite Element Analysis? (Ultimate Guide) | SimScale, 2023). Thus, FEA usually will be run right after optimization has been ran to a design. Many big and reliable companies such as Altair and Ansys have FEA features.

2.6.1 Linear Structural Analysis

One of the most important parts of engineering design is structural analysis, which deals with how a structure responds to various loading scenarios. The fundamental technique of analysing and forecasting a structure's reaction to outside pressures is known as linear structural analysis. Linear analysis is the most typical method used in FEA. To perform linear analysis, mathematical equations which are equilibrium, compatibility and constitutive equations must be employed to the structure under different loading conditions (Prasad, 2023). Solving all the equations are essential to determine the internal forces and moments within the structure, accurately predict the structure response, and getting a precise linear analysis.

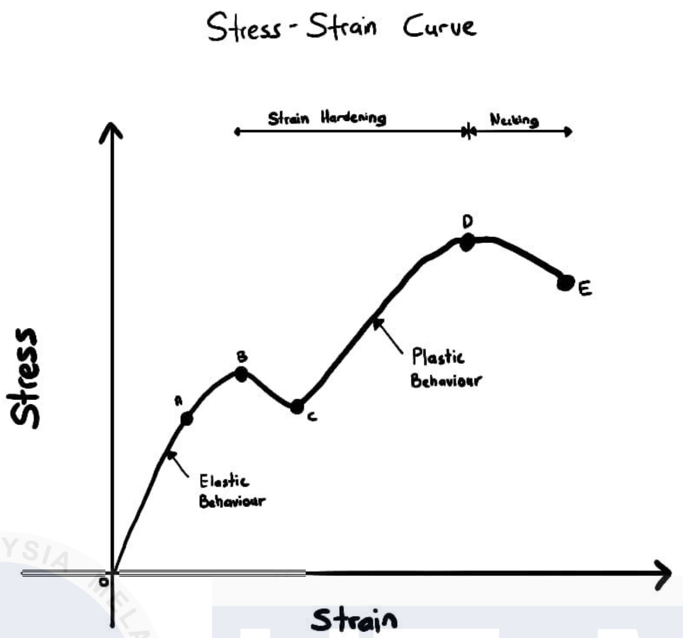

Figure 2.6 Stress-Strain Curve Graph

Figure 2.6 shows the stress-strain curve graph or as known as Hooke's Law graph. Materials that obey Hooke's Law are called linear elastic materials. In the state of OA in the graph, the linear elastic materials will return to their shape after unloading. This is called elastic behaviour. But if the material reached an excessive amount of stress and reached the CD state, the material would reach the state of plastic behaviour where the material does not come to its original size and will have a permanent deformation. In that state, the stress has gone beyond the yield strength of the material. This property and information are a crucial factor that needs to be considered during this case study where the material must be strong enough to withstand the applied load and overcome the deformation.

2.6.2 Load Cases

A load case is a set of loads and supports, displacements, and temperatures. Setting load case is one of the processes of FEA. Multiple loads and supports can be applied in one load case. Load case is essential to imitate the real-life situations by adding calculated loads and supports into the structure. Calculated load cases have been gathered and will be use as the load cases for this study. Figure 2.7 shows the load cases that will be used for this study. The load cases are 20,321N, -12,133N, 21,883N and -16,000N with different situations.

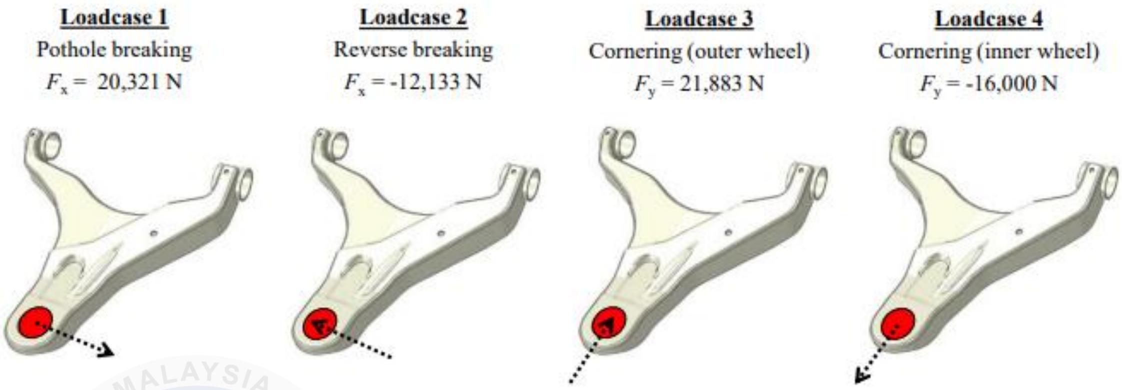

Figure 2.7 Load Cases for the LCA (Sookchanchai et al., 2021)

2.7 Summary

From this chapter, it has been decided that several software will be used to achieve the objectives of this research. The usage of the software consisting of creating the 3D design by parts of the LCA using Catia V5, optimizing by reducing the materials from the design and analysing the structural integrity of optimized design using topology optimization and LSO in Altair Inspire. Thus, this two software will be the main tools of this research because it will be used multiple time throughout the process.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In the manufacturing industry, manufacturers are racing with each other to optimize vehicle components to achieve improvements in performance, and efficiency. Vehicle LCA is an important part of the suspension system to deliver a smooth driving experience and overall stability. Traditionally, designing and optimizing vehicle LCA is time consuming due to physical prototyping. However, with the advancement of 3D software technology, this process has cut short the time to design and optimize. This research will cover on optimizing and analysing vehicle LCA by using topology and lattice structural optimization using computer-aided design (CAD) and finite element analysis (FEA). The use of these tools allows for detailed simulations of a real-life conditions and situations, providing valuable data and insights about stress and deformation.

3.2 Flow Chart

Flow chart is a visual way to represent the process flow of a project. This will help to keep in track of every step of the process if there is any problem encountered. Figure 3.1shows the flow chart of this project in detailed. On the top of the flow chart, a design will be selected to be the base design. The base design will run a few optimizations which consisting of topology and lattice structural optimizations. Right after every optimization, the design will be running FEA to make sure that the design is still in acceptable specifications. If not, the design will be tweaked in the previous optimization process.

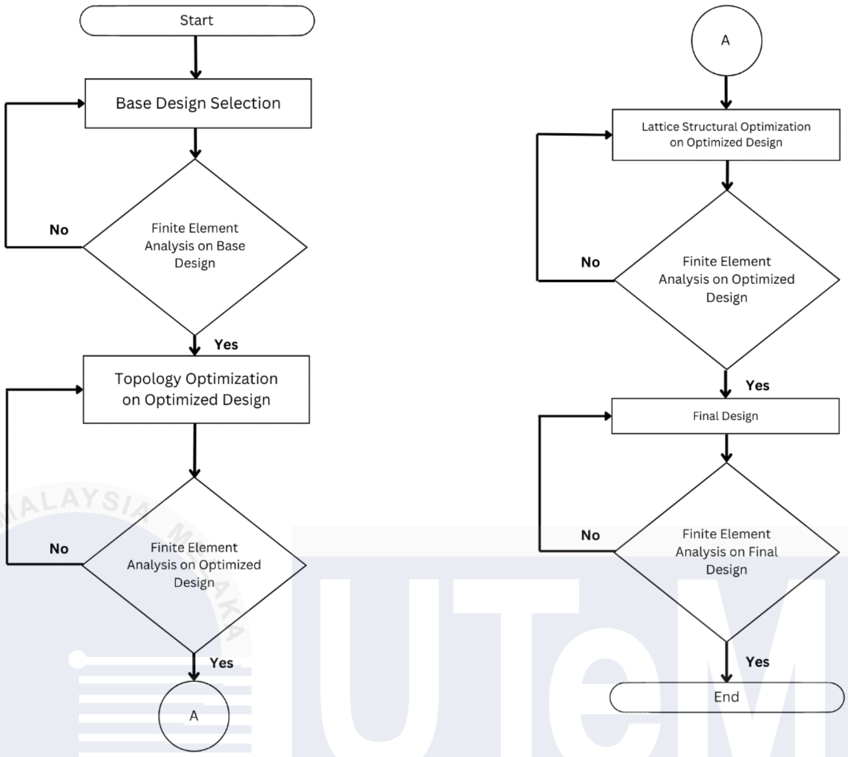

Figure 3.1 Flow Chart of the Research

3.2.1 Base Design Selection and 3D Part Design

In this process, a few sketches of base design have been made from a typical wish bone LCA design. Base design is essential to be done before doing a topology optimization because it will remove low stress areas of the part. Thus, the base design needs to have a bigger surface area than the original design. Figure 3.2 shows the three sketches that have been made. Base design 1 has the same thickness as the original design of the wish bone LCA but with a wider surface area. Base design 2 has a thicker body and thicker bushing connections compared to the original LCA design. Base design 3 has the same thickness throughout the body and the bushing connections.

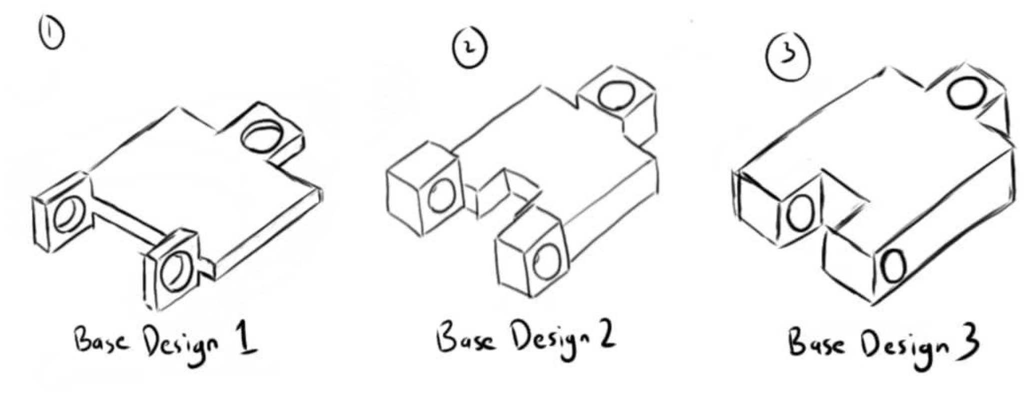

Figure 3.2 Base Design Sketches

Body of base design 1 has too thin of a body which will not be effective during topology optimization and base design 3 has too thick of a body and it will not be a necessary to make it that thick. Also, the duration of the topology process will be too long to remove the excessive material. Of all the base designs, base design 2 has been selected to be the main base design. It is because it has a balanced thickness for the body and bushing connections compared to the other two. Figure 3.3 is the final base design that has been selected.

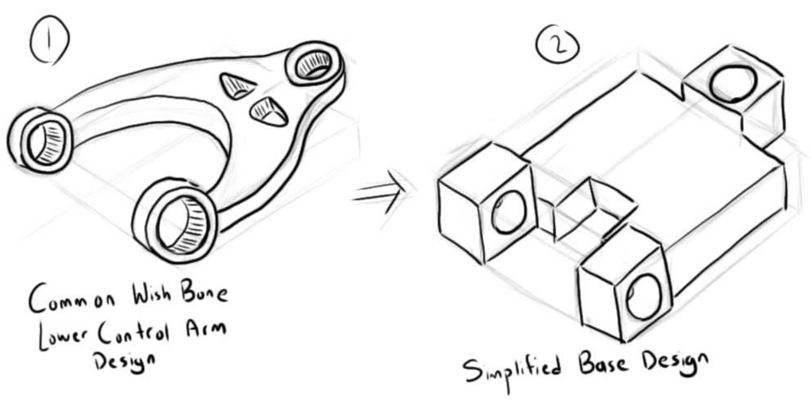

Figure 3.3 Final Base Design Selection

After the sketch has been selected, the 3D design of the part has been done in Catia V5 software. Figure 3.4 is the orthographic drawing of the base design with its dimensions.

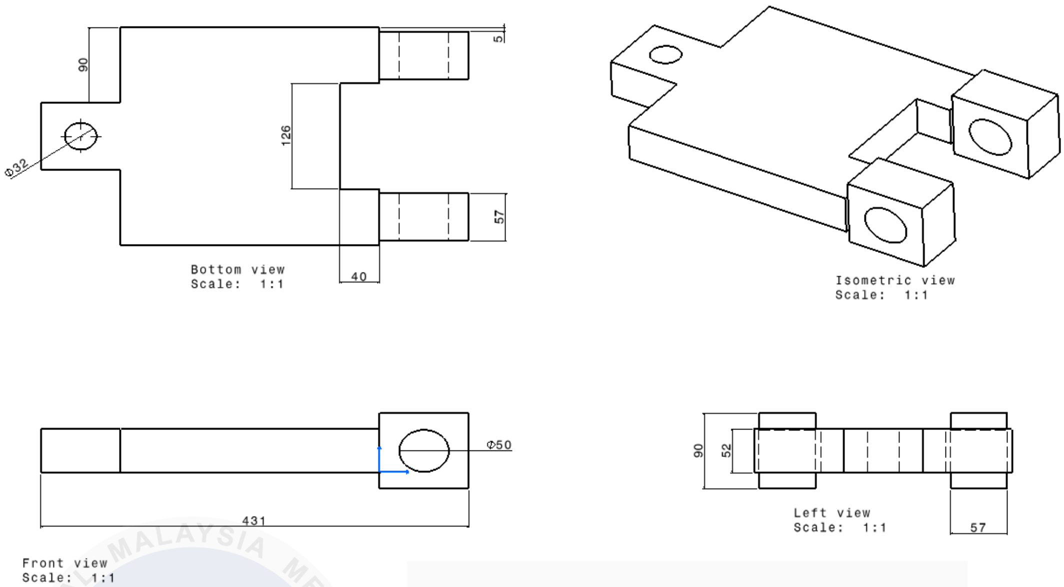

Figure 3.4 Orthographic Drawing of the Base Design

3.2.2 Finite Element Analysis (FEA) Process Design

Table 3.1 Forces Applied and Supports for All Load Cases

	Force Applied (N)	Axis Applied	Load Case 1	Load Case 2	Load Case 3	Load Case 4
Force 1	20,321	X-axis	✔			
Force 2	-12,133	X-axis		✔		
Force 3	21,883	Y-axis			✔	
Force 4	-16,000	Y-axis				✔
Support Bushing (Left)	-	-	✔	✔	✔	✔
Support Bushing (Right)	-	-	✔	✔	✔	✔

After the 3D base design has been created, the design will undergo FEA in Altair Inspire. Table 3.1 is the summarization of the load cases with its forces and supports. The load cases consist of 20,321 N at x-axis for load case 1, -12,133N at x-axis for load case 2, 21,883 N at y-axis for load case 3 and -16,000 N at y-axis for load case 4 in Altair Inspire. Figure 3.5 shows that fixed supports have been setup on the back bushings of the LCA while the forces from the load cases have been setup on the front bushing of the LCA.

Material selection also needed to be done in this process to identify the yield strength of the part. If the result has smaller value of von Mises Stress than the yield strength of the material, the base design passed. If the design cannot withstand the load during FEA, the base design needs to be redesigned. For every step moving forward, FEA process with the same conditions of load cases needs to be done because this process will check if the part is still in working order and did not exceed the yield strength of the part's material.

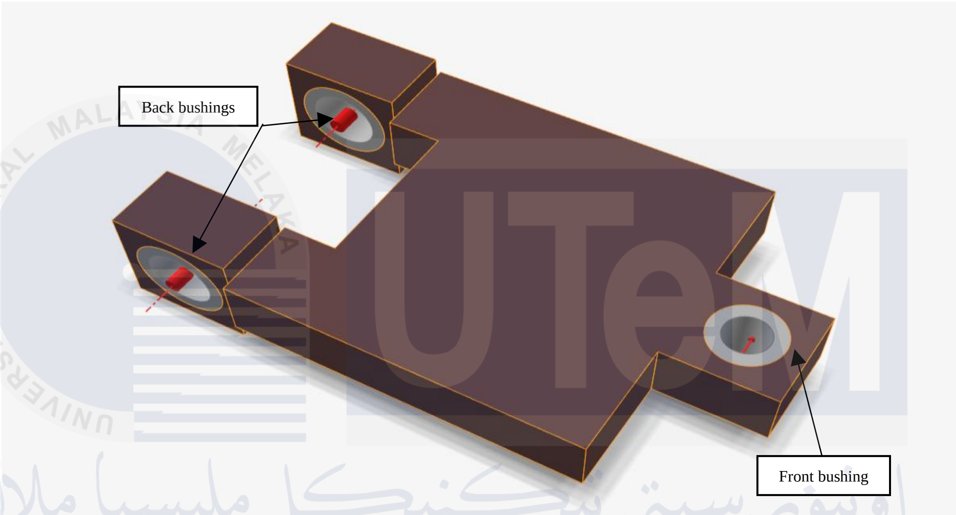

Figure 3.5 Supports and Forces Setup on the Base Design in Altair Inspire

3.2.3 Topology Optimization on Optimized Design and FEA

The optimized design will undergo topology optimization in this process. The optimization will be held in Altair Inspire software. Boundaries need to be set up before the process. This is to prevent areas that are crucial for the parts like bushing connections being removed during the optimization. Figure 3.6 shows an example of boundaries that have been set up. The maroon area will undergo topology optimization while the grey area will be excluded. 30% of the material will be removed after the optimization is completed. After the optimization, the amount of material that has been removed still can be adjusted to increase or decrease according to desired shape.

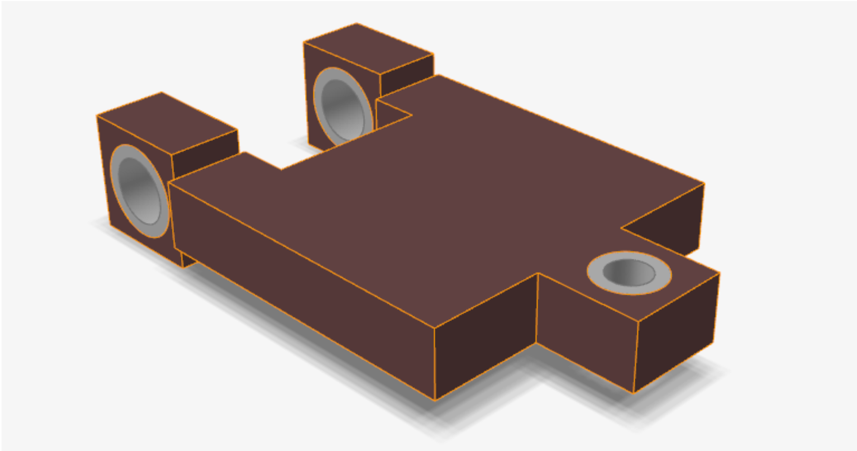

Figure 3.6 Boundaries Set Up in Altair Inspire

After getting the right amount of materials removed, the design needs to be adjusted due to imperfection after topology optimization. Figure 3.7 shows an example of the imperfection on the design after topology optimization (Altair Global Academic Program, 2020).

Figure 3.7 Example of Materials Residue after Topology Optimization in Altair Software (Altair Global Academic Program, 2020)

After the cleanup, the optimized design will undergo FEA again to see if the structural integrity still can be accepted. If the design cannot withstand the load during FEA, the optimization process must be done again.

3.2.4 Lattice Structural Optimization on Optimized Design and FEA

In this process, the optimized design will undergo LSO in Altair Inspire software. As in Topology Optimization process, boundaries need to be made before the optimization process to prevent important parts from being removed. Figure 3.8 shows an example of boundaries that have been set up (Lattice Optimization, n.d.). Maroon area will undergo the lattice structural optimization and grey area will be excluded.

Figure 3.8 Example of Boundaries Selection for LSO in Altair Software (Lattice Optimization, n.d.)

When the boundaries have been set up, the selected area will be filled with lattice structure. The amount of lattice can be set is from 50% up to 100%. Figure 3.9 shows the result after a successful LSO (Lattice Optimization, n.d.). After the optimization is completed, the design needs to undergo FEA again to check the structural integrity.

Figure 3.9 Result after LSO in Altair Software (Lattice Optimization, n.d.)

3.2.5 Final Design and FEA

After finishing the two optimizations, the optimized design needs to be touched up on the design and it can already be called the final design. Figure 3.10 shows the illustration of the final design for this case study. The final design is the combination of topology and lattice structure design optimization. For the highest stress area of the design will be kept as topology optimization whereas low to medium stress area of the design will be optimized using LSO. The final design will undergo FEA for the last time to make sure its properties are within the range of yield strength and within the acceptable Factor of Safety (FoS).

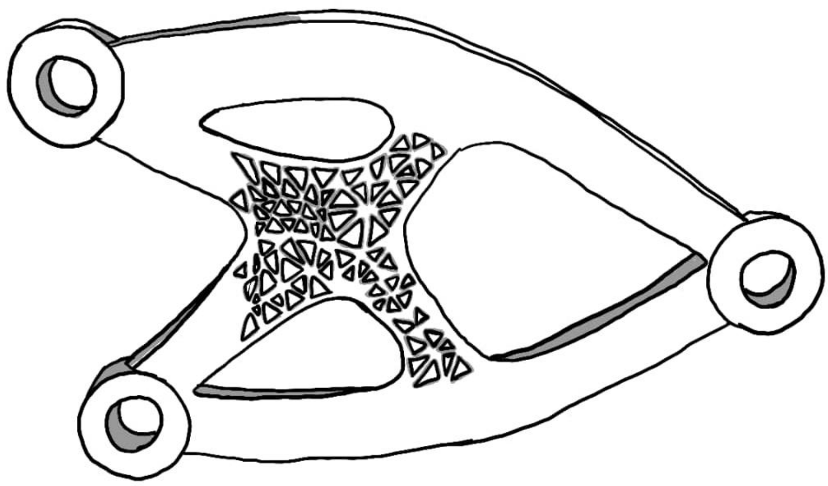

Figure 3.10 Illustration of Final Design

3.3 Mechanical Properties of Steel (AISI 316)

Table 3.2 Material Properties of Steel

Material Name	Density kg/mm3	Yield Stress (MPa)
Steel (AISI 316)	8.00e-06	205

Table 3.2 is the material properties of the steel that will be used for the analysis. The yield strength of the steel (AISI 316) is 205 MPa. The steel has been chosen as the material for the design because it has the average yield strength for the material used to manufacture LCA which is between 30 to 500 MPa. During the FEA in the future, the yield strength of the steel will indicate the limit of the design before it deformed. The density of the steel will affect the weight of the final design. The higher the density of a material, the higher the weight of the design will be.

3.4 Factor of Safety

FoS is the ratio of the applied load or stress to the maximum strength or yield strength of the material can withstand before deformation. It provide as a safety margin to evaluate whether the design is safe to use after applying real-life load onto it. From past study, FoS value greater than 1 is already considered as acceptable and safe to use (Roziqin et al., 2021). For this case study, FoS value of 1.2 has been selected as the minimum acceptable FoS to add more structural integrity and the design can withstand greater forces than the load cases applied. If the FoS is higher than 1.2 during analysis, the design will proceed to the next process. However, if the design cannot reach the minimum Factor of Safety of 1.2, the design will be rejected and will not be considered as an option for the next process.

3.5 Summary

Summary of this chapter, multiple iterations will be done to get various designs for each process. This is to ensure to analyse the designs from multiple angles to get the best design for each process. It has been estimated that the highest reduction of mass will occur during topology optimization and minor mass reduction will occur during LSO. It is because topology optimization will completely remove low stress area of the design while during LSO, the material will be converted to lattice structure to balance out material reduction and structural integrity.

CHAPTER 4

RESULTS

4.1 Introduction

This chapter represents the results and analysis on the development of the vehicle lower control arm. The early phase of this study focused on establishing a base design of LCA and conducting initial simulations and virtual prototype testing. Through this structured approach, the aim is to uncover more potential areas for improvement and optimizations for more detailed testing in the next thesis. The design will undergo multiple FEA processes throughout the whole process by slowly optimizing and observing the performance before moving to the next step on the methodology.

4.2 Result and Analysis of Base Design of Vehicle LCA

This will be the results of the FEA done to the base design of the LCA in Altair Inspire software with 4 different load cases that have been mentioned before. From the results, the data that will be considered and highlighted are the maximum von Mises Stress in unit MPa and the minimum FoS. Von Mises stress is the amount force that is applied to the part. If the stress is higher that the yield strength of the material, the part will be deformed and malfunctioned. FoS is defined as ratio between the yield strength of the material over the working stress that has been applied. Thus, the higher the ratio, the stronger the part can withstand the force.

All the data that will be presented is the data that has been generated from Altair Inspire software after the FEA process of the base design. In addition, the mass of the base design is 34.057 kg. The mass will be crucial piece of information to determine how much material that have been removed from the base design.

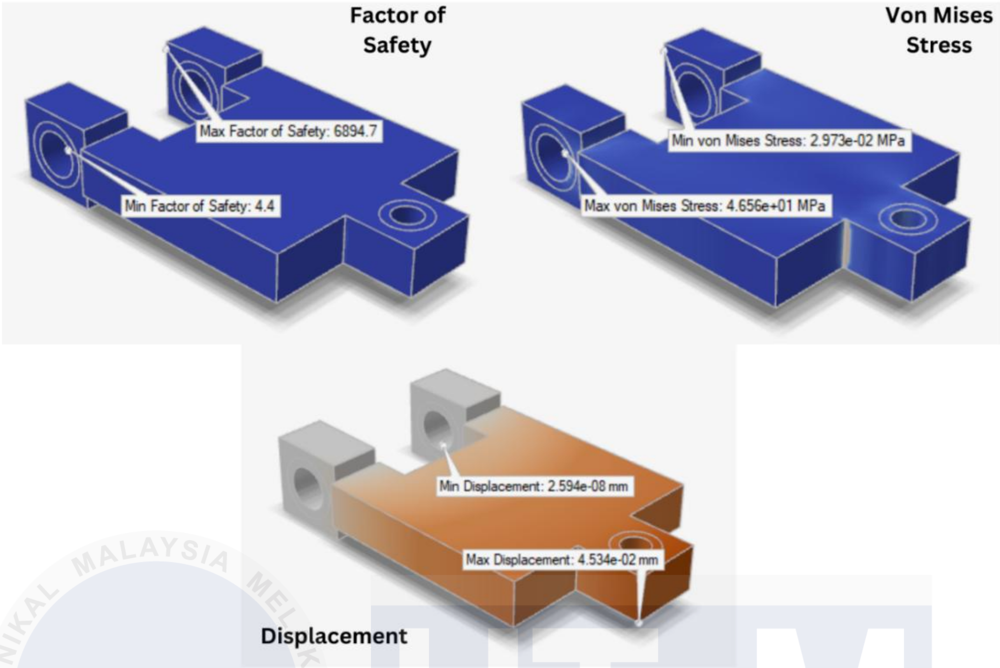

Figure 4.1 Result for Load Case 1

Figure 4.1 is the result of Load Case 1. The maximum von Mises Stress is 46.56 MPa and the minimum FoS is 4.4 which are both located at the back bushing of the LCA. The maximum displacement is located at the lower front bushing of the LCA with a value of 0.0453mm.

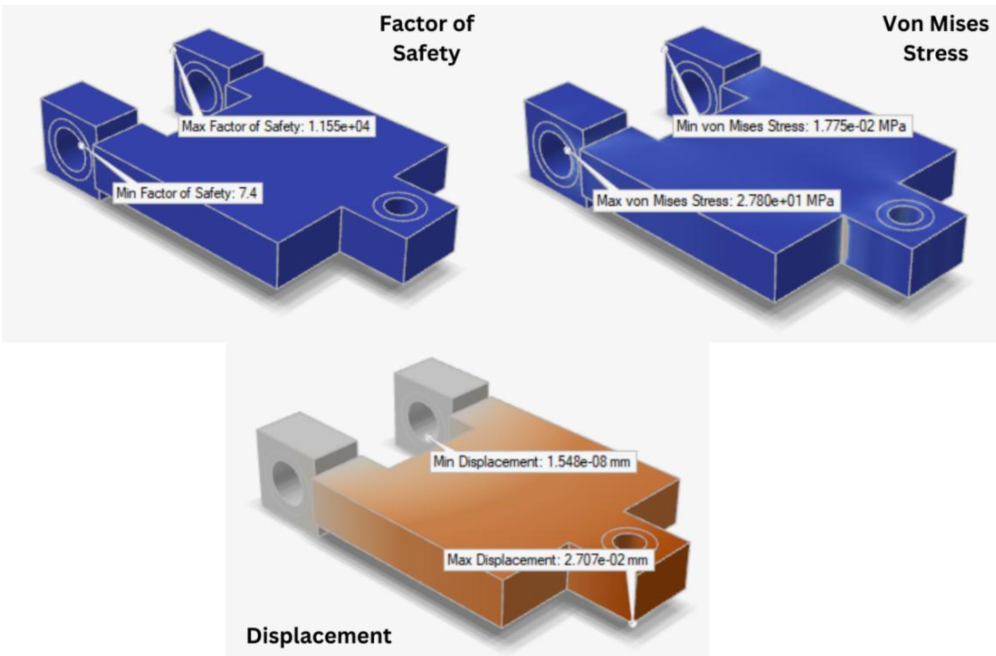

Figure 4.2 Result for Load Case 2

Figure 4.2 is the result for Load Case 2. The maximum von Mises Stress is 27.80 MPa and the minimum FoS is 7.4 which are also both located at the back bushing of the LCA. The maximum displacement is located at the lower front bushing of the LCA with a value of 0.0271mm.

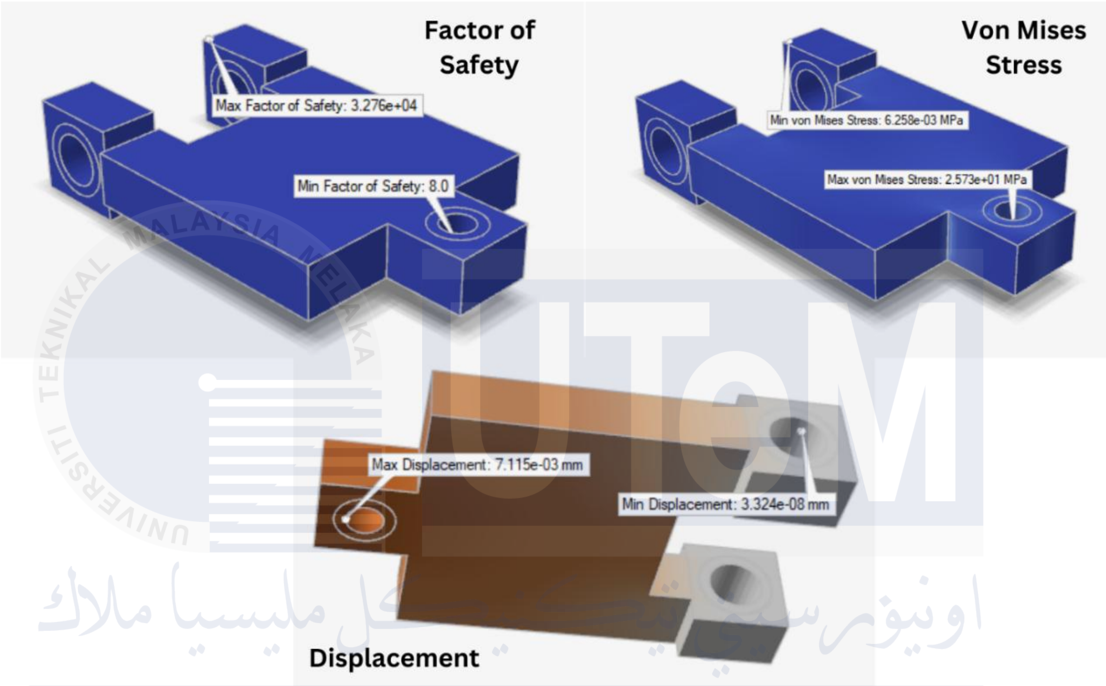

Figure 4.3 Result for Load Case 3

Figure 4.3 is the result for Load Case 3. The maximum von Mises Stress is 25.73 MPa and the minimum FoS is 8.0 which are both located at the front bushing. The maximum displacement is located at the lower front bushing of the LCA with a value of 0.0071mm.

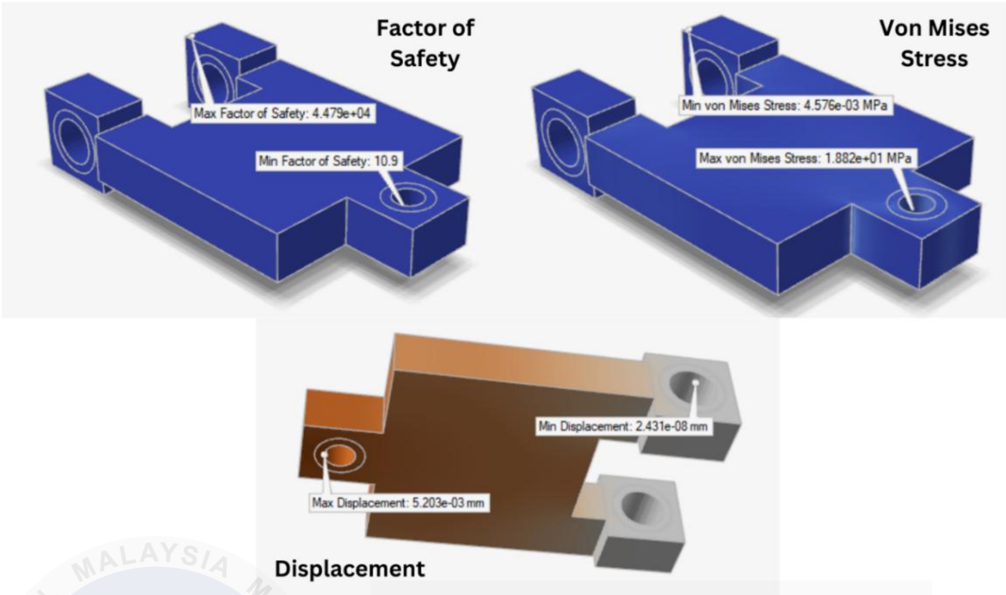

Figure 4.4 Result for Load Case 4

Figure 4.4 is the result for Load Case 4. The maximum von Mises Stress is 18.82 MPa and the minimum FoS is 10.9 which are also both located at front bushing of the LCA. The maximum displacement is located at the lower front bushing of the LCA with a value of 0.0052mm. The summation of all the results have been displayed in Table 4.1.

Table 4.1 Results for all Load Cases for the Base Design

Load Case	Force Applied (N)	Axis Applied	Von Mises Stress (MPa)		FoS	Displacement (mm)
			Min	Max	Min	Max
1	20,321	X-axis	0.0297	**46.56**	**4.4**	0.0453
2	-12,133	X-axis	0.0178	27.80	7.4	0.0271
3	21,883	Y-axis	0.0626	25.73	8.0	0.0071
4	-16,000	Y-axis	0.0458	**18.82**	**10.9**	0.0052

The red highlighted value indicates that the load case has the highest value of maximum von Mises stress, while the blue highlighted value is the lowest maximum von Mises stress. From all the results of the load cases that has been gathered, the base design has passed all the analysis with a very high FoS ranging from 4.4 to 10.9. The bigger the value of FoS, the higher the design can withstand the load in the load case. Thus, there will be more room to do optimizations in the future because all the load cases have not even passed the midway of the yield strength of the material which is 205 MPa. The maximum von-Mises Stress value is on load case 1 which is 46.56 MPa.

4.3 Topology Optimization

This will be the process of Topology Optimization after finishing FEA on the base design. It will include the process of creating iterations of the base design, results comparison of the iterations, schematic diagram of the selected design and the result analysis of the selected design.

4.3.1 Iterations of the Base Design

After finishing the base design analysis, Topology Optimization has been done to continue forward to the next step. In the Altair Inspire software, Topology feature has been used with another feature called 'Shape Control' to manipulate the shape of the design. Shape Control feature has a few options which have been used to create several iterations design. Table 4.2 is the shape control that has been used for all the iterations.

Table 4.2 Iterations of the Base Design

Iteration	Shape Control
1	Single Draw
2	Symmetry
3	Split Draw
4	Split Draw + Symmetry

With all the iterations have been created, the designs have been undergoing the same FEA analysis with the same load cases as previous test. Figure 4.5 is the designs generated in Altair Inspire for all 4 iterations of the base design and the results from the software has been summarized into Table 4.3 for easier comparison.

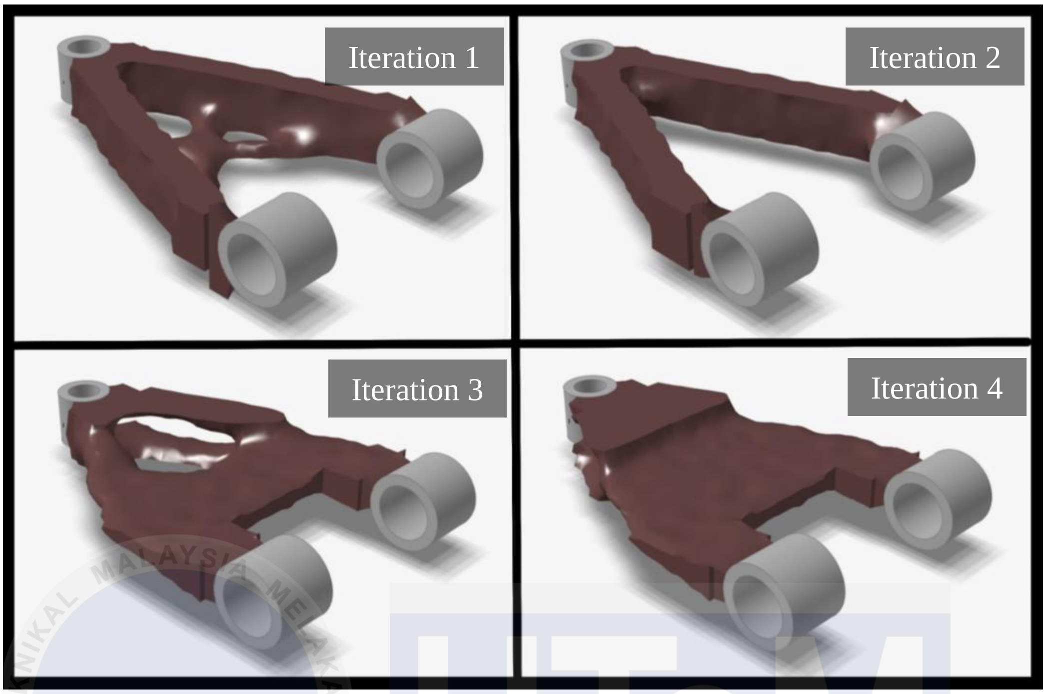

Figure 4.5 Iterations of the Optimized Base Design

Iteration 1 and 2 have the typical wishbone shaped like existing LCA while Iteration 3 and 4 have a rather unique design near the back bushing. Iteration 1 has no more room or area to be optimized during the LSO. Same goes for Iteration 2 which left no more area to be optimized. In the other hand, Iteration 3 and 4 still have wide and flat area that can be future optimized.

Comparing the design of Iteration 3 and 4, Iteration 3 has a vertical and horizontal hollow shape near the front bushing while Iteration 4 has only a horizontal hollow shape near the front bushing. Considering for future optimization, Iteration 3 will not have a lot of solid structure in the middle after the LSO while Iteration 4 will still have solid structure near the top bushing if LSO being done in the middle of the design.

4.3.2 Results and Discussion of Base Design Iterations

Figure 4.6, Figure 4.7, and Figure 4.8 are all the results for the first iteration of the optimizations. The results consist of displacement, FoS, and von Mises Stress respectively.

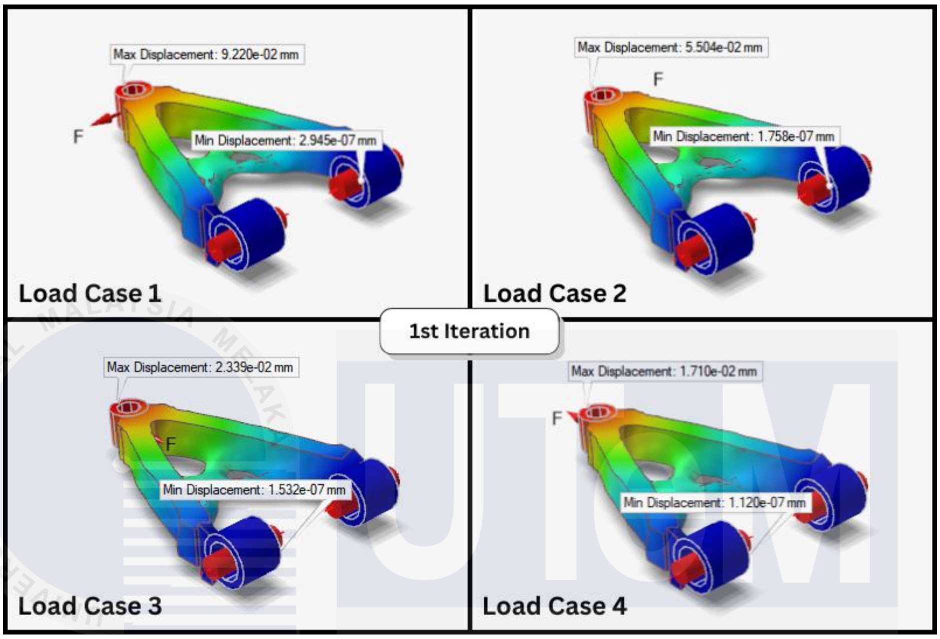

Figure 4.6 Displacement Result for the 1st Iteration

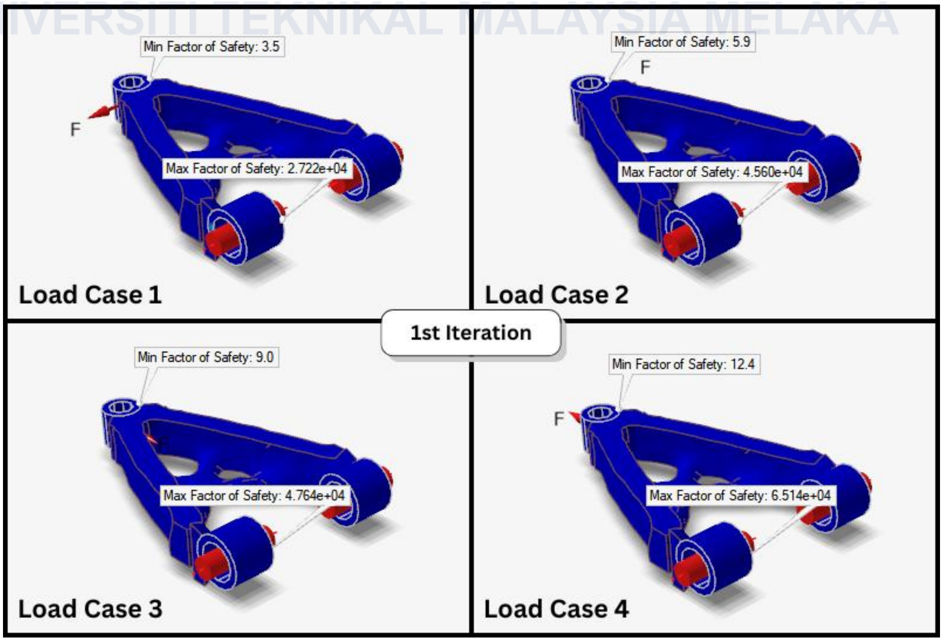

Figure 4.7 FoS Result for the 1st Iteration

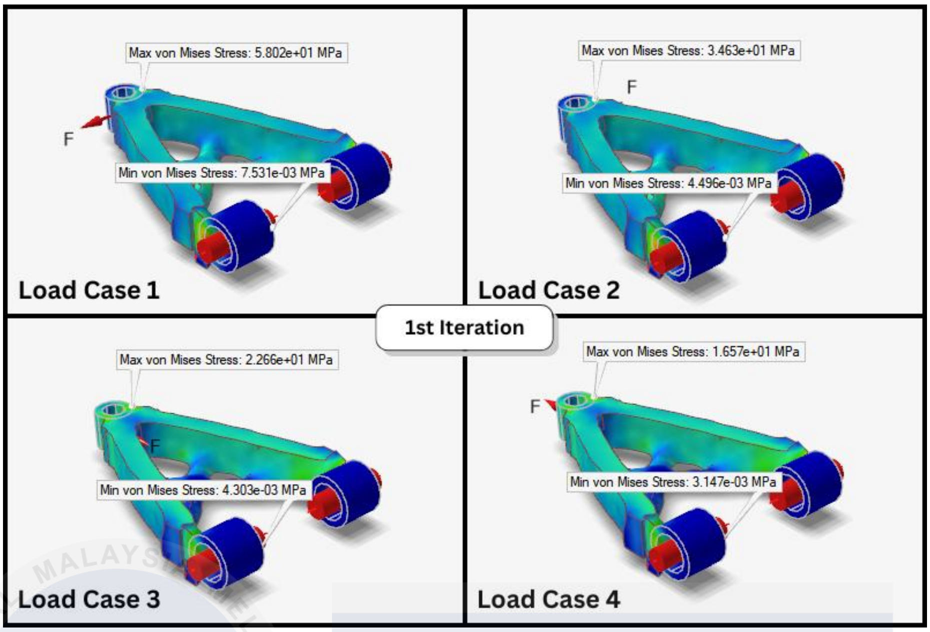

Figure 4.8 Von Mises Stress Result for the 1st Iteration

Next, Figure 4.9, Figure 4.10, and Figure 4.11 are all the results for the second iteration of the optimizations. The results consist of displacement, FoS, and von Mises Stress respectively.

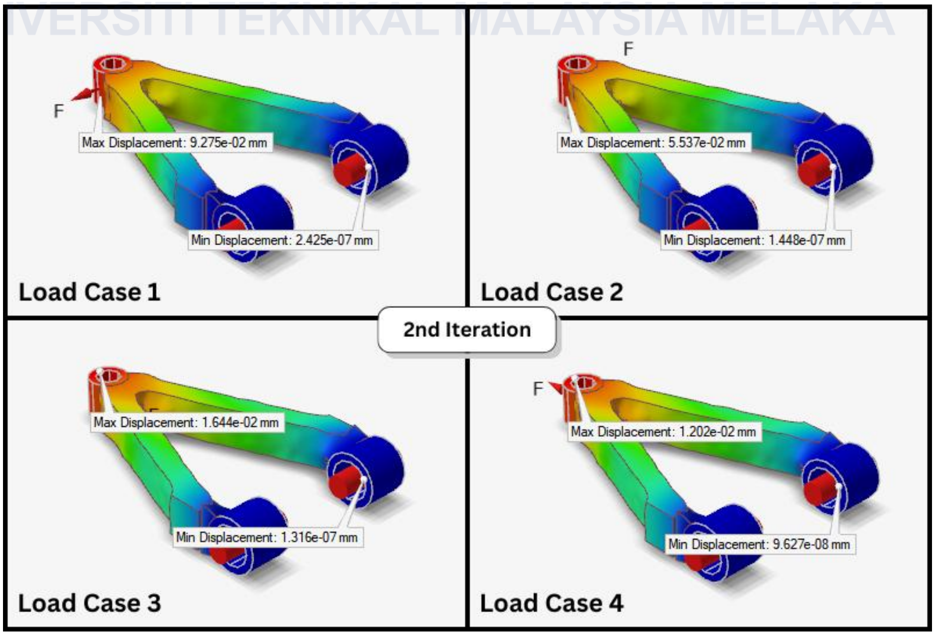

Figure 4.9 Displacement Result for the 2nd Iteration

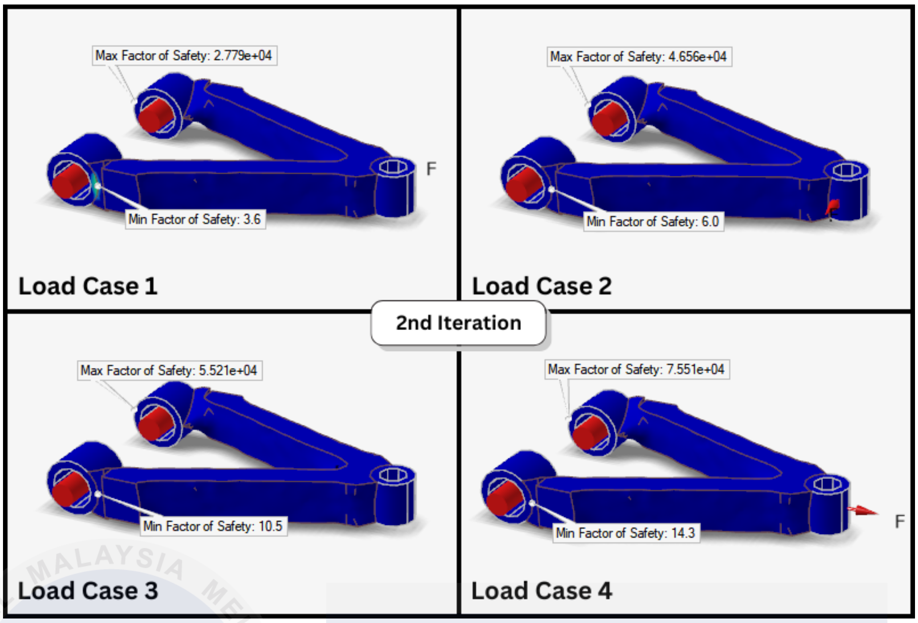

Figure 4.10 FoS Result for the 2nd Iteration

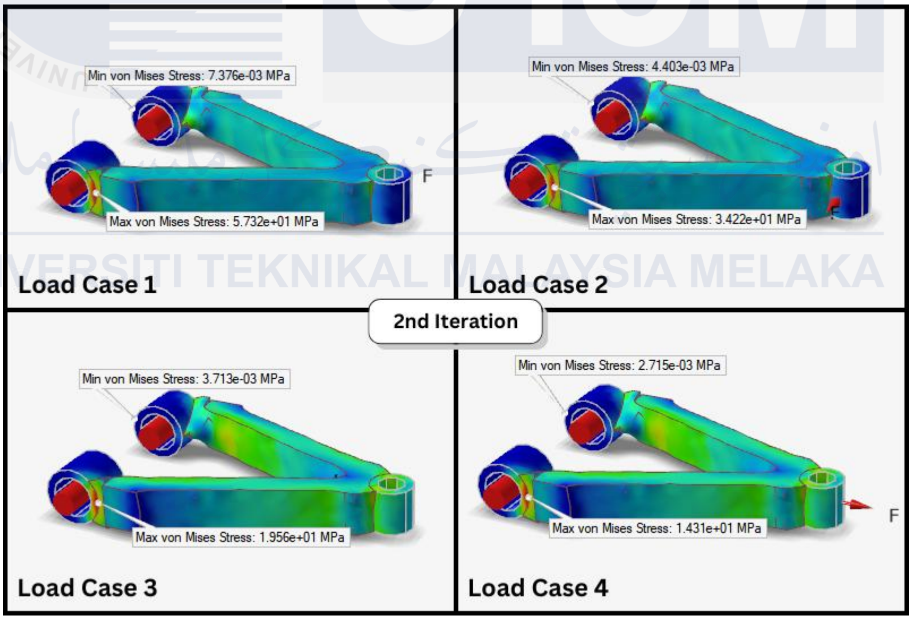

Figure 4.11 Von Mises Stress Result for the 2nd Iteration

Next, Figure 4.12, Figure 4.13, and Figure 4.14 are all the results for the third iteration of the optimizations. The results consist of displacement, FoS, and von Mises Stress respectively.

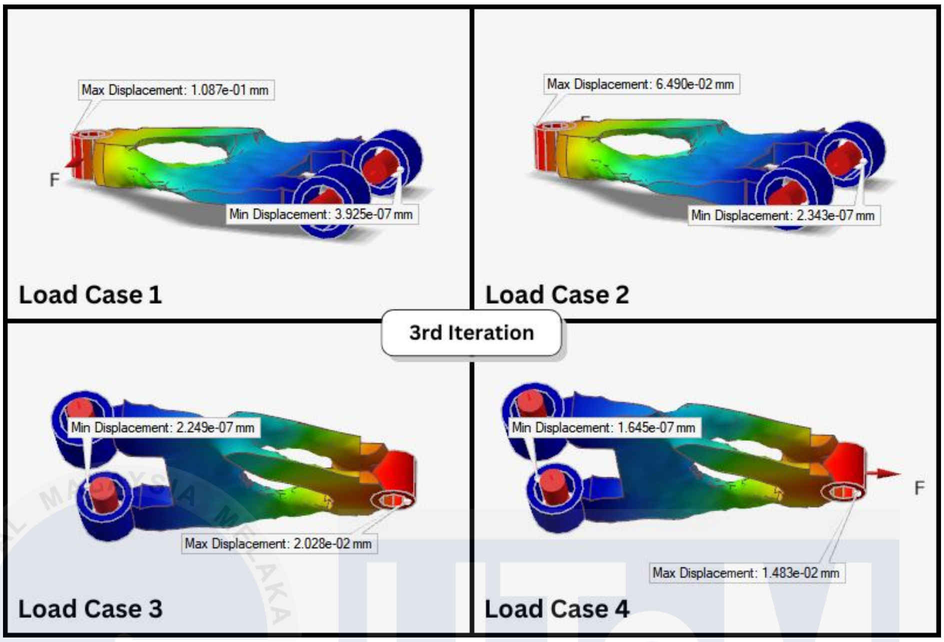

Figure 4.12 Displacement Result for the 3rd Iteration

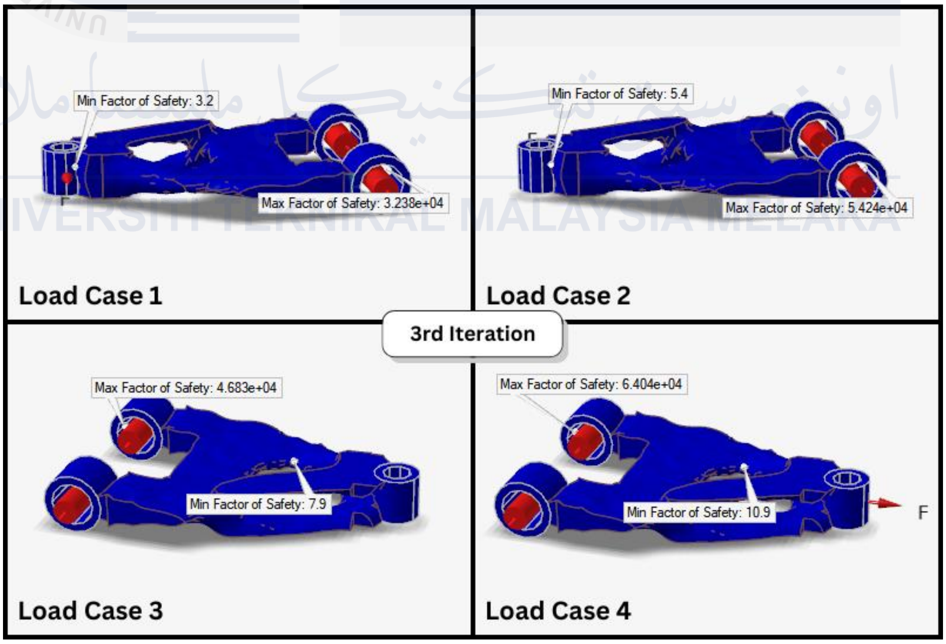

Figure 4.13 FoS Result for the 3rd Iteration

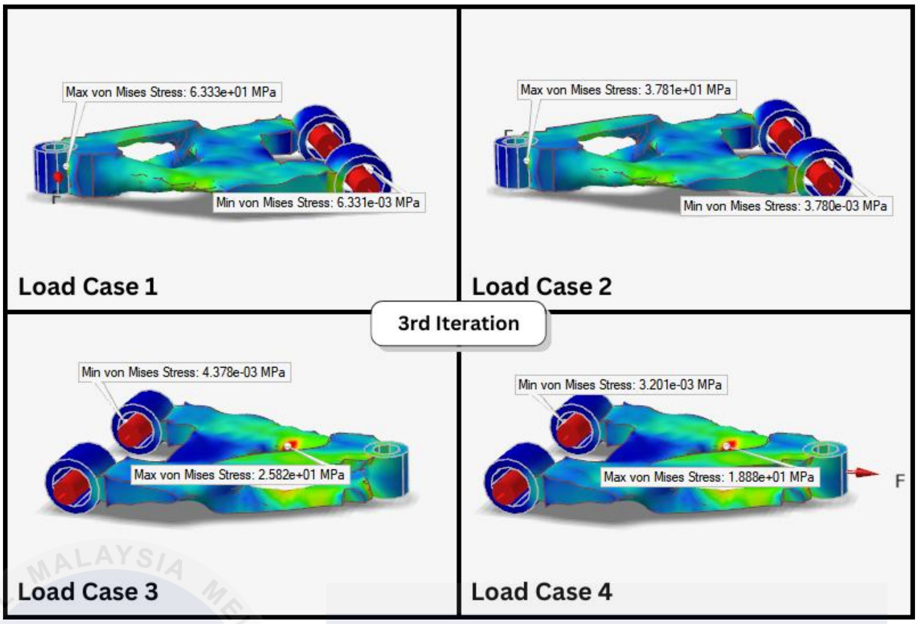

Figure 4.14 Von Mises Stress Result for the 3rd Iteration

Finally, Figure 4.15, Figure 4.16, and Figure 4.17 are all the results for the forth iteration of the optimizations. The results consist of displacement, FoS, and von Mises Stress respectively.

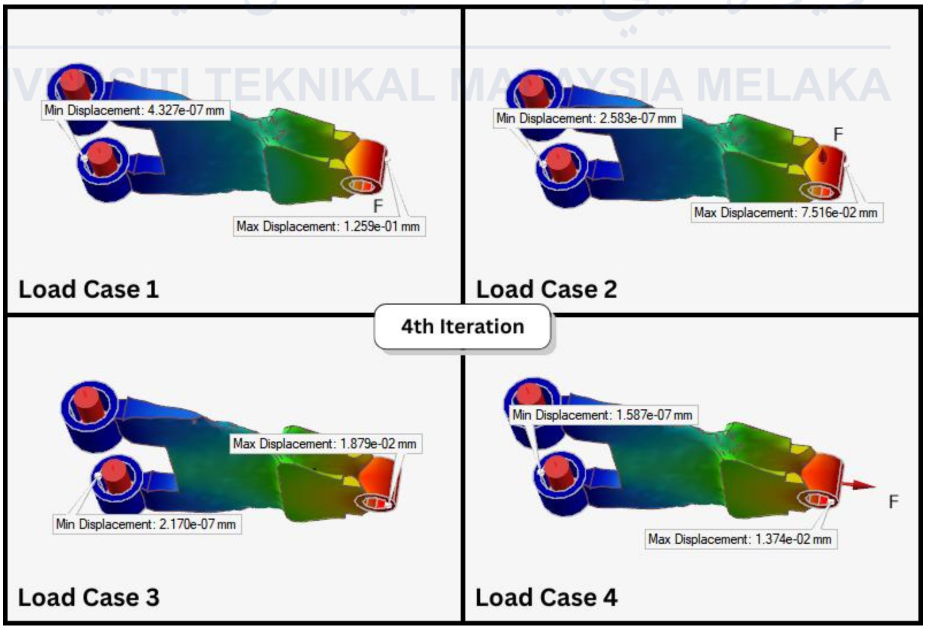

Figure 4.15 Displacement Result for the 4th Iteration

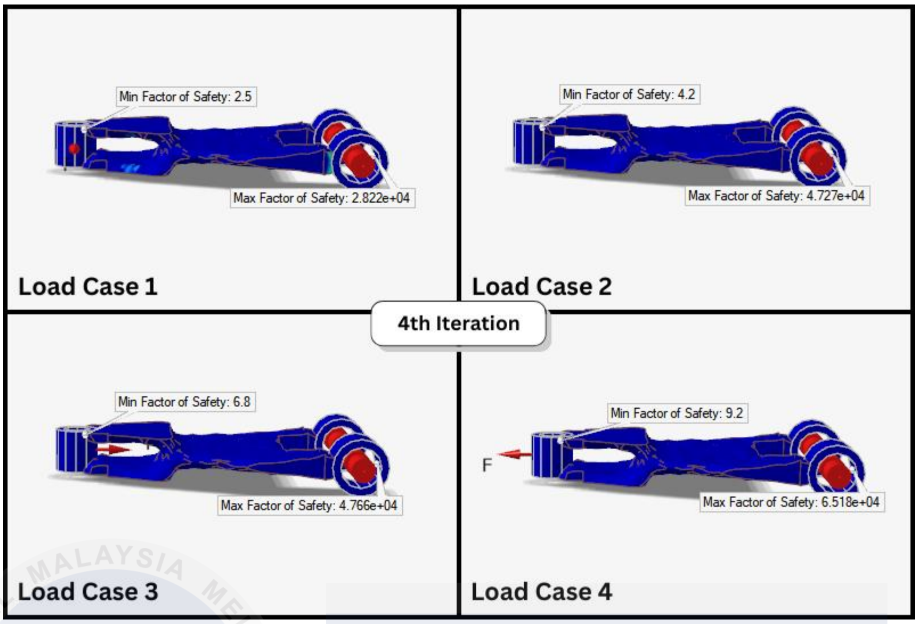

Figure 4.16 FoS Result for the 4th Iteration

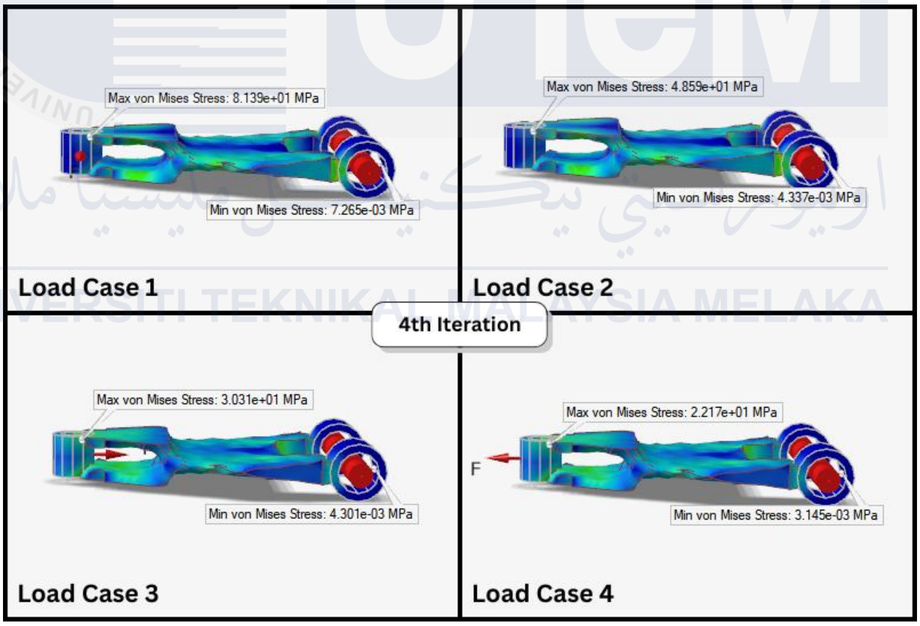

Figure 4.17 Von Mises Stress Result for the 4th Iteration

The results of the optimizations from all four iterations are a lot to take and it is difficult to do comparison. Thus, Table 4.3 is the summarization of all the results for all four iterations for easier comparison.

Table 4.3 Analysis Data of the Iteration Designs

Iterations	Mass (kg)	Load Case	Von Mises Stress (MPa) Min	Von Mises Stress (MPa) Max	FoS Min	Displacement Max
1	11.662	1	0.0075	58.02	3.5	0.0922
		2	0.0045	34.63	5.9	0.0550
		3	0.0043	22.66	9.0	0.0234
		4	0.0031	16.57	12.4	0.0171
		Average	0.0049	32.97	7.7	0.0469
2	11.184	1	0.0074	57.32	3.6	0.9280
		2	0.0044	34.22	6.0	0.0554
		3	0.0037	19.56	10.5	0.1640
		4	0.0027	14.31	14.3	0.0120
		Average	0.0046	31.35	8.6	0.2899
3	11.353	1	0.0063	63.33	3.2	0.1087
		2	0.0038	37.81	5.4	0.0649
		3	0.0044	25.82	7.9	0.0203
		4	0.0032	18.88	10.9	0.0148
		Average	0.0044	36.46	6.9	0.0522
4	12.761	1	0.0073	81.39	2.5	0.1259
		2	0.0043	48.59	4.2	0.0752
		3	0.0043	30.31	6.8	0.0188
		4	0.0031	22.17	9.2	0.0137
		Average	0.0048	45.62	5.7	0.0584

From the data in Table 4.3, the highlighted columns representing the maximum and minimum value of von Mises stress for each iteration. The red highlighted colour represents the maximum value while the blue highlighted column represents the minimum. The relationship between von Mises Stress value with FoS is inversely proportional. The higher the value of von Mises Stress, the lower the FoS.

For Iteration 1, the maximum displacement value is located on the top bushing. It is the same case for the minimum value FoS and maximum von Mises stress result. The hotspot area has solid material that branching out towards the back bushing so it is safe to say that the design could withstand higher stress.

For Iteration 2, the maximum displacement value is still on the front bushing but the minimum FoS and maximum von Mises Stress values are located at the right bushing. If there are excessive forces that been applied to right bushing, the design may break off the right bushing from the main part of the LCA.

For the third iteration, the maximum displacement values for load case 1 and 2 are located at the top of the front bushing while for the load case 3 and 4, it is located at the bottom of the front bushing. For the minimum FoS and maximum von Mises stress value, load case 1 and 2 are located at the left side of the front bushing and for load case 3 and 4 are located at the middle of the design. Thus, the forces will be dispersed to multiple areas if there is excessive force been applied to this design.

Finally for Iteration 4, the maximum displacement values for all load cases are located at the front bushing. For the minimum FoS and maximum von Mises stress values are located the same spot for all load cases which is at the top of the front bushing. This will not be an issue because the front bushing is not the hotspot of failure compared to the back bushing which is been attached to the chassis.

Iteration 2 has the highest mass reduction of 22.873 kg among all iterations from the original mass of the base design which is 34.057 kg. In addition, all the iterations still pass the minimum FoS of 1.2 and ranging from 2.5 to 14.3.

4.3.3 Iteration Selection and Optimized Topology Design

From the past analysis on all four iterations, Iteration 4 have been selected to be use onward. It is because it has a wide back surface that can be utilized for LSO although it has the highest mass among all four iterations. From the Iteration 4 that has been generated from Altair Inspire software, a revised design has been made in Catia V5 software. Figure 4.18 is the schematic diagram of the optimized topology design.

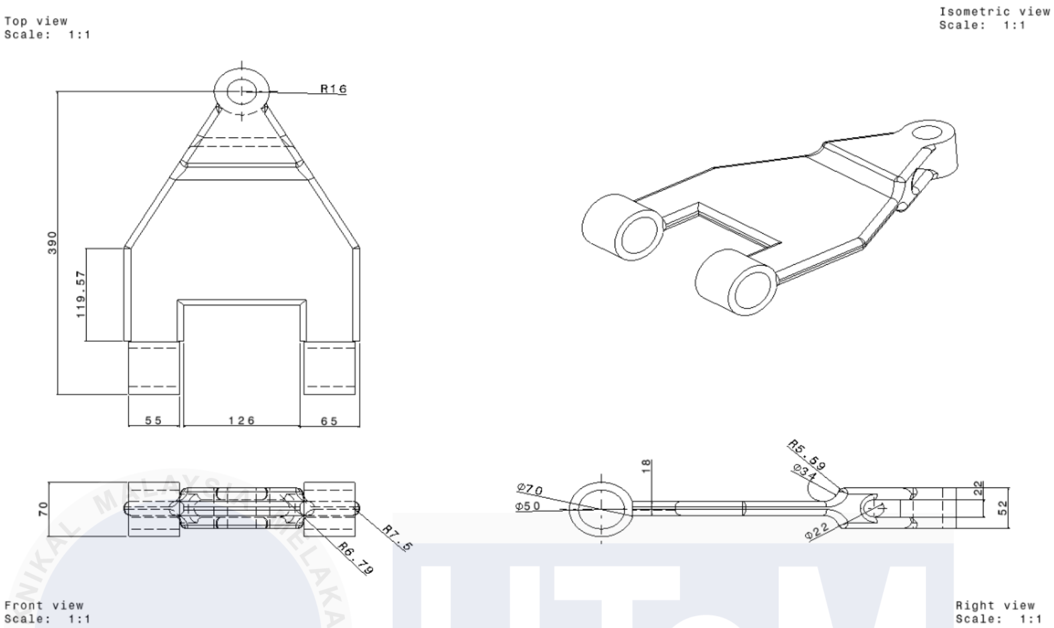

Figure 4.18 Orthographic Design of Optimized Topology Design

4.4 Lattice Structure Optimization

After finishing the topology optimization process, we will proceed to the next step which is LSO. The optimized topology design will undergo a new FEA before running LSO.

4.4.1 Setting up LSO

Before doing the LSO, the optimized topology design needs to be set up the boundaries and load cases like previous process. Figure 4.19 is the boundaries that have been set up on the optimized topology design.

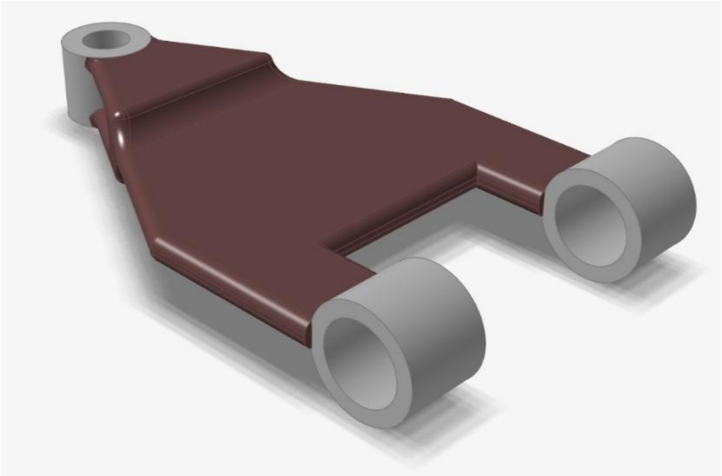

Figure 4.19	Boundaries Set-up on Optimized Topology Design

At the same time, the same boundaries can be used to do LSO on the design for a full lattice design. However, an adjustment needed to be done on the design for the partial lattice design. The adjustment is to make a separate part for the partial lattice design from the LCA to separate the design space. The adjustment has been done on Catia V5 software and the measurement is on Figure 4.20. After the adjustment, the design space has been changed to only the separated part. Figure 4.21 is the design space that has been setup for the partial lattice design.

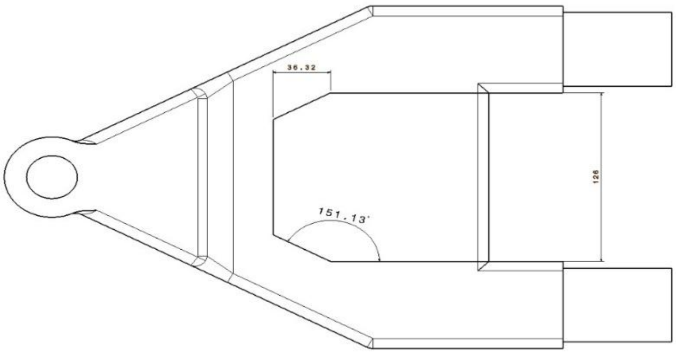

Figure 4.20	Measurement for the Partial Lattice Design

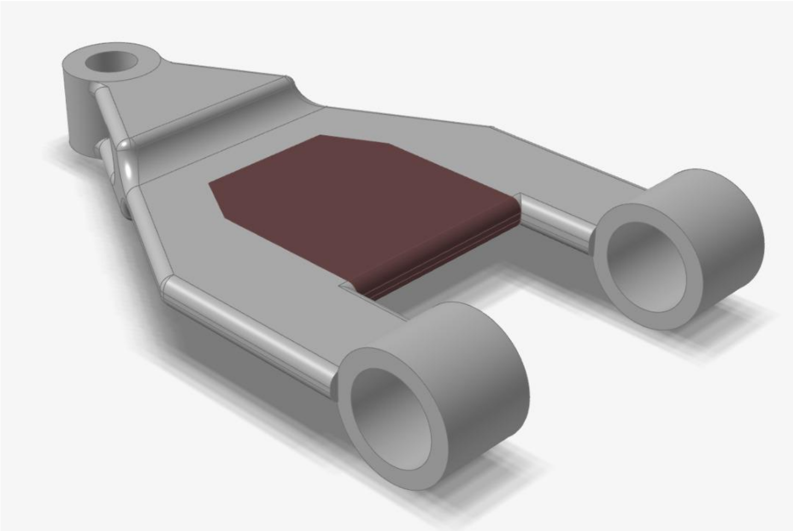

Figure 4.21 Separated Design Space for Partial Lattice Structure

After finishing all the boundaries for the partial and full lattice, both designs undergo LSO, and the lattice structure have been generated. Figure 4.22 is the lattice structures that has been done to the optimized topology design.

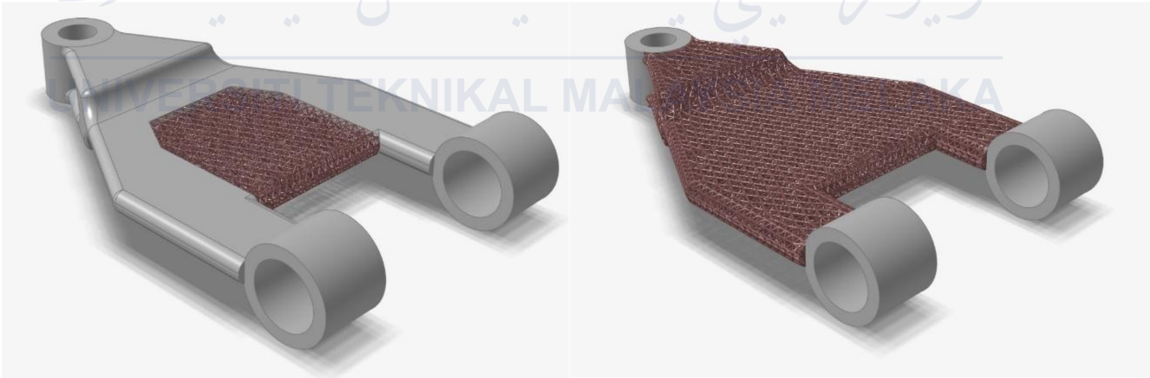

Figure 4.22 a) Partial Lattice b) Full Lattice

4.4.2 LSO Analysis

All the designs which are the base optimized topology design, partial lattice and full lattice design have been undergo FEA with the same load cases as previous process in Altair Inspire. All the results from all three designs have been generated from the software itself. Figure 4.23, Figure 4.24, and Figure 4.25 are the results for Optimized Topology design while

Figure 4.26, Figure 4.27, and Figure 4.28 are the results for Partial Lattice design and for the Full Lattice design are Figure 4.29, Figure 4.30, and Figure 4.31. All the results are in the sequence of displacement, FoS, and von Mises Stress. The summarization of the results has been gathered into the Table 4.4 for easier comparison.

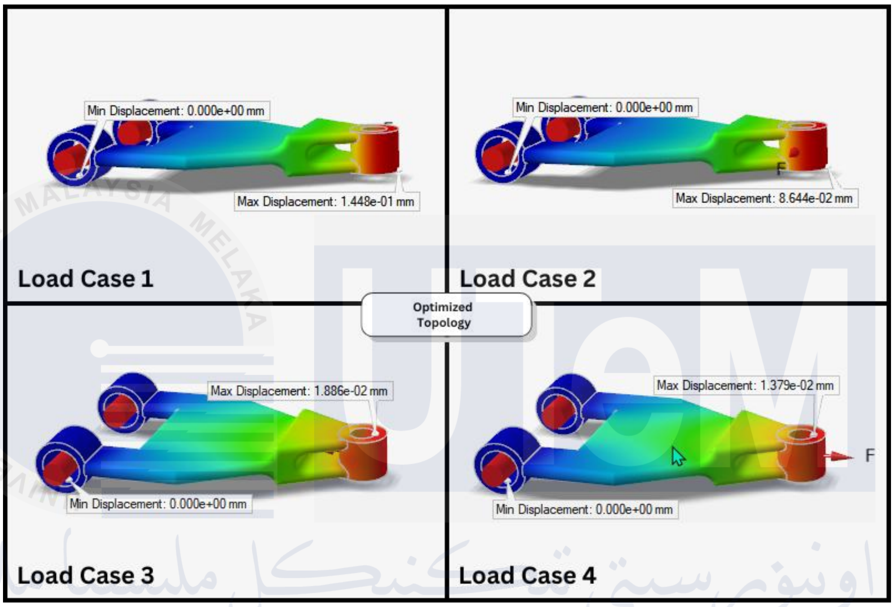

Figure 4.23 Displacement Result for Optimized Topology

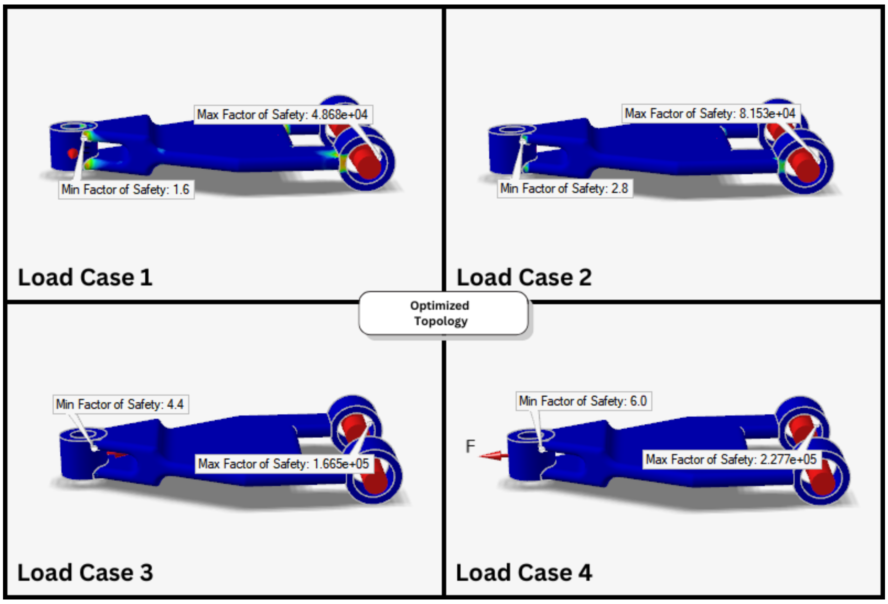

Figure 4.24 FoS Result for Optimized Topology

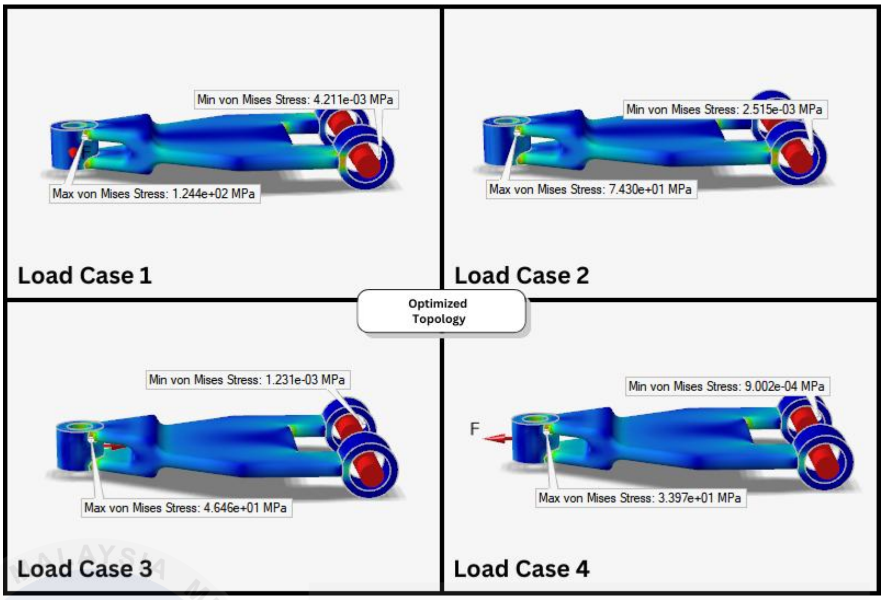

Figure 4.25 Von Mises Stress Result for the Optimized Topology

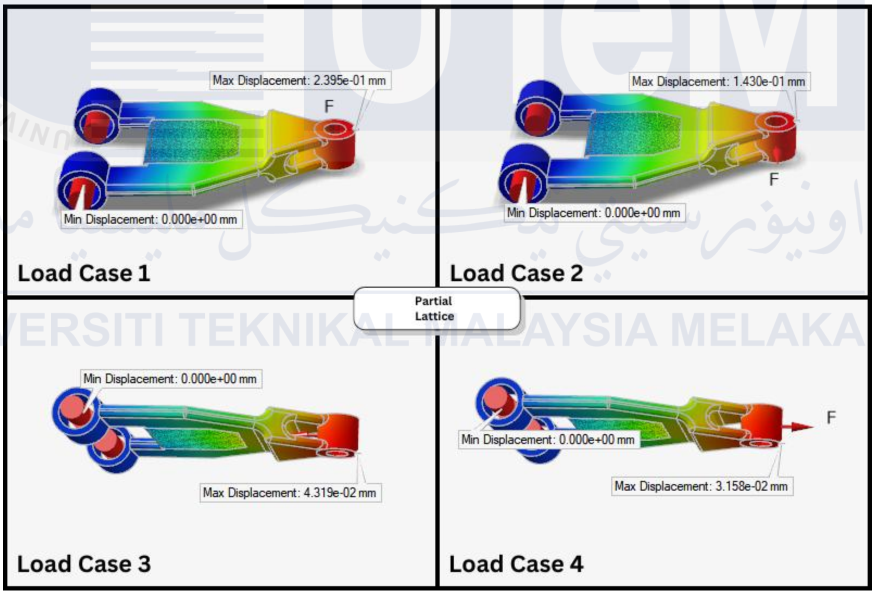

Figure 4.26 Displacement Result for the Partial Lattice

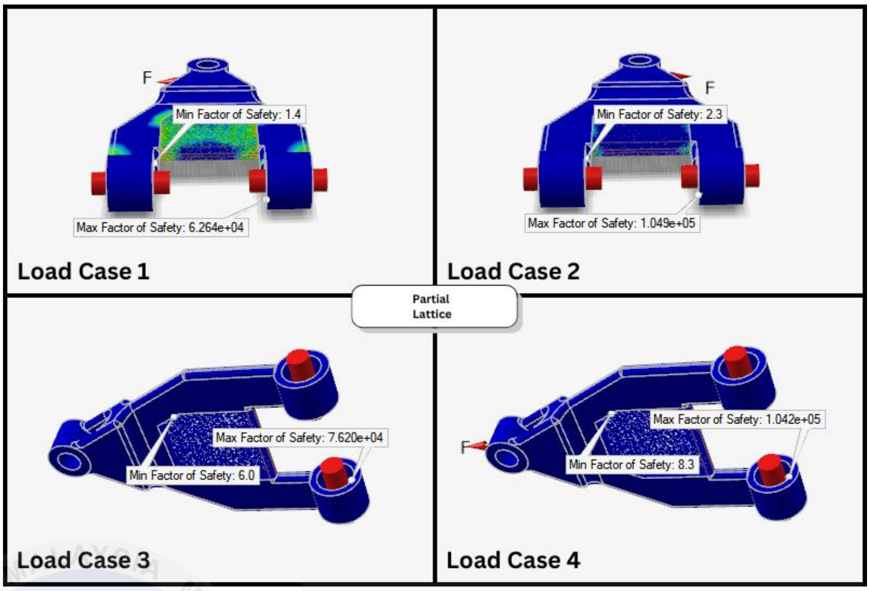

Figure 4.27 FoS Result for the Partial Lattice

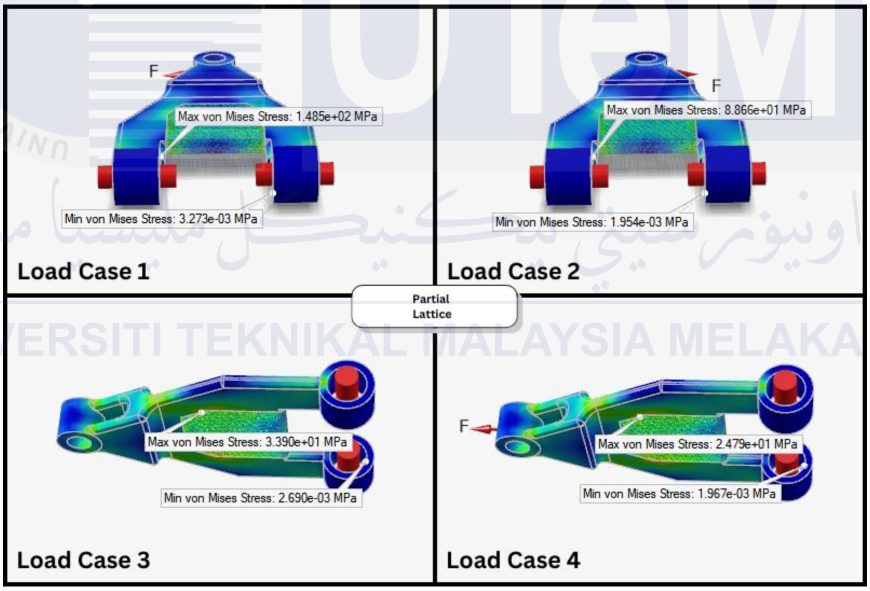

Figure 4.28 Von Mises Stress Result for the Partial Lattice

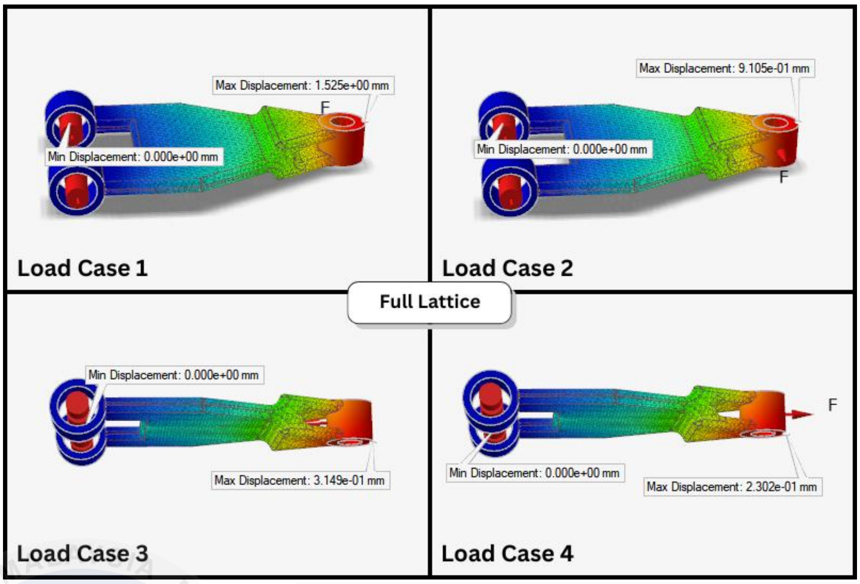

Figure 4.29 Displacement Result for the Full Lattice

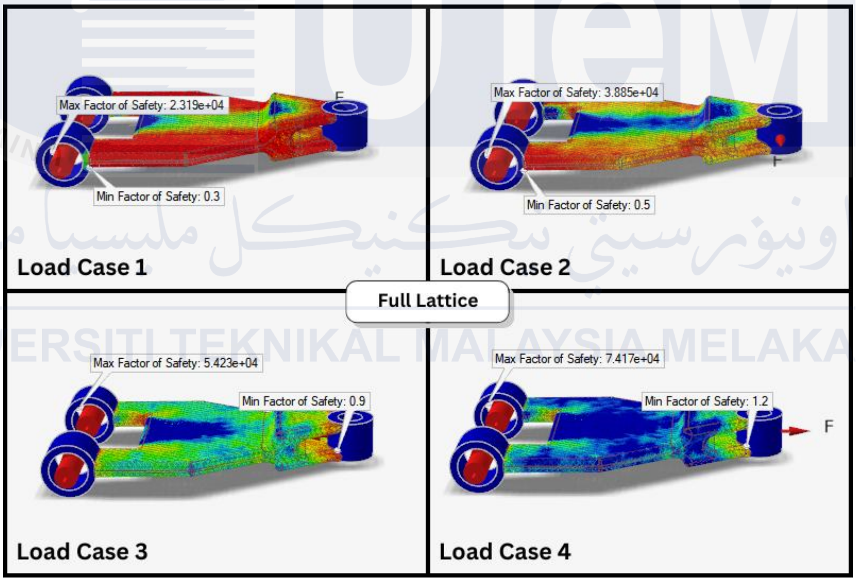

Figure 4.30 FoS Result for the Full Lattice

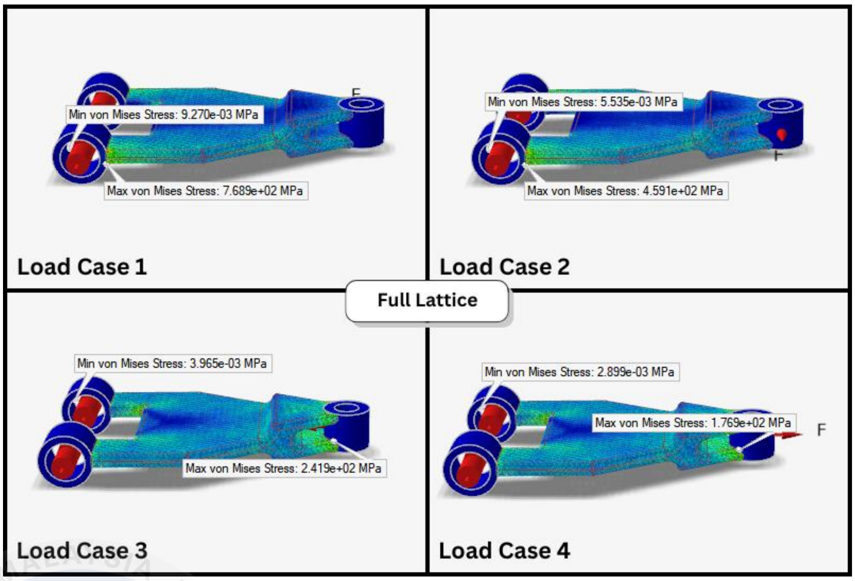

Figure 4.31 Von Mises Stress Result for the Full Lattice

Table 4.4 Summarization of All Three LSO Designs

	Mass (kg)	Load Case	Von Mises Stress (MPa)		FoS	Displacement
			Min	Max	Min	Max
Optimized	11.437	1	0.0042	124.40	1.6	0.1448
		2	0.0025	74.30	2.8	0.0864
		3	0.0012	46.46	4.4	0.0189
		4	0.0009	33.97	6.0	0.0138
		Average	0.0022	69.78	3.7	0.0660
50% Lattice	9.923	1	0.0033	148.50	1.4	0.2395
		2	0.0020	88.66	2.3	0.1430
		3	0.0027	33.90	6.0	0.0432
		4	0.0020	24.79	8.3	0.0316
		Average	0.0025	73.96	4.5	0.1143
100% Lattice	4.972	1	0.0093	768.90	0.3	1.5250
		2	0.0055	459.10	0.5	0.9105
		3	0.0040	241.90	0.9	0.3149
		4	0.0029	176.90	1.2	0.2302
		Average	0.0054	411.70	0.7	0.7452

From Table 4.4, as expected, the optimised design has the same hotspot of maximum von Mises stress value for all load cases. The value is higher than iteration 4 due to its design which narrower than iteration 4. The result is still acceptable.

Next is on the LSO design. The mass of the design is inversely proportional to the area that has been undergo lattice structure. For Partial Lattice design, the highest von Mises stress value for load case 1 and 2 is at the back of the main LCA body. For load case 3 and 4, the maximum von Mises stress result is at the connection of solid material and the lattice structure. Load case 1 and 2 have lower FoS result than load case 3 and 4 thus, the lattice structure proven that the lattice structure is strong.

For Full Lattice design, the mass has been reduced by 43.47% from the based topology design to the 100% lattice structure design. However, with all the material that has been removed, the integrity of the design also decreased. From all the load cases on the 100% lattice structure design, three out of four from the load cases didn't reach the standard limit of the FoS and only one load case barely reached the limit of 1.2. Highest stress area for load case 1 and 2 is on the right bushing while on the load case 3 and 4 is on the connection of the main LCA body with front bushing. From the result, Full Lattice design will crumple at the left and right side of the LCA, and bushing will immediately break. Thus, Full Lattice design did not pass the test.

Hence, the Partial Lattice design will be selected as the final design because all the load cases managed to pass the minimum FoS, with the lowest result is 1.4. The partial lattice has reduced the weight by 1.514 kg and the design still can be optimized due to its high FoS on load cases 3 and 4.

4.5 Final Design Iterations

After the previous analysis, the last optimization will be done to the design. Some of the materials will be reduced to lower the weight of the LCA and some area still can be optimized by LSO. Thus, two more iterations had been made in Catia V5 to further reduce the weight of the design. Figure 4.32 is the first iteration that has been done. 3 areas of the LCA had been reduced its thickness by 5 mm. The middle lattice has been revised and there is solid material on the bottom half of the LCA to counter improve structural integrity. Figure 4.33 is the second iteration that has been done. Compared to the first iteration, the top of the LCA will be optimized using LSO while the other part remains the same.

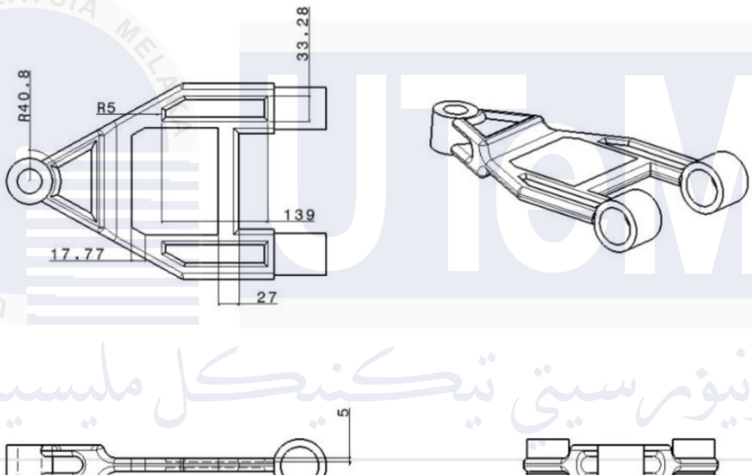

Figure 4.32 1st Iteration of the Final Optimization

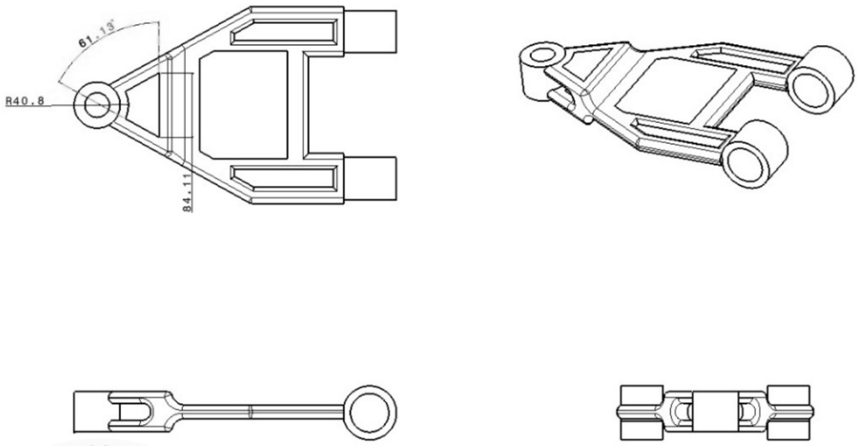

Figure 4.33 2nd Iteration of the Final Optimization

Like previous process, boundaries and design space had been setup for both iterations with the same load cases. Next, the iterations have been successfully optimized using LSO. Figure 4.34 is the optimized designs first iteration and second iteration respectively. First iteration only has one lattice area while the second iteration has two lattice areas, but both have reduced thickness on both left and right side of the LCA.

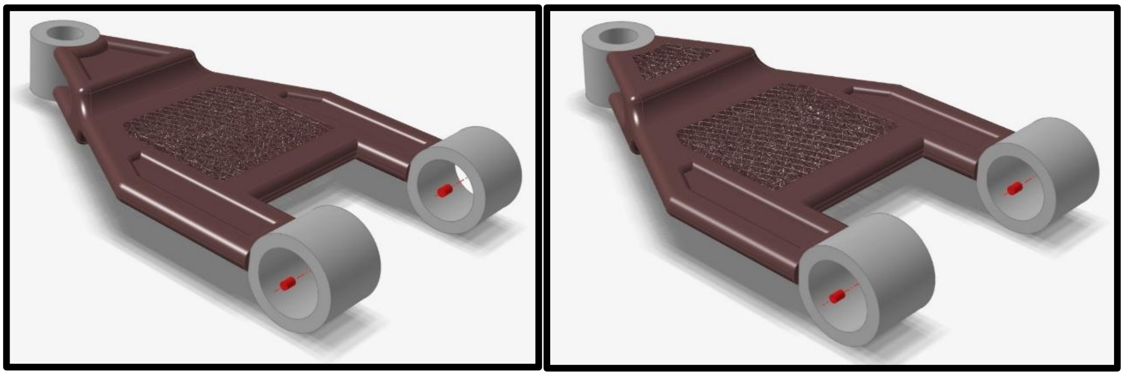

Figure 4.34 a) 1st Iteration b) 2nd Iteration

Final FEA has been done for both iterations with the same load cases in Altair Inspire. Figure 4.35, Figure 4.36, and Figure 4.37 are the results generated for first iteration of the final design. Figure 4.38, Figure 4.39, and Figure 4.40 are the results for second iteration of the final design. All the results have been summarized into Table 4.5.

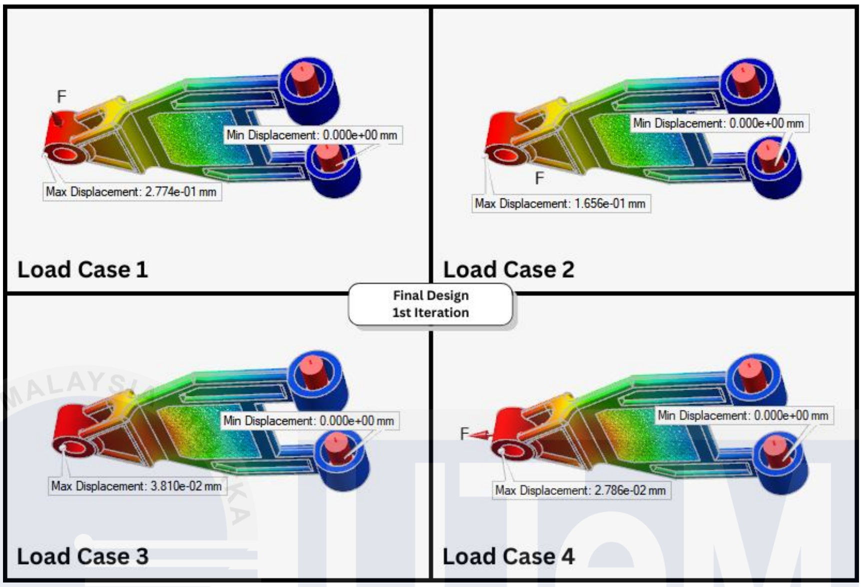

Figure 4.35 Displacement Result for 1st Iteration of Final Design

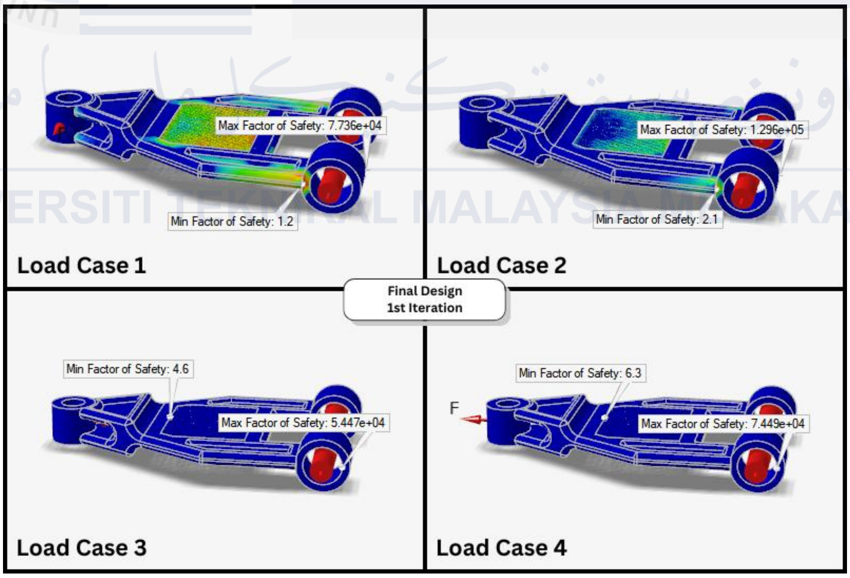

Figure 4.36 FoS Result for 1st Iteration of Final Design

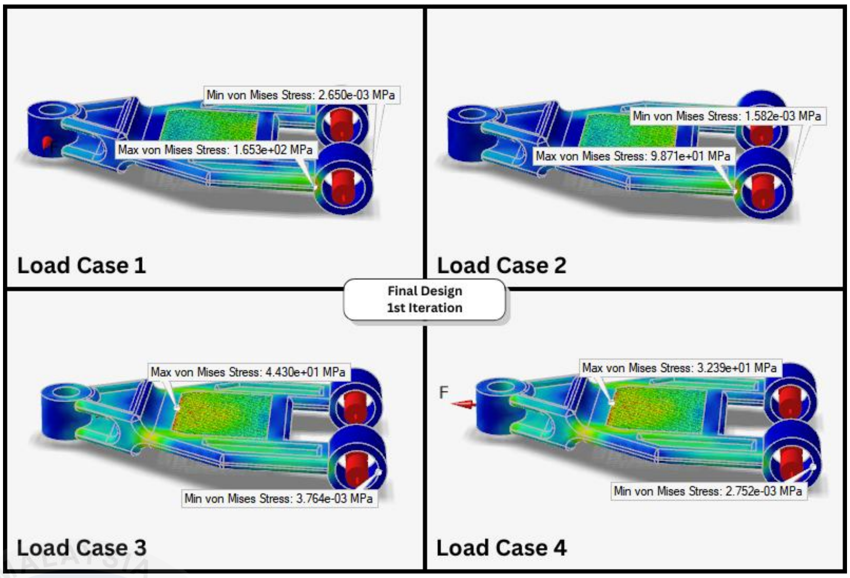

Figure 4.37 Von Mises Stress Result for 1st Iteration of Final Design

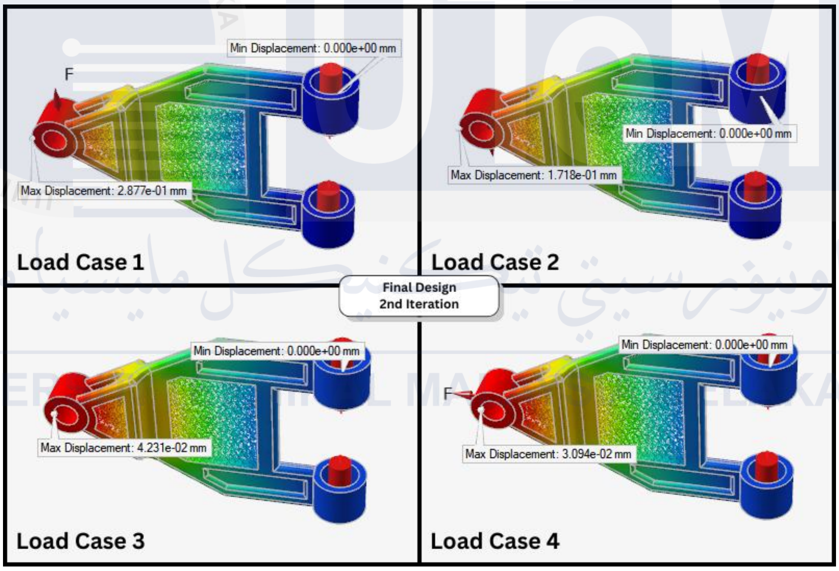

Figure 4.38 Displacement Result for 2nd Iteration of Final Design

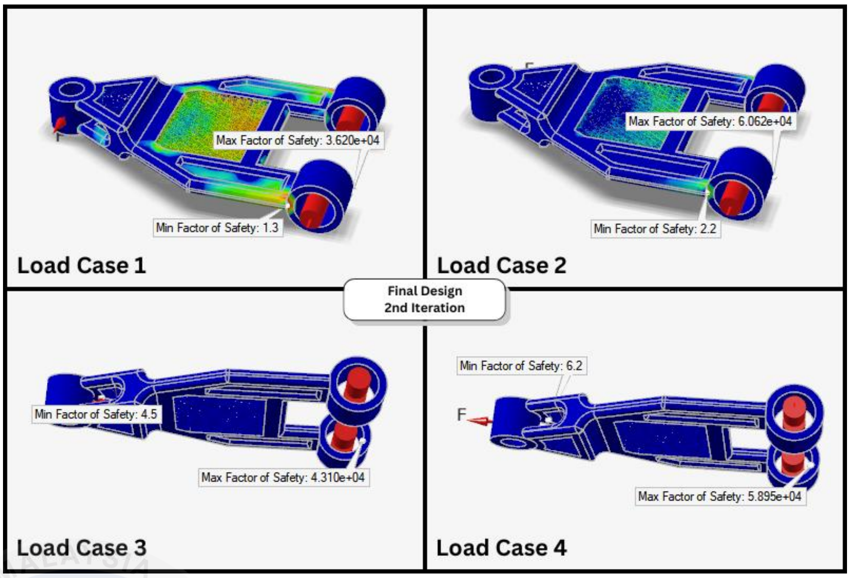

Figure 4.39 FoS Result for 2nd Iteration of Final Design

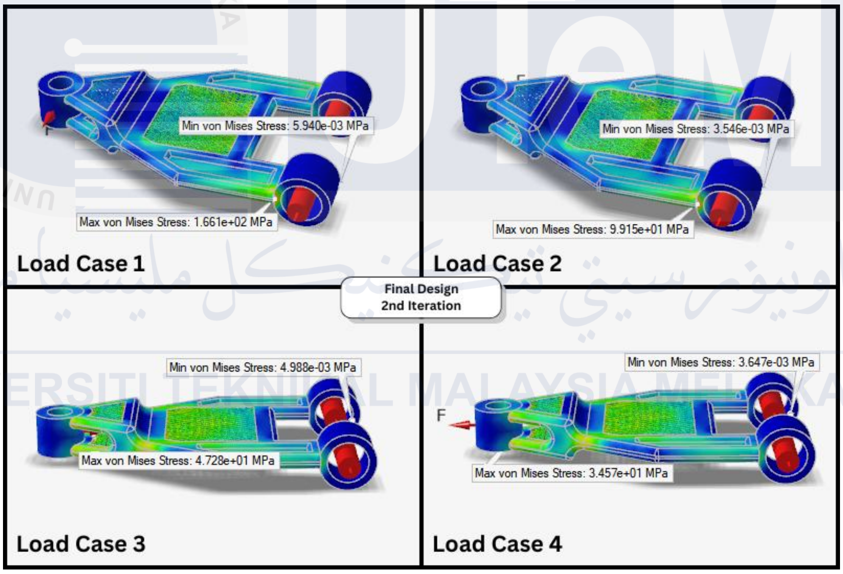

Figure 4.40 Von Mises Stress Result for 2nd Iteration of Final Design

Table 4.5 Summarization of the Result for Final Iterations

	Mass (kg)	Load Case	Von Mises Stress (MPa)		FoS	Displacement
			Min	Max	Min	Max
1st Iteration	8.55	1	0.0027	165.30	1.2	0.2774
		2	0.0016	98.71	2.1	0.1656
		3	0.0038	44.30	4.6	0.0381
		4	0.0028	32.29	6.3	0.0279
		Average	0.0027	85.15	3.6	0.1273
2nd Iteration	8.129	1	0.0059	166.10	1.3	0.2877
		2	0.0035	99.15	2.2	0.1718
		3	0.0050	47.28	4.5	0.0423
		4	0.0036	34.57	6.2	0.0310
		Average	0.0045	86.78	3.6	0.1332

Referring to the table above, both iterations had barely passed the minimum FoS on Load Case 1. Comparing the FoS for both load cases, they have almost similar result with the difference of 0.1 throughout all load cases. The hotspot area of high stress is also the same. The maximum von Mises stress and minimum FoS results for both iterations are located at the connection of the left bushing with the main body of the LCA. However, the most obvious difference is the mass which is the second iteration is lower than the first iteration by 0.421kg. It also has higher minimum FoS for all four load cases. Thus, second iteration has been chosen as the final design with the mass of 8.129kg.

4.6 Summary

Summary of this chapter, optimization is a crucial step in Research and Development process. It will reduce the material that will be used to make a product, and manufacturer can reduce the cost of material. Topology optimization is a very useful feature that can remove the material with the lowest stress and keeping the material in the high stress area. LSO is also useful because it will further reduce the material even on the medium to high stress area but still can keep the structure integrity of the product. Both features have been used in this experiment, and it has proven its capabilities to reduce material while keeping the product's strength. From the base design to the final design, the mass of the LCA has been reduced by overwhelmingly 25.928kg. In another word, the design has been reduced by 76.13% from its original mass.

CHAPTER 5

CONCLUSION

5.1 Conclusion

This study focused on the design and analysis of a front LCA and been optimized by multiple features to address the need for lightweight but strong and sturdy automotive components. This is to help improve fuel consumption and reduce emission from vehicles. By integrating advanced methodologies such as topology and lattice structure for the optimizations and finite element analysis, the research aimed to find the perfect balance of material efficiency and structural integrity. However, LSO is new to be done to automotive components, thus, this study will find its effectiveness.

This research successfully achieved its objectives of designing and analysing a lighter, structural sound LCA. The integration of topology and LSO not only reduced material usage on the design but also keeping the design on par to safety and performance standards. The results highlight the potential of combining these two optimizations to make a new path of designing automotive components. The key findings from the result of multiples analysis throughout the thesis are as below:

a) Base design is to help getting the general shape of the design before doing any optimization. The result usually will get a very high FoS due to its thickness all around.
b) Topology optimization resulted in significant weight savings by removing excessive material on the low stress area of the design. This study's result is an example of how it reduced the mass of the base design from 34.057kg to 12.761kg.

c) The lattice structural optimization is a more complex optimization due to its narrow and hollowed design. It is because it can reduce material not only on the medium stress area, it also can be done on the high stress area but not overall of the design. Example from the thesis is on the full lattice design which it failed to reach the minimum FoS.

d) The final iteration achieved an optimal trade off, showcasing the practicality of combining multiple optimizations techniques.

5.2 Recommendations

Although the objectives of the research have been achieved, there are still many improvements that can be done to get a better results and implementation in real-life environments. Here are some recommendations for further improvement:

a) Exploring more alternative materials such as composites, to further enhance the performance and reducing the mass.

b) Conducting real-world dynamic tests to validate simulation findings.

c) Researching about manufacturing constraints and costs to verify the industrial capability of the design.

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