FINITE ELEMENT ANALYSIS OF AN INDEPENDENT STEERING SYSTEM FOR A PENDULAR VEHICLE

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A report submitted in fulfilment of the requirements for the degree of

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DECLARATION

I declared that this project report entitled "Finite Element Analysis of an Independent Steering System for a Pendular Vehicle" is the result of my own work except as cited in the references.

Signature : ……………………………

Name : ……………………………………

Date : ……………………………………

APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature :..

Name of Supervisor :..

Date :..

DEDICATION

This report is dedicated to my beloved mother and father.

ABSTRACT

Independent steering system is the most important system in any vehicle. This lets the driver get full control over the car maneuver. The cradle or subframe is an important component of the vehicle with various functions. It is used to improve the ride comfort and handling capability. The aim of using an automotive subframe is to spread large local loads across wider area of the body structure and making the vibration and harshness separated from the body structures. This paper is aim to find the most suitable thickness for the cradle in order to withstand the stresses. This paper also described the type of steering system such as steer-by-wire, four wheel steering, rack and pinion and the recirculating ball steering. Material used for manufacture this cradle are aluminium. The analysis of the cradle is by using Finite Element analysis (FEA) of CATIA software. The analysis are done using thickness of 6mm, 8mm and 10mm. The amount of force for rear cradle is 883N and 442N for the front cradle. From the analysis it is concluded that 6mm thickness is the most suitable thickness for the cradle and the minimum thickness that can be used to manufacture the cradle is 2mm.

ABSTRAK

Sistem stereng bebas adalah sistem terpenting untuk mana-mana kenderaan. Ini membolehkan pemandu mengawal sepenuhnya manuver kereta. Tujuan stereng adalah untuk memandu roda depan dengan maklum balas pemanduan supaya pelbagai jenis permukaan dapat dikendalikan sepenuhnya. Cradle atau subframe adalah komponen penting kenderaan dengan pelbagai fungsi. Ia digunakan untuk meningkatkan keselesaan perjalanan dan kemampuan pengendalian. Tujuan menggunakan subframe automotif adalah menyebarkan muatan lokal yang besar ke kawasan struktur badan yang lebih luas dan membuat getaran dan kekerasan dipisahkan dari struktur badan. Kertas ini bertujuan untuk mencari ketebalan yang paling sesuai untuk menahan tekanan. Kertas ini juga menerangkan jenis sistem stereng seperti kawalan oleh wayar, roda empat roda, rak dan pinion dan kawalan bebola berpusing. Bahan yang digunakan untuk pembuatan cradle ini adalah aluminium. Analisis cradle ini adalah dengan menggunakan analisis Elemen Terhingga (FEA) menggunakan perisian CATIA. Analisis dilakukan dengan menggunakan ketebalan 6mm, 8mm dan 10mm. Jumlah daya untuk cradle belakang adalah 883N dan 442N untuk cradle depan. Dari analisis tersebut is dapat disimpulkan bahawa ketebalan 6mm adalah ketebalan yang paling sesuai untuk buaian dan ketebalan minimum yang boleh digunakan untuk membuat buaian adalah 2mm.

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LIST OF SYMBOLS

σ	**=**	**Stress**
F	=	Force applied
A	=	Cross sectional area of the object
ε	=	Strain
e	=	Extension
$l_{\circ}$	=	Stretched length
E	=	Young’s modulus
I	=	Moment of inertia
M	=	Internal bending moment in the beam

CHAPTER 1

INTRODUCTION

1.1 Background

The most traditional steering system is to control the front wheels using a hand operated steering wheel that is located in front of the driver, via the steering column that may include universal joints, allowing it to deviate somewhat from a straight line. There have been several phases in the vehicle steering system, such as manual steering, hydraulic steering, electro-hydraulic steering, electrical power steering and by-wire steering (Tian, Tong, & Luo, 2018). Steering is a mixture of materials, linkages, etc. that helps the vehicle to follow the desired direction. The sole purpose of the steering system is to giving license or permission for the driver to navigate the vehicle along the exact route they want (Ruban, Sathishkumar, Shanmugavelan, Srinath, & Ramesh, 2017). Figure 1.1 below shows the basic steering components.

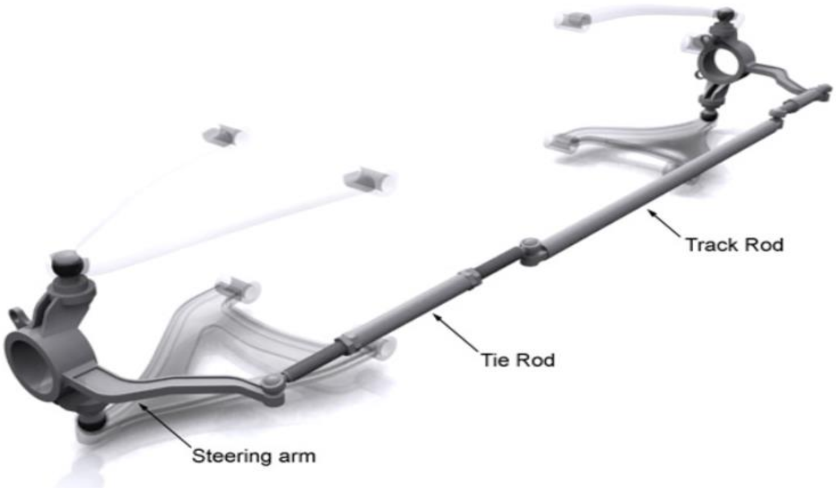

Figure 1.1: Basic steering components

There are various types of steering system such as steer-by-wire, four-wheel steering, rack and pinion, recirculating ball steering, etc. One of it is the four-wheel steering. Four wheel steering also known as independent steering system. Four wheel steering is an advanced control technique which can improve steering characteristics. A four wheel steering vehicle has the advantage of improving the ability of the vehicle to corner by steering the rear wheels according to the status of the vehicle and the lateral stability and overall handling efficiency of the vehicle can also be improved (Ronci, Ferrer Lng, Artuso Phd, & Bocci, 2011). The most sophisticated system consists of electric motors for each wheel and the development of this kind of system opens the possibility to use independent wheel torque control to steer the vehicle resulting in the removal of the mechanical steering linkage, greatly simplifying the mechanical design and allowing cost savings (W. Li, Potter, & Jones, 1998). Dynamic yaw-moment control (DYC) is a method for controlling the lateral motion of a vehicle with the input of the yaw moment produced by the difference in the left and right wheels torque (Sakai, Sado, & Hori, 1999). Figure 1.2 below shows the four wheel steering system.

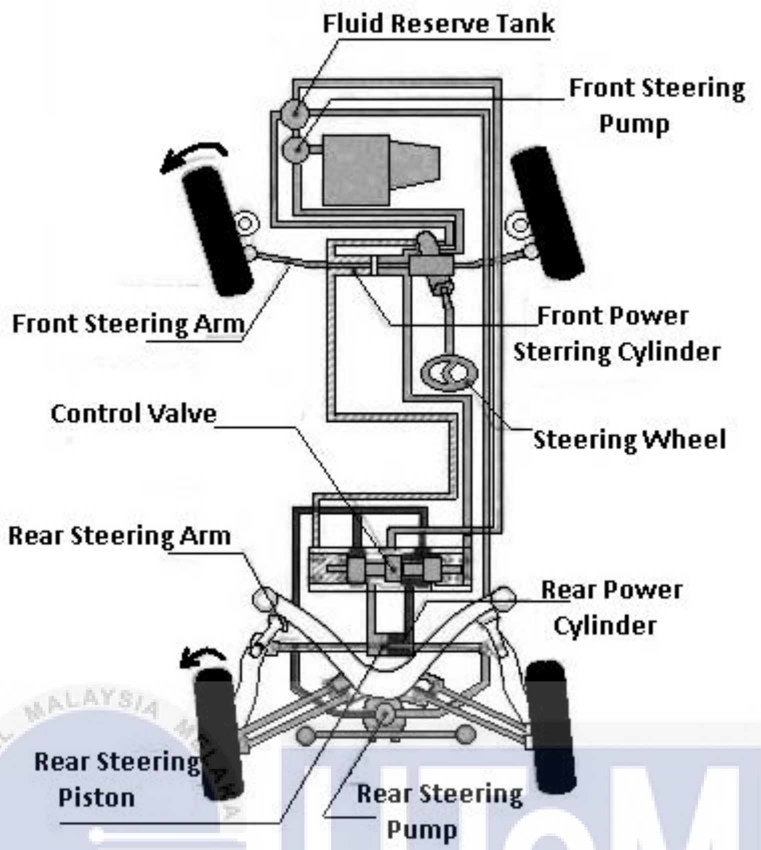

Figure 1.2: Four wheel steering system

An independent steering system or four wheel steering system is the most suitable type of steering system to be utilized when developing a pendular vehicle. A pendular vehicle is a tilting vehicle that is a result of combining the forces of gravity, centrifugal force and ground resistance of the wheels and places itself in equilibrium. This type of vehicle will have no actuator because of the slow respond of the actuator itself, which can mean delays in the tilt movement. This can lead to problems, especially in emergency situations. The driver's compartment and the wheels are mounted on longitudinal axes, allowing the driver's compartment to tilt on turns or a slope. This mechanism for lean in turn means the wheels are parallel to the angle of the driver's compartment hanging down while driving. Figure 1.3 below show an example of pendular vehicle.

Figure 1.3: Example of pendular vehicle

The sole purpose of an all-terrain vehicle (ATV) is off-roading. It is designed for very rough terrain such as the countryside, mountain, etc. All-terrain vehicle or also known as quad bikes consist of 4 wheel geared or non-geared systems. The only different between the normal all-terrain vehicles with the pendular vehicle is the existence of the pendulum mechanism. Pendular vehicle is an all-terrain vehicle that is combined with the pendulum mechanism. Pendular vehicle is a new mode of driving, good for all kinds of surrounding including hills, valleys, snow and sand. The nature of pendulum means that the vehicle is tilting on a bend and staying level on slopes. This means that the articulated legs splay out on the roughest terrain to keep the wheels in contact with the ground. All controls are grouped and easy to use around the steering wheel.

1.2 Problem statement

A problem statement is a concise summary of a problem to be solved or a situation to be changed. This defines the difference between a system or product's current state and the desired state.

The pendular vehicle is suitable for the off road or cross country vehicle that capable of operating across a wide variety of terrains. This kind of vehicle also suitable for peoples of reduced mobility because it is controlled only using hands and that making it very accessible. However there is a problem where the cradle is not strong enough to withstand the force from the suspension and not suitable for the long term used, thus, can affect the performance of the vehicle.

1.3 Objectives

- To investigate the suitable thickness of the cradle or subframe that can withstand the applied stress using Finite Element Analysis (FEA).
- To provide a complete analysis on the cradle or subframe and to propose engineering solutions.
- To determine the performance of the vehicle based on the analysis of the subframe.

1.4 Scope of project

The scopes of this project are:

- This report is to obtain the most suitable thickness for the cradle or subframe and can enhanced the performance of the vehicle. The variable that is to be manipulating in this project is the thickness of the cradle or subframe.
- The variable that is to be ignoring in this project is the material of the cradle which is concluded as the aluminium as the overall material for the component.
- The method that is used in this project is the final element analysis (FEA).

1.5 General methodology

The methodology is a way that is used in the project to collect the data and how to obtain the result with high accuracy.

1. The literature review: The journals, articles or any materials regarding the project.
2. Simulation: The simulation using the Final Element Analysis (FEA).
3. Analysis and proposed solution: Analysis will be presented on the thickness of the cradle that is suitable for the pendular vehicle to operate smoothly.
4. Report writing: A report on this study will be written at the end of the project.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The steering system is the most important system in any vehicle. This lets the driver get full control over the car maneuver. The steering purpose is to guide the front wheel with the driving feedback so that the various types of terrain can be fully controlled

2.2 Type of steering system

There are various types of steering system such as steer-by-wire, four wheel steering, rack and pinion and the recirculating ball steering.

2.2.1 Steer-by-wire

There is no mechanical link between the steering wheel and the front wheel system in steer-by-wire system. It is completely different compared to the conventional steering system. Steer-by-wire system consist no steering shaft, column gear reduction mechanism, etc. By getting rid of the steering shaft, it will provide more space efficiency that enables a much better use of the engine compartment space, more fuel efficiency in term of functionality. Besides that, steer-by-wire system can also avoid oil leaking, offer a larger space in cabin that lead to freedom of interior design and also can minimise the injury during accident.

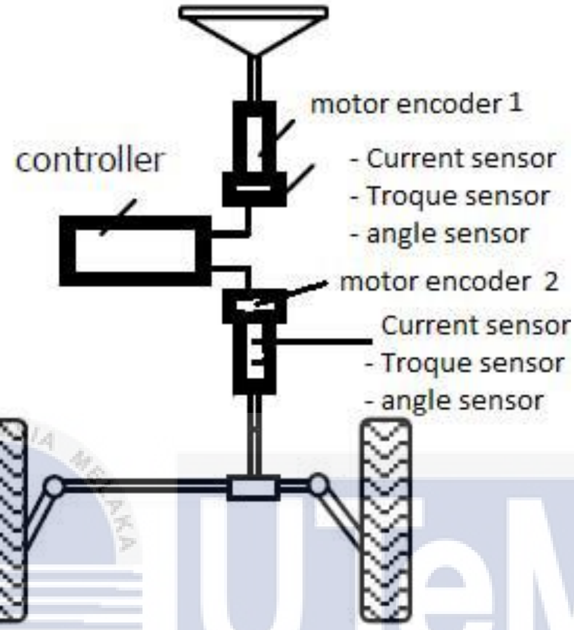

Figure 2.1: Steer-by-wire system

Attached to the steering wheel and front wheel assembly are sensors and actuators. The signal of the rotation angle is controlled by the electronic control unit (ECU) and sent to the front wheel actuators to turn the front wheels components in the same way as the action of the steering wheel. Steer-by-wire system can be broken down into three major subsystems which are steering wheel, front wheel and vehicle model system. Based on the Figure 2.1, the torque sensor, current sensor, steering angle sensor and motor encoded are situated within the steering wheel system. As for the front wheel system, it contains rack pinion gear, angle sensor, motor encoded and other related mechanism (Fahami, Zamzuri, Mazlan, & Zakaria, 2012).

Steer-by-wire system can lead to energy reduction effectiveness due to the reduction of the vehicle's weight. In addition, when a front-end collision occurs, the possibility of a driver being killed is reduced because there is no steering wheel. The aim of the steering wheel motor control is to enhance the driver's steering feel by producing reactive torque. Thus, making the steering wheel easier to maneuver at low speeds especially during the parking process and also to enhance the driver's steering feel of the driver during high speeds by making steering wheel tight. Correctly guide the front wheel angle to increase and enhance the ability to move and the stability of the vehicle is the main purpose of the front wheel motor control. On the other hand, the vehicle's rapid response to the driver's steering with front wheel steering is more critical in improving vehicle performance. The high performance control method is a more reliable method of controlling the front wheel and an advanced control system by incorporating high-quality sensors that give the electronic control unit (ECU) precise state feedback. Using sensor feedback data to control motor torque, the vehicle dynamics control system operates to reduce vehicle instability factors when the vehicle reaches the instability limit such as rollover, yaw moment, and rear sway (Oh, Chae, Yun, & Han, 2004).

2.2.2 Four-wheel steering

Four-wheel steering system, also called rear-wheel steering or all-wheel steering enables the rear wheels to be effectively steered during turning maneuvers. It is a mechanism used by some vehicles to enhance steering response, increase the stability of vehicles when steering or driving at high speed and reduce the turning radius at low speed. Most of the driving is done by the front wheels. The turning of the rear wheel during the opposite direction is usually limited to half. When the both the front wheels and rear wheels going in the same direction, these are said to be in-phase, and this results in a kind of low-speed sideways motion of the vehicle. A sharper, tighter turn can be produce when the front and rear wheels are going in the opposite way, which is called anti-phase, counter-phase or opposite-phase (Singh, Kumar, Chaudhary, & Singh, 2014).

Figure 2.2: In-phase steering

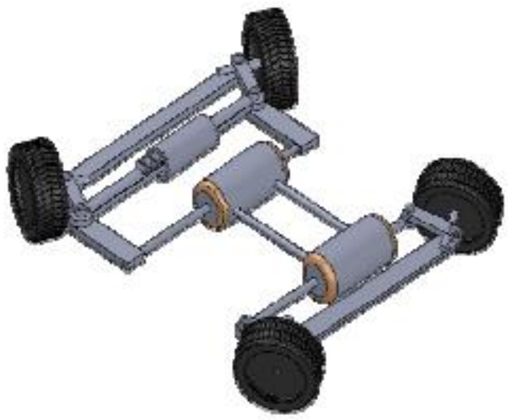

Figure 2.3: Counter phase steering

Four wheel steering (4WS) contains two degrees of freedom which are the centre steering angles in the front and rear axle. In order to reduce the degrees of freedom to one, four wheel steering angles cannot be mechanically linked together easily, unless additional kinematic constraints were introduced (Oksanen & Linkolehto, 2013). The rear wheels are controlled by a computer and actuators and some systems make it possible to steer the rear wheels in the opposite direction as the front wheels at low speeds. Thus, enables the vehicle to turn in a considerably smaller radius (Singh et al., 2014).

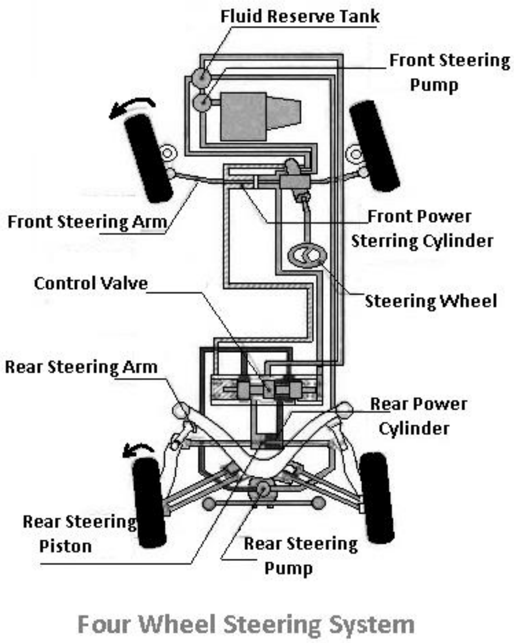

Figure 2.4: Example of four wheel steering system

Supporting the front wheels instead of steering them by themselves is the main objective of the rear wheels. Four wheel steering system has various advantages compared to the conventional two wheel steering system, which is higher stability when cornering. At high speed, as well as on wet slippery road surfaces, vehicle curve behaviour becomes more stable and controllable. Next is enhanced steering reaction and precision. The response of the vehicle to steering input is faster and accurate throughout the vehicle. Besides, high speed straight line stability. The straight-line stability of the vehicle during high speed is getting better resulting in the reducing of the negative effects of the road irregularities and crosswinds. Furthermore, the advantage of four wheel steering system is enhanced rapid lane-changing manoeuvres. The stability of the car during the lane changing at high speed is enhanced which making the car less possible to go into spin even when the driver needs to change course abruptly and quite extensively. The four wheel system is effective in various driving situations such as lane changes, gentle curves, junctions, narrow roads, U-turn and parallel parking (Singh et al., 2014).

2.2.3 Rack and pinion

Rack and pinion steering system has becoming the most popular steering device for various automobiles like cars, small trucks and SUVs. It is a quite simple mechanism. A rack and pinion is encircled by a metal tube with each end of the rack protrude outwards of the metal tube. The pinion gear is connected to the steering shaft and it will spins according to the movement of the steering wheel whether to the right or left resulting in the movement of the rack. The rack and pinion have two functions which are transforming the turning action of the steering wheel into the linear motion necessary to control the wheels and making the wheels much easier to control by providing a gear reduction (Karim Nice, 2001).

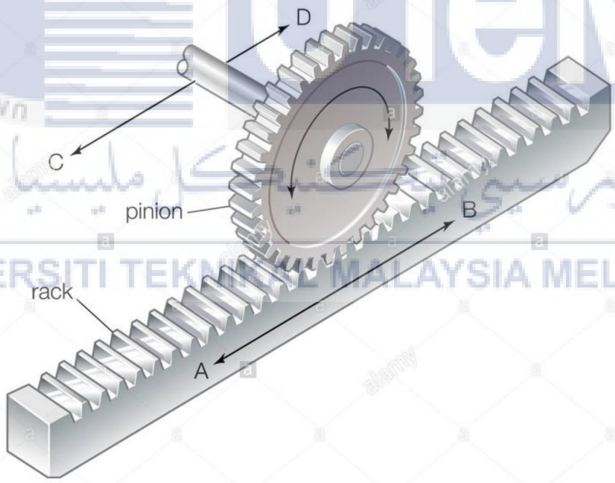

Figure 2.5: Rack and pinion

The most commonly used steering system in passenger cars is rack and pinion steering system compared to other steering system because of its design simplicity and compactness. Central take-off and side take-off is the two usual configuration of the rack and pinion steering system (Rahmani Hanzaki, Rao, & Saha, 2009).

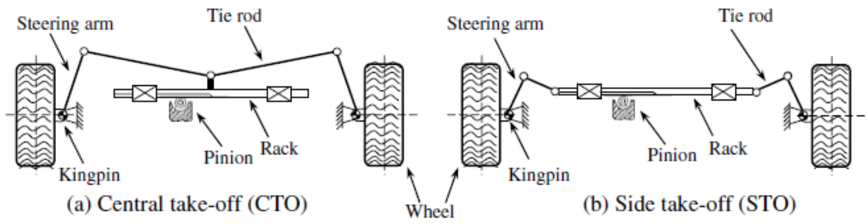

Figure 2.6: Rack and pinion steering system and its configuration

Rack and pinion steering system has some advantages and also disadvantages. Some of the advantages are it is not a complicated kind of construction, economical and easy to manufacture and easy to use because of high efficiency. Despite all these advantages, there are a few disadvantages which are increasing of sensitivity to impacts, steering wheel disruption can be felt easier, cannot be used on rigid axles and lower steering ratio resulting in tougher steering during parking unless the vehicle have power-assisted steering (Reimpell, Stoll, & Betzler, 2001).

The steering ratio is ratio of how far the steering wheel can be turn to how far can the wheels turn. A higher ratio means that the steering wheel need to be turn a lot more to make the wheels to turn at a certain distance but it will be easier to turn the steering wheel. A lower ratio means that the steering wheel need to be turn a lot lesser to make the wheels to turn at certain distance but it will be tougher to turn the steering wheel. Most of the larger and heavier vehicle have higher steering ratio that resulting the steering wheel to be much easier to turn. But it is very different compared to race cars which typically have a very low steering ratio making the steering wheel harder to turn.

2.2.4 The recirculating ball steering

The recirculating ball steering also converts steering input from the driver for turning the wheels. Most truck and SUVs now use recirculating ball steering. The relation between the wheels is slightly different than that of a rack-and-pinion system. A block with threaded hole consist a worm gear is found within the recirculating ball steering system. This block has gear cut in its exterior which includes a mechanism that drives the pitman arm. Pitman arm is a car or truck steering component which the angular movement of the sector shaft into the linear movement needed to guide the wheels.

Figure 2.7: Pitman arm

This kind of steering system is more complex in passenger cars with individually or independently suspended front wheels. It also more expensive compared to the rack and pinion steering system. Nevertheless, the steering elastically is sometimes greater, reducing reaction and steering sensation within the on-centre distance (Reimpell et al., 2001).

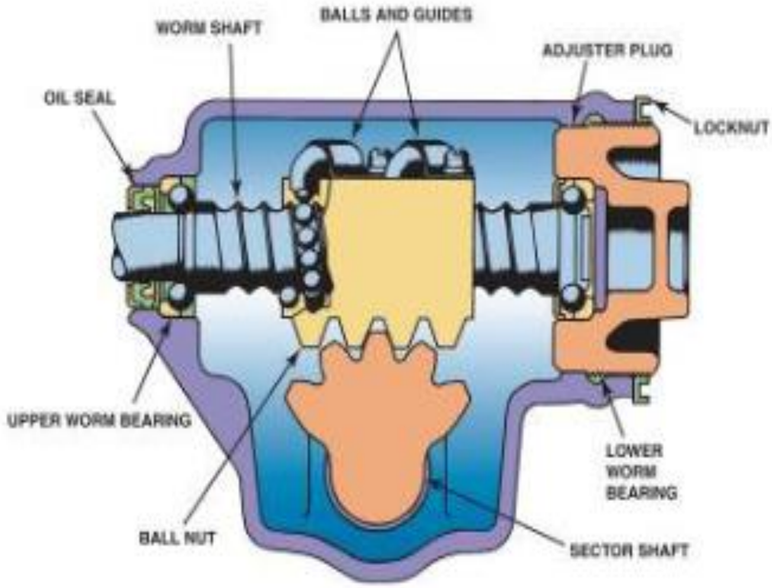

Figure 2.8: Recirculating ball steering

As the worm spins, the nut moves up and down the worm threads. Not only does the ball bearing reduce friction between the worm and the nut, the wear actually decreases significantly because the balls recirculate constantly through the system, which stops just one region from bearing the brunt of the wear.

2.3 Steering cradles or subframes

A cradle is an important component of a vehicle with various functions. Engine cradles first emerged in the late 1960s and were used to improve the ride comfort and handling capability of luxury cars. The energy-absorption and force-distribution capabilities have also improved significantly due to the introduction of the cradle. The cradle will lower the production time and the costs as well as making the broken parts to be easily removed by the mechanics. Thus, reducing the restoration times and maintenance expense. The weight of the vehicle increases because of the addition of the cradle which can affect the fuel efficiency and also increased carbon emission. The development process such as CAD modelling, numerical analysis and physical testing will increased the process period and the cost of product development will increase (C. Li, Kim, & Jeswiet, 2015).

Subframes are functional structures designed to carry specific components of the vehicle, such as the motor or axle and suspension. The aim of using an automotive subframe is to spread large local loads across a wider area of the body structure and making the vibration and harshness separated from the body structure. The subframe is attached and or welded to form a single unit, which is connected to the framework of the car or cabin. The subframe must be designed to minimize weight, but without losing the strength because it holds the vehicles engine load, suspension and steering parts (Dash, 2015)

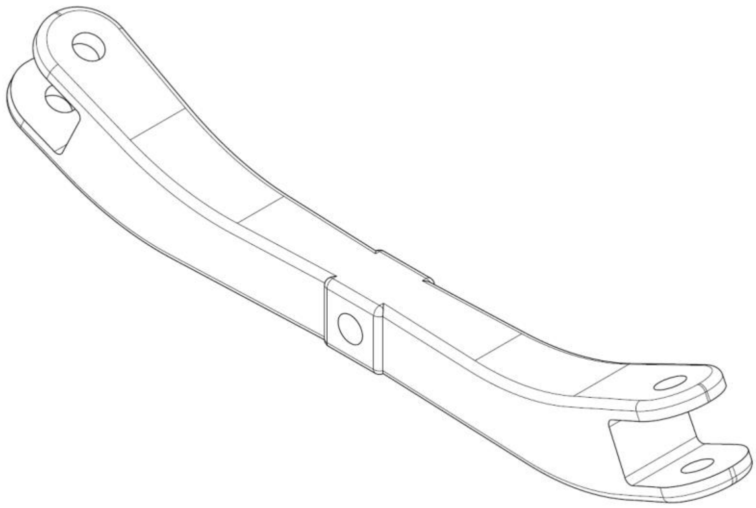

Figure 2.9: Subframe or cradle

Pressed steel panel is the material that is usually used to make a subframe which is much thicker compared to the body shell panels. Basically there are three basic forms of the subframe or cradle. One of them is a simple axle type where the lower arms and steering rack usually carried. Next is a perimeter frame where the above components are carried and also act as a support for the engine. Lastly, a perimeter frame where the above components are carried and also where the engine, transmission and full suspension are supported (Dash, 2015).

2.3.1 Material of the cradle or subframe

In order to provide excellent road communication, the subframes must be robust and compact, and to guarantee high comfort for occupants regardless of unevenness in surface area. So the most suitable material for the cradle or subframe is aluminium. The general benefit of light weighting, light weighting of unsprung masses decreases friction forces and provides a smoother ride. The manufacturing costs of aluminium subframes can be minimized by using properly designed high-quality aluminium castings depending on the production volume. In addition, removing or reducing assembly joints increases the subframe's overall performance. The use of aluminium resulted in a weight reduction of 30% compared to a similar axle made of steel, reducing the unsprung mass of the car.

2.4 Analysis of the steering cradle using Finite Element Analysis (FEA)

Analysis includes the analysis of materials through the application of external factors such as weights, temperature, pressure etc., and the obtaining of stresses (bending, tangent, and normal), etc. in order to determine the safety of the components when executed in practical use. This analysis obtains the optimal result for system protection and minimizes failure chances. The analysis is done by doing simulation using Finite Element Analysis (FEA) which is less expensive and can reduce the time consuming for the experiment.

Finite element analysis (FEA) is a computerized system of research to analyse how a manufactured product would respond to the physical world. The testing or analysis involves getting the material into interaction with the force, temperature, vibration, liquid motion and other physical conditions. The FEA will determine whether the material is likely to break, tear, strain or behave the way it is made. FEA basically measures the actions of the individual components and analyses them in order to predict the aggregate activity of the product that has been manufactured. Today, FEA typically uses computers to design the object, which is then stimulated and evaluated to achieve the desired results. The subframe will be evaluated in term of stiffness, strength, stress and deflection.

One of the advantages of the Finite Element Analysis (FEA) is it can be used to analyse various type of problems such as irregular geometries, different material properties, different boundary conditions, variables element types and size, and easy modification.

2.4.1 Stiffness

The stiffness, k, is the level to which the material avoids deformation in response to the pressure applied.

$$k = \frac{F}{\delta} \tag{2.1}$$

Where, F is the force acting on the body.

δ is the displacement produced by the force along the same degree of freedom.

2.4.2 Strength

In mechanics of material, the durability of a component is its ability to withstand applied loads without collapse or plastic deformation. The strength of materials deals with the stresses and deformations arising from their impact on a products or material. The forces that work on the surface allow the materials to bend in different ways, like completely breaking them. Yield strength and tensile strength are some of the strength's parameters. Yield strength is the lowest strain resulting in a component being permanently deformed. Tensile strength or also known as ultimate tensile strength is restricted condition of the tensile stress that contributes to a tensile failure in the manner of a ductile failure.

2.4.3 Stress

- Stress, σ, is defined as the force per unit material of the material.

$$\sigma = \frac{F}{A} \tag{2.2}$$

Where, F is the force applied

A is the cross sectional area of the object

- Strain, ε, is defined as the extension per unit length.

$$\varepsilon = \frac{e}{l_{\circ}} \tag{2.3}$$

Where, e is the extension

l is the stretched length

- Young Modulus, E, the gradient of the straight line graph which is a constant and does not change for given material.

$$E = \frac{Stress}{Strain} = \frac{\sigma}{\varepsilon} \tag{2.4}$$

2.4.4 Deflection

Deflection, in structural engineering terms, means the displacement of a beam or node from its original position due to the stresses and loads applied to the component. It may result from external loads applied, or from the weight of the system itself, and from the force of gravity in which it is applied. Deflection can occur to any type of structures whenever there is a force applied to it. Beam deflection is measured on the basis of a variety of factors, including the materials of the components, the moment of inertia of the component, the pressure applied and the distance from the support.

The term deflection generally refers to the deformed shape and location of a component subjected to bending loads. Excessive deflection of the structural component results in a geometric distortion of the entire structure, whereas excessive deflection of the mechanism can result in disruption between moving parts, thus increasing the rate of wear or total failure due to broken or stuck parts (Agarwal, 2018).

$$\frac{d^2y}{dx^2} = \frac{M}{EI} \tag{2.5}$$

Where, E is the Young's Modulus

I is the moment of inertia

M is the internal bending moment in the beam.

2.5 Factor of safety

A factor of safety is the load-bearing capacity of the system beyond what the system actually supports. Bridges, houses, safety equipment and drop prevention equipment all start with a safety factor. Safety factor expresses how much more powerful a system is than it should be. Safety factor is the ratio of absolute strength (structural capacity) of a structure to actual load applied; this is a measure of a particular design's reliability. Usually, systems are designed stronger than necessary to ensure durability. This is the case where a system has a heavier-than-expected load. A safety factor improves a person's protection and reduces the risk of a product malfunction. The safety factor is highly important when it comes to security equipment and drop protection. If the system collapses, there is a risk of injury and death, as well as a financial loss of the business. The safety factor is greater if there is a chance that the error could occur in these issues.

There are several methods to assess the safety factor of structures. Essentially, all the various equations calculate the same thing that is how much stronger a system is than it should actually take.

$$Factor\ of\ Safety = \frac{Yield\ Strength}{Maximum\ Stress} \tag{2.6}$$

The factor of safety for most cars is 5. So the factor of safety obtained from this analysis and experiment will be compared whether it is greater than 5 or lower than 5. The performance of the vehicle can be determined after comparing the factor of safety.

CHAPTER 3

METHODOLOGY

3.1 Overview

Methodology is a problem-solving guidance system with specific components such as phases, tasks, processes, procedures and tools. This chapter describes the methodology used in this project to obtain the data. All the flow and plan on how to complete this project are explained. This project is focused on the result of the safety factor obtained from the analysis in order to determine the suitable thickness of the credle or subframe, thus determine the performance of the vehicle. Figure 3.1 below shows the flow chart of this project from the beginning to the end. This project started with an experimental setup. Then the data is collected by using the Finite Element Analysis (FEA). The data obtained from the FEA is then used to calculate the factor of safety. Finally, the report will be written to obtain the performance of the vehicle.

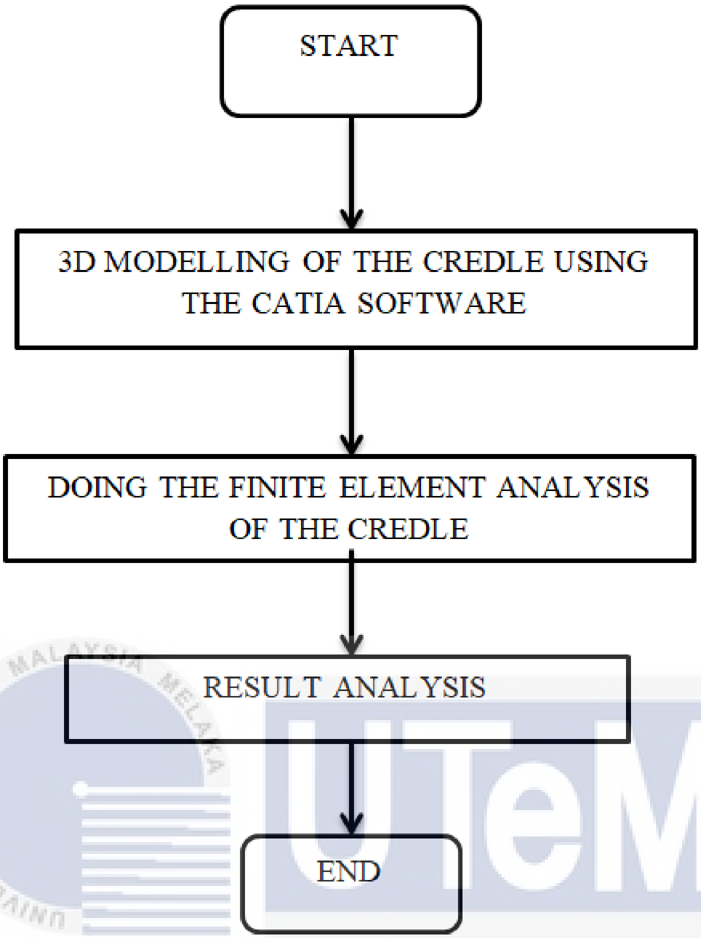

Figure 3.1: Flow chart of methodology

3.2 Experimental setup

This section will explain the details step in order to run this experiment or analysis to determine the safety factor of the cradle. The first step is sketching the suitable design for the credle or subframe with accurate dimension. The detailed design is then drawn into the CATIA software. After the design is finished drawn into the CATIA, the analysis is then run to obtain the result of stress, and etc. The manipulated variable of this experiment is the thickness of the wall of the cradle of subframe.

3.3 3D modelling using CATIA software

The 3D modelling of the cradle is started by sketching the design of the cradle roughly. The design is then drawn in the CATIA software based on the dimension from the sketched cradle that is suitable for real life usage. The design is using hollow type of cradle so that the thickness of the wall will be the manipulating variable.

3.4 Finite Element Analysis of cradle

The analysis is carried out by using Finite Element Analysis (FEA) software to find out stress. By using the result of the stress, the suitable thickness of the wall of the cradle can be determined. The analysis of the cradle will be done during the steady state of the cradle. The analysis of the component will be done in three dimensional (3D) states. The analysis will be done for both front and rear cradle with different amount of applied force.

The case of analysis that is conducted is where the distributed force is applied from the bottom as shown in the Figure 3.2 below.

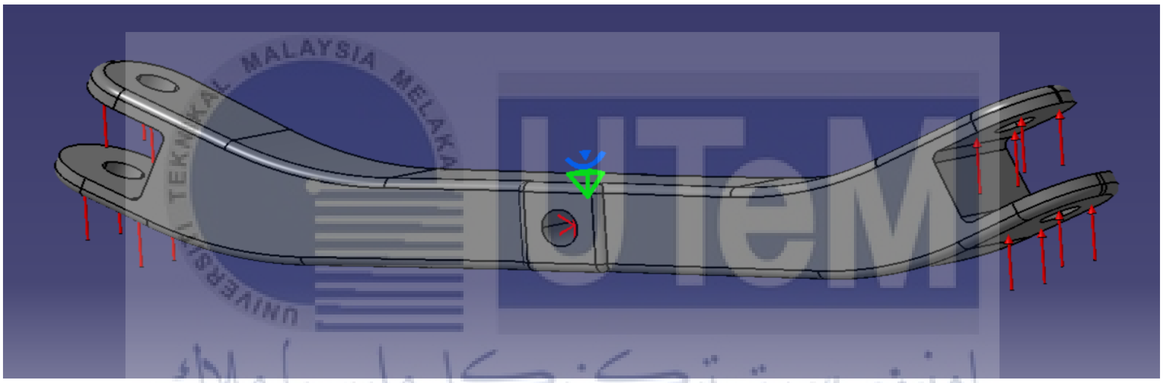

Figure 3.2: Force applied from the bottom

First and foremost is to create the part that the analysis will be done which is the cradle or the subframe. The part will be done according to the real life dimension of the part. The material of the part should be applied first, which is in this project the material is the aluminium. This is a very important step because the simulation cannot be run if the material is not applied to the component. Figure 3.4 shows the physical properties of the aluminium: Young's Modulus (7 x 10^{10} N/m^2), the coefficient of Poisson (0.346), density (2710 kg/m^3), coefficient of thermal expansion (2.36 x 10^{-5} K) and yield strength (9.5 x 10^{7}N/m^2).

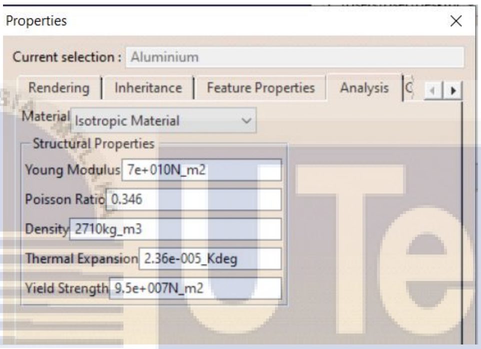

Figure 3.3: Physical properties of aluminium

To start the analysis, the model from the Part Design workbench will be transfer into the Generative Structural Analysis workbench and set up the type of analysis case as the Static Analysis.

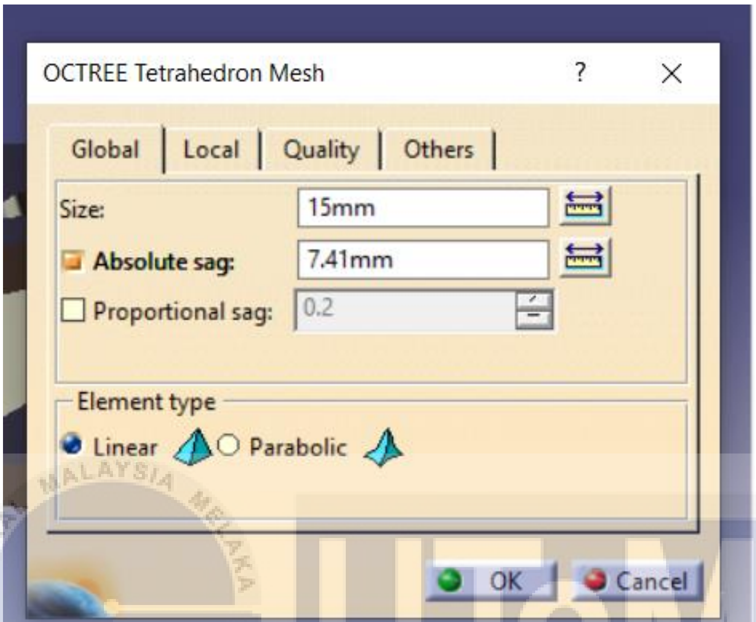

Figure 3.4: Mesh size used for the analysis

Figure above shows the size of the mesh used for the analysis of both front and rear cradle which is 15mm and the absolute sag is 7.41mm.The smaller the size of the mesh, the more accurate the analysis.

The Clamp restraint is the applied to the surface of the cradle as shown in Figure 3.5 below. The Clamp restraint is applied to the pivot point of the cradle.

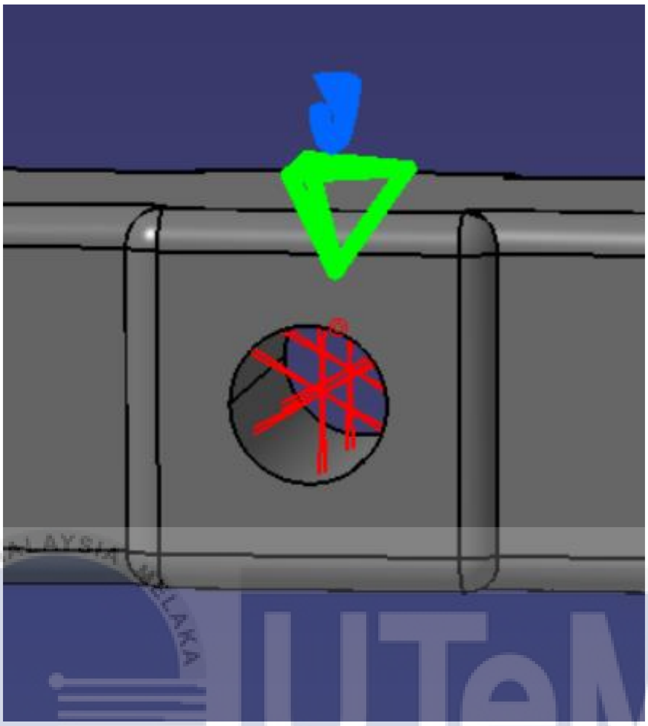

Figure 3.5: Clamp restraint at pivot point

The distributed forces are 883N for the front cradle and 417N for the rear cradle are applied to the cradle in the direction of Z axis at the place where the cradle is connected to the suspension at both right and left side as shown in the Figure 3.6 below.

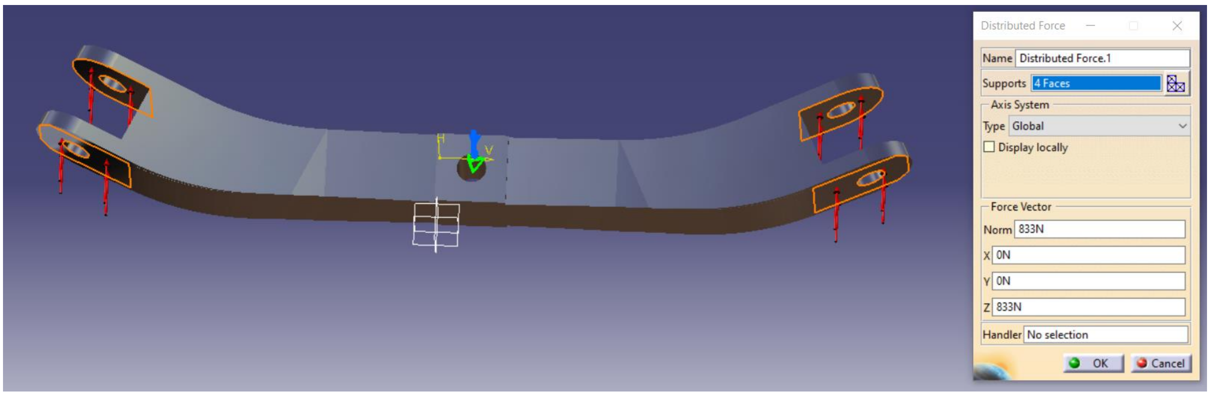

Figure 3.6: Distributed force applied to the front cradle

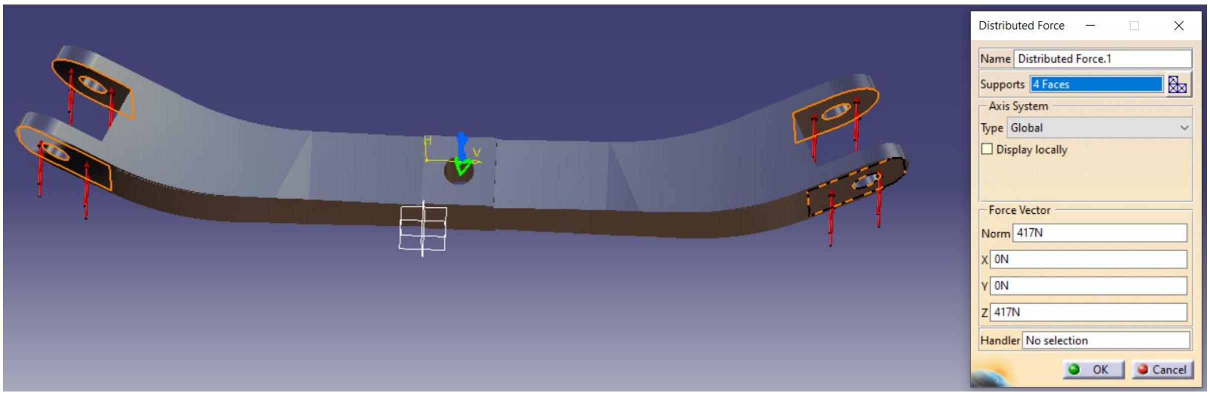

Figure 3.7: Distributed force applied to the rear cradle

The force is represented by eight arrows symbol for each side of the cradle and characterized by a value and direction. The next step is to calculate the model behaviour running the Compute routine as shown in the Figure 3.7 below.

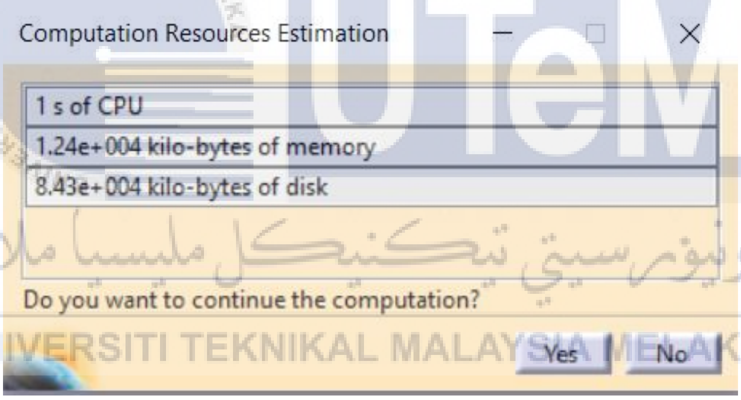

Figure 3.8: Compute routine

After the compute process is finished, the result of the analysis can be viewed according to the user's choice whether principal stress, Von misses stress, and displacement.

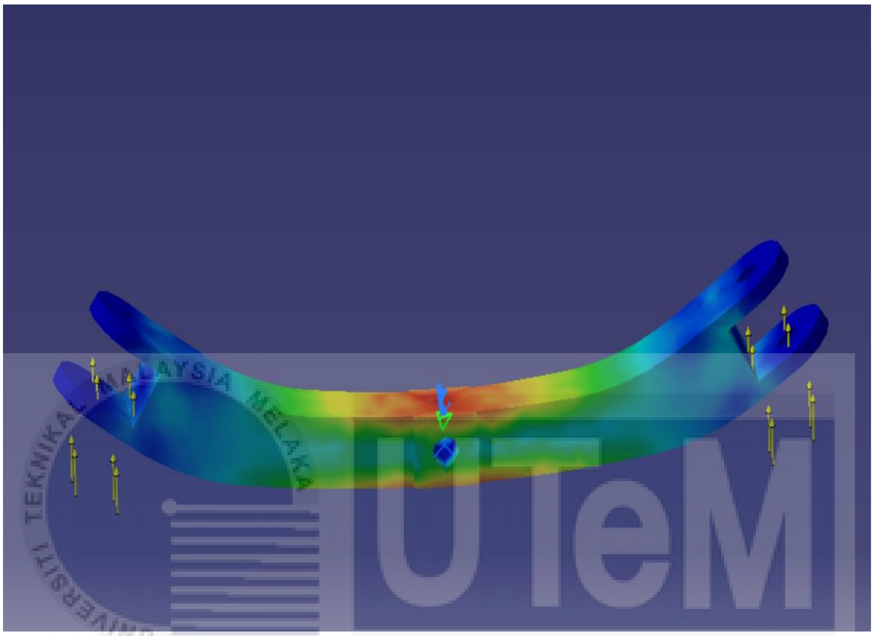

Figure 3.9: Von Mises Stress

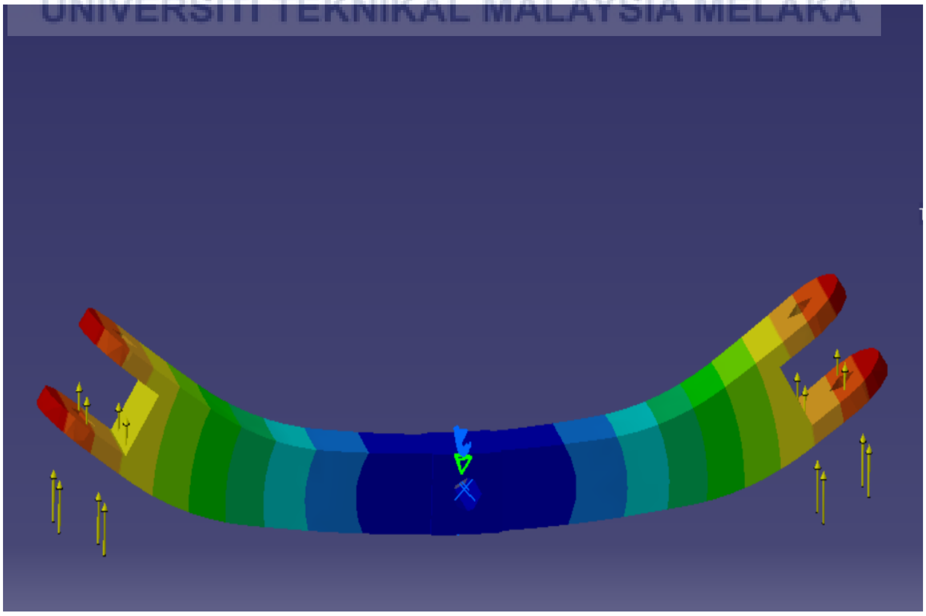

Figure 3.10: Displacement

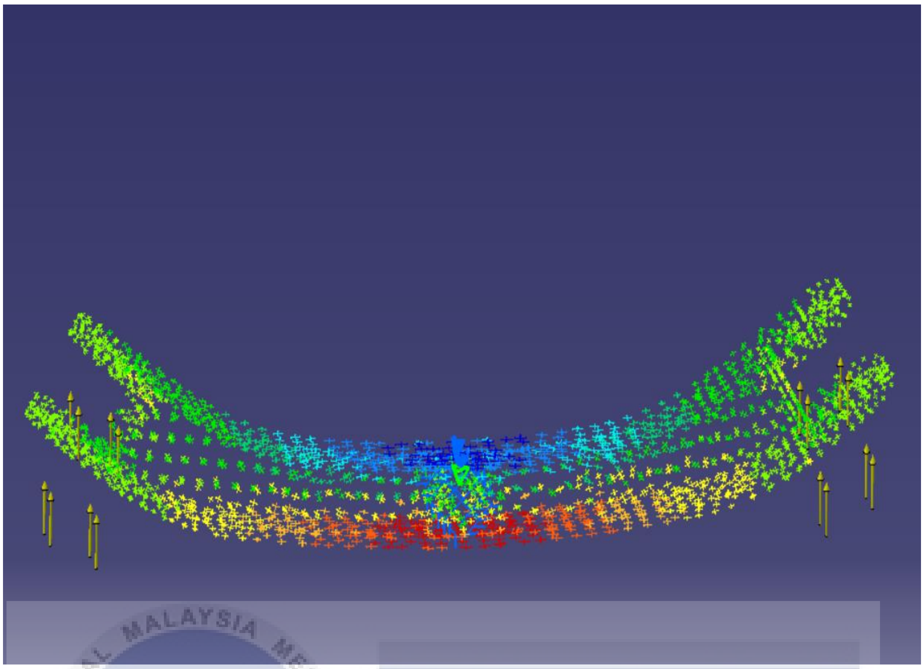

Figure 3.11: Principal stress

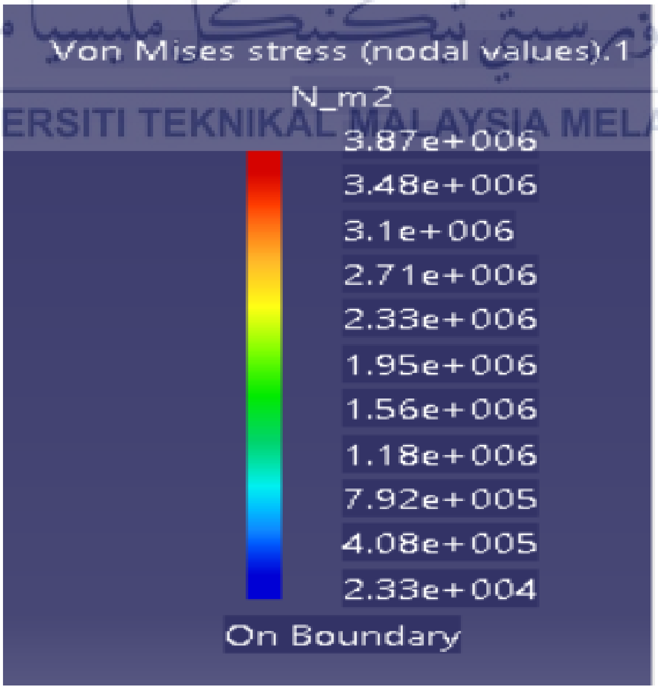

Figure 3.12: Stress value scale

The maximum and the minimum stress value can be obtained from the Stress Value Scale. From the Figure 3.11, the maximum stress is the one that is situated at the top of the scale or the red one on the scale which is (3.87×10^{6} N/m^2). As for the minimum stress that is at the bottom of the scale or the blue one on the scale which is (2.33×10^{4} N/m^2).

The finite element mesh or also known as grid generation is the way of producing a polygonal or polyhedral mesh that approximates a geometric domain. This process can make the problem solvable using finite element analysis. Meshing can increase the accuracy of the result of the analysis. There are a few types of meshing size which are course, medium and fine.

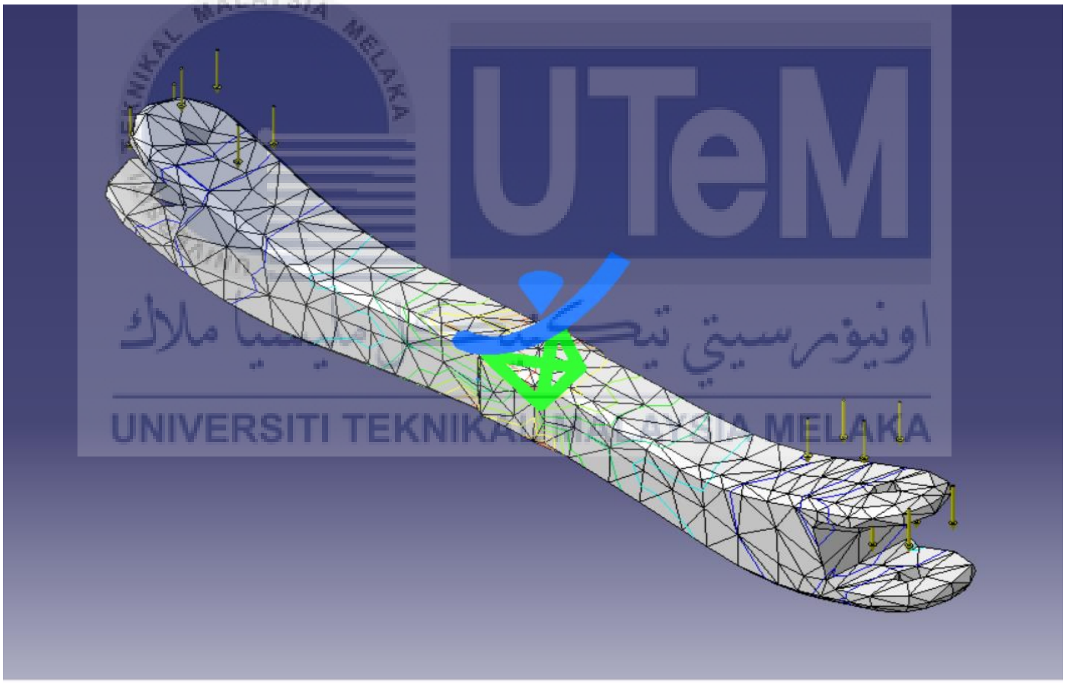

Figure 3.13: Coarse mesh

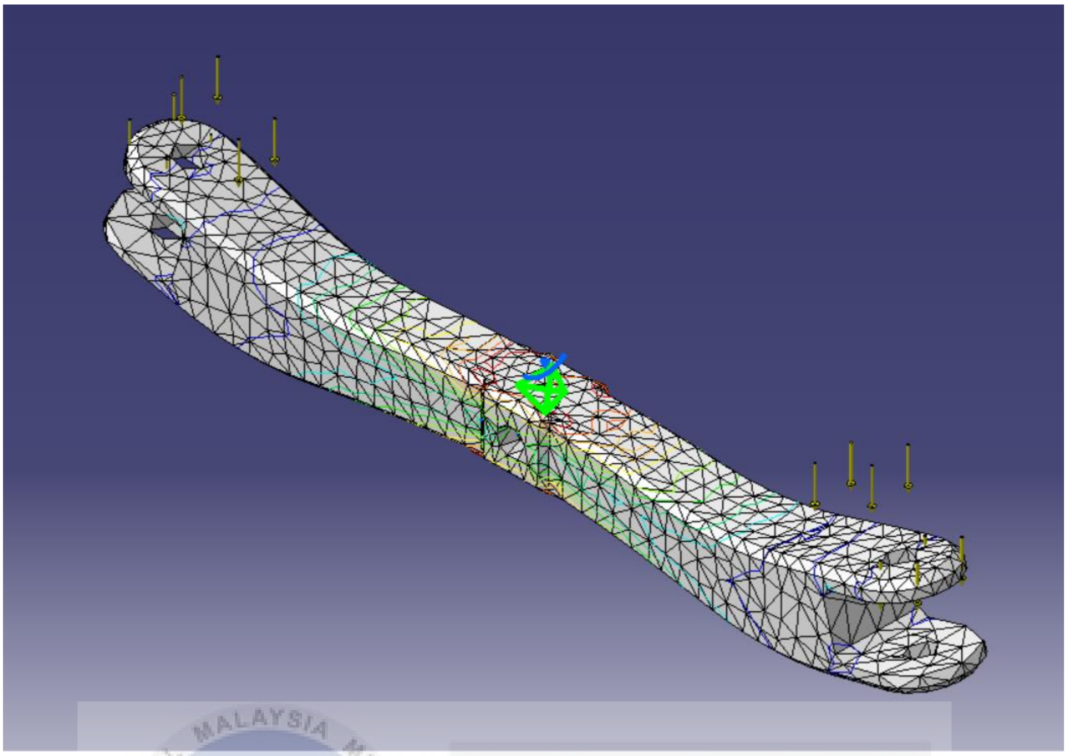

Figure 3.14: Medium mesh

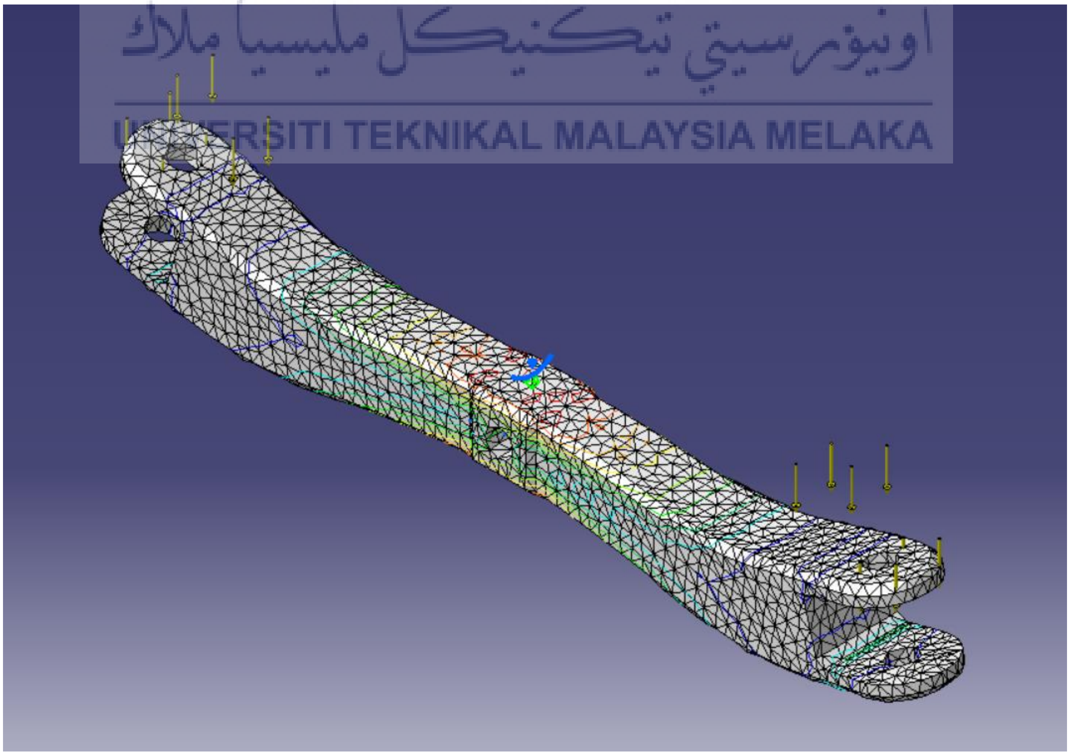

Figure 3.15: Fine mesh

3.5 Result analysis

The data obtain from the analysis will be used to calculate the factor of safety according to the different thickness of the wall of cradle. The calculated factor of safety is then compared to the theoretical factor of safety which is 5 in order to determine the most suitable thickness for the cradle to withstand all the stress. Thus, the performance of the vehicle can be determined at the end of the project.

CHAPTER 4

RESULT AND ANALYSIS

4.1 Introduction

In this chapter, the results for the analysis of the cradle using different thickness will be presented and discussed. The analysis is done by doing simulation using Finite Element Analysis (FEA). The thicknesses used are 6mm, 8mm, and 10mm and the analyses done on the cradle are Von Mises stress, displacement, and principle stress analysis.

4.2 Analysis of rear cradle

This is the analysis that has been done on the rear cradle. The analyses are Von Mises stress, displacement, and principle stress analysis. The amount of distributed force applied on the rear cradle is 883N. It is applied for both left and right side of the cradle.

4.2.1 Von Mises stress

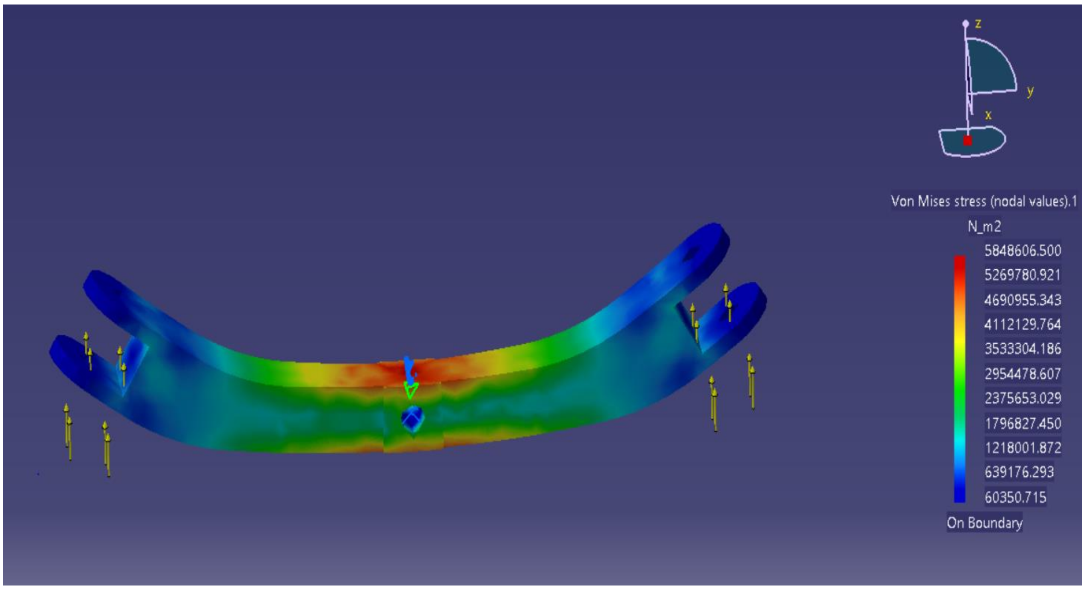

Figure 4.1: Analysis for 6mm thickness.

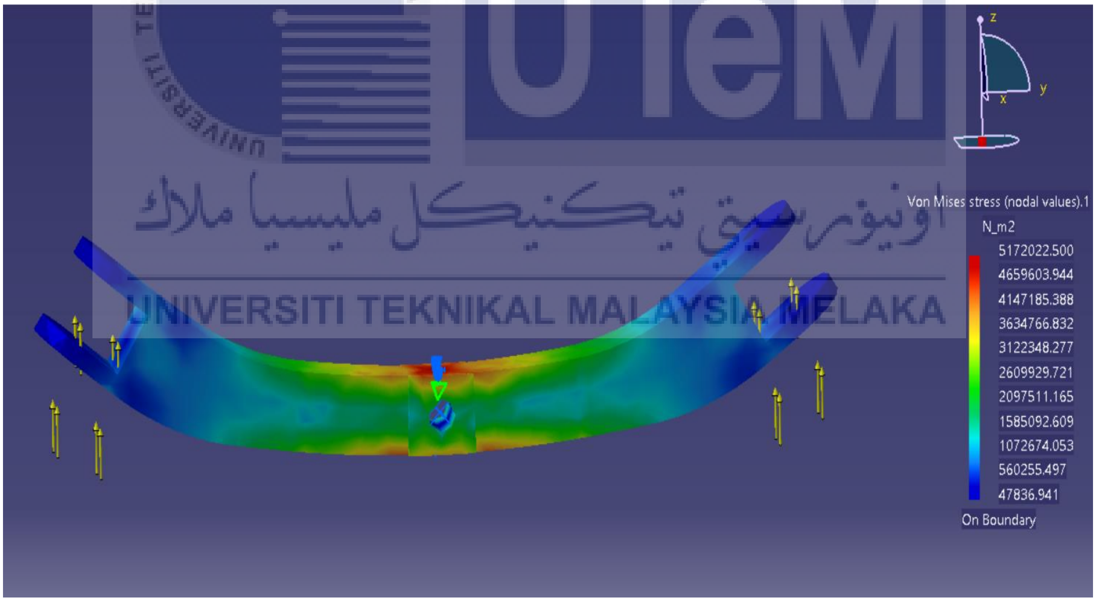

Figure 4.2: Analysis for 8mm thickness.

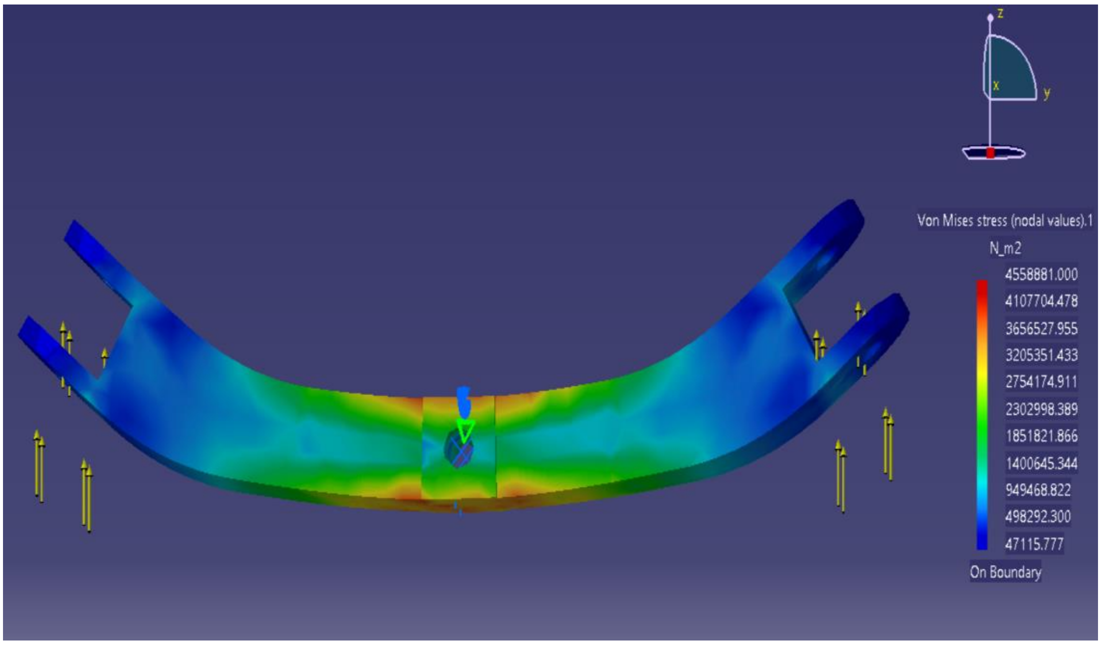

Figure 4.3: Analysis for 10mm thickness.

Table 4.1: Von Misses analysis of the rear cradle.

Thickness (mm)	Maximum Von Mises (N/m²)	Minimum Von Mises (N/m²)
6	5848605.500	60350.715
8	5172022.500	47836.941
10	4558881.000	47115.777

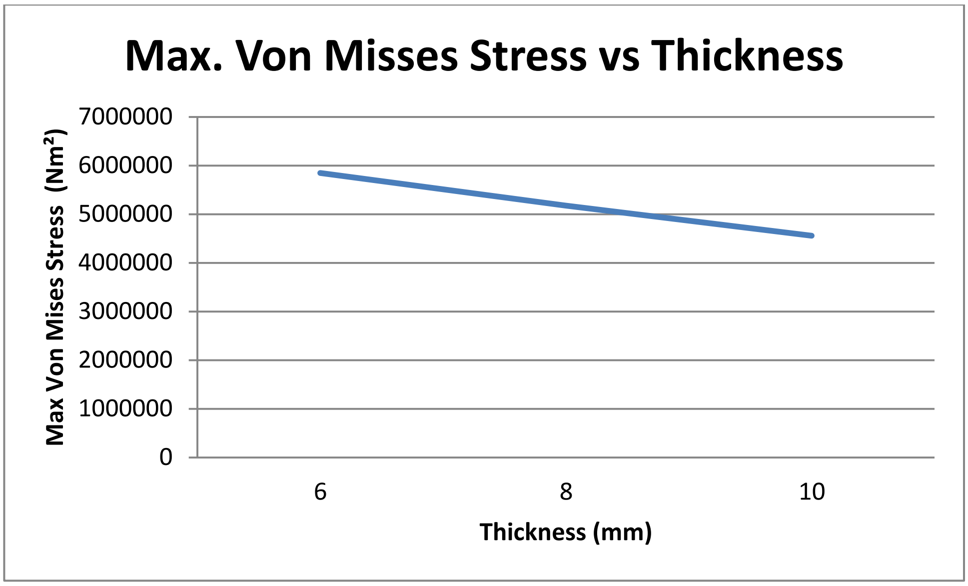

Figure 4.4: Graph of Maximum Von Mises stress against thickness.

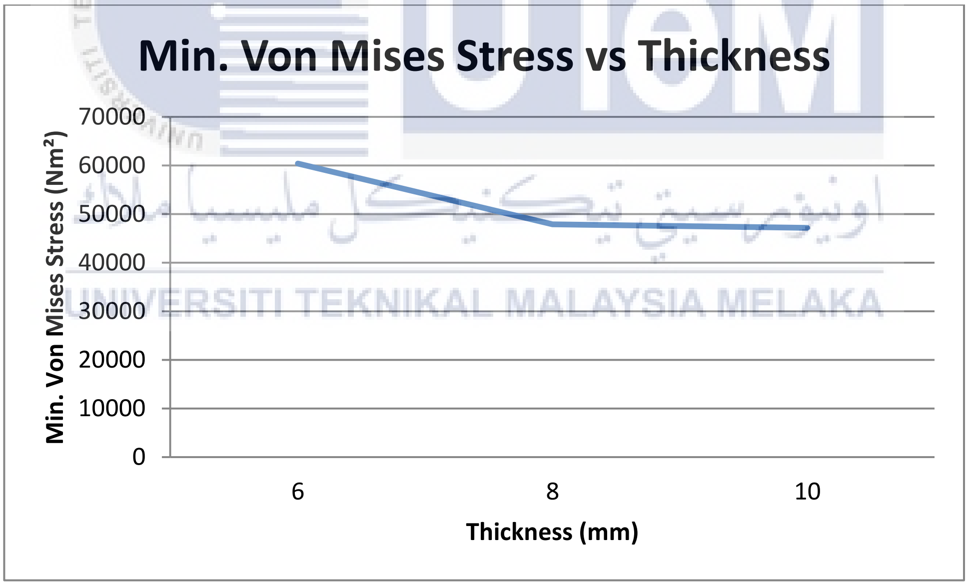

Figure 4.5: Graph of Minimum Von Mises stress against thickness.

4.2.2 Principle stress

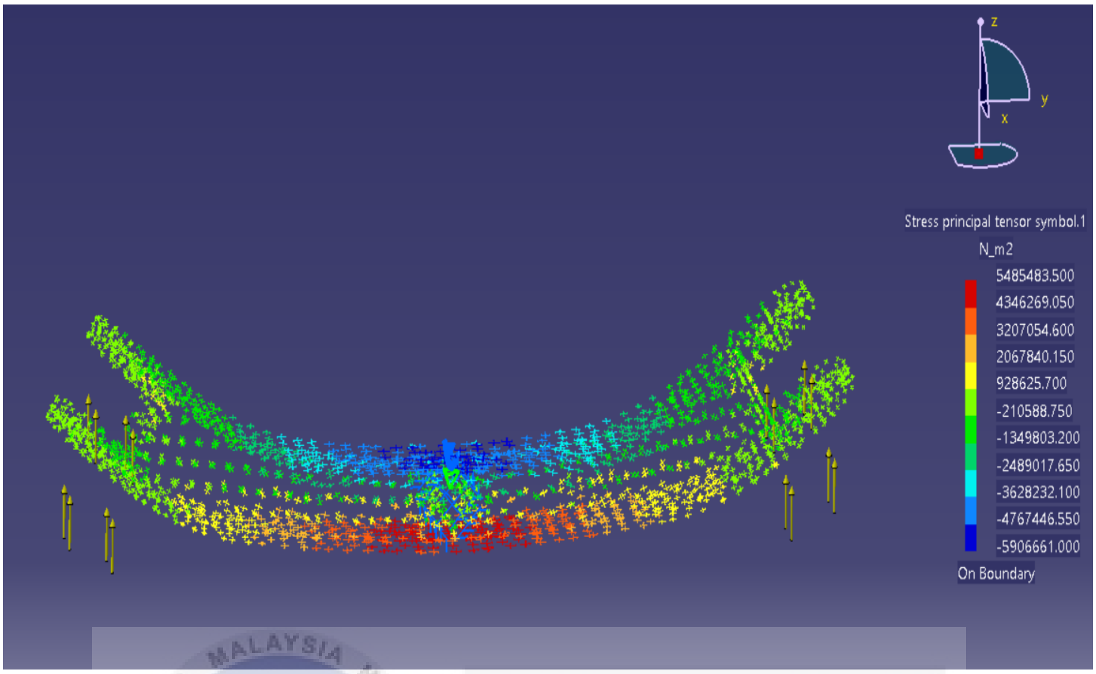

Figure 4.6: Analysis for 6mm thickness.

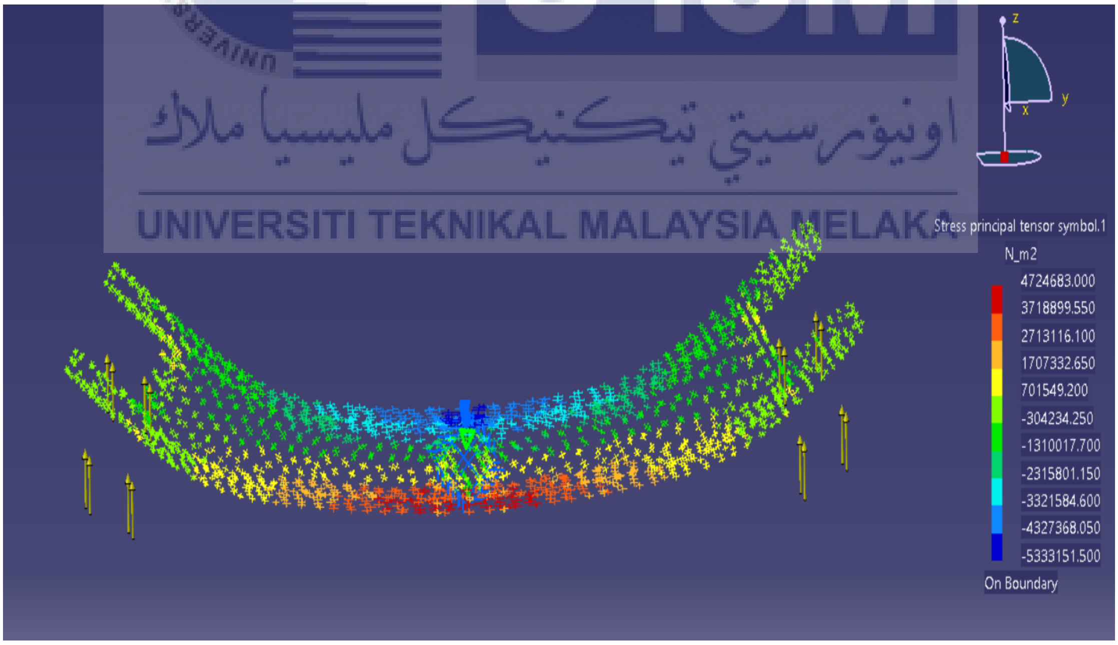

Figure 4.7: Analysis for 8mm thickness

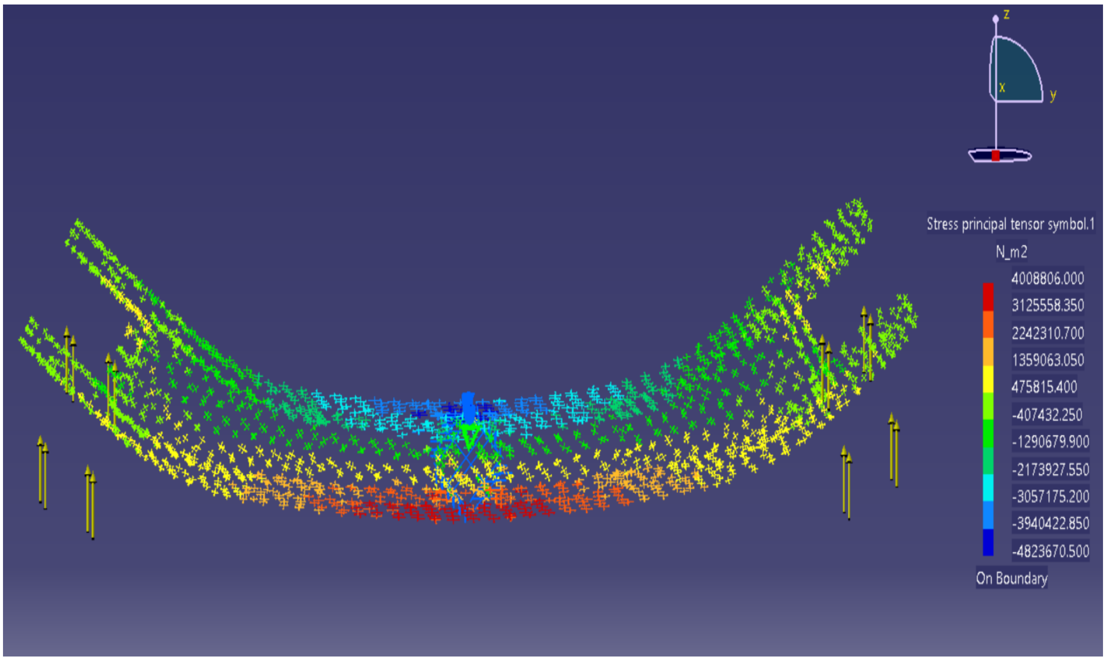

Figure 4.8: Analysis for 10mm thickness.

Table 4.2: Principle stress analysis of the rear cradle.

Thickness	Max. principle stress (N/m²)	Min. principle stress (N/m²)
6	5485483.500	-5906661.000
8	4724683.000	-5333151.500
10	4008806.000	-4823670.500

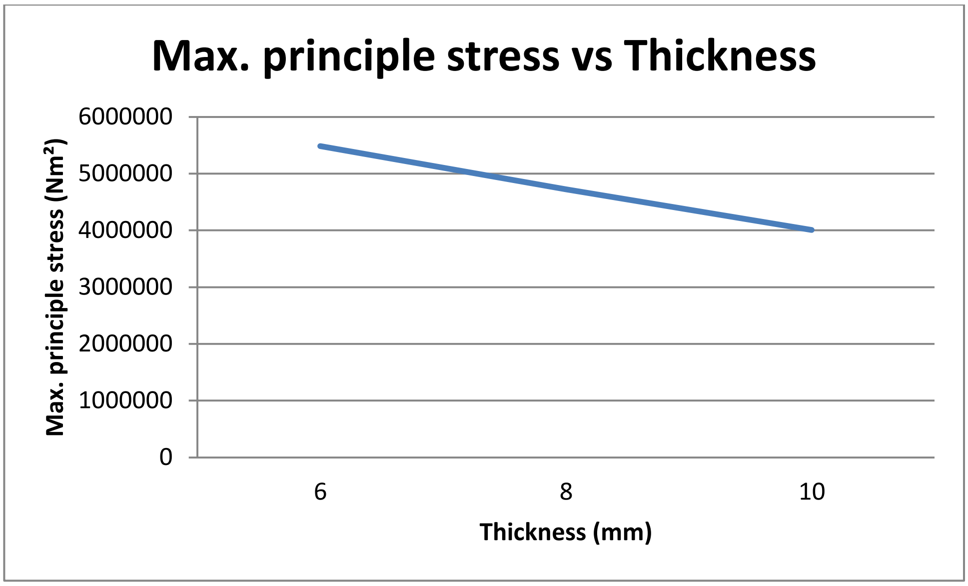

Figure 4.9: Graph of max. principle stress against thickness.

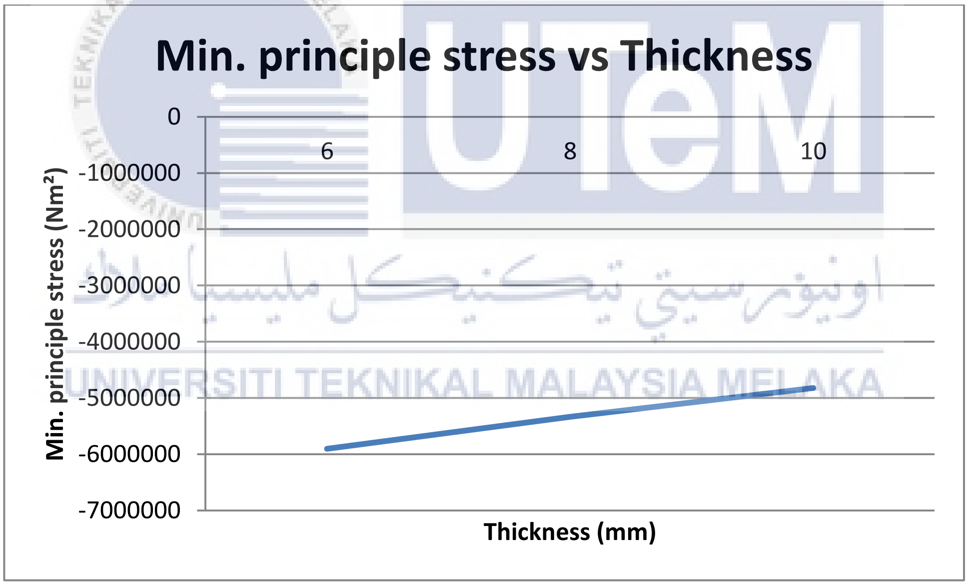

Figure 4.10: Graph of min. principle stress against thickness.

4.2.3 Displacement

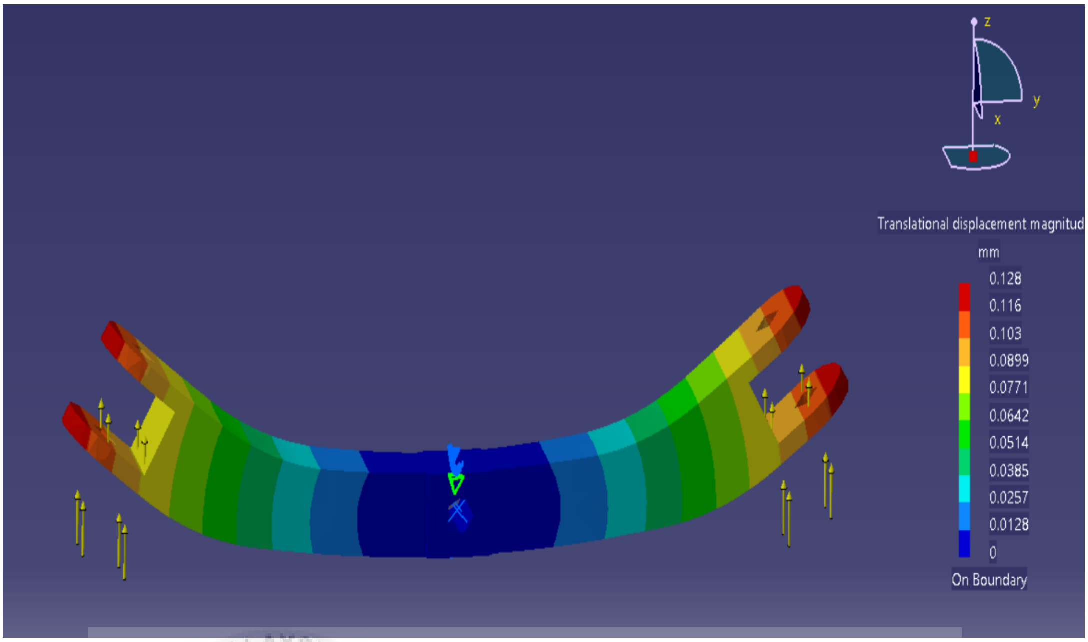

Figure 4.11: Analysis for 6mm thickness.

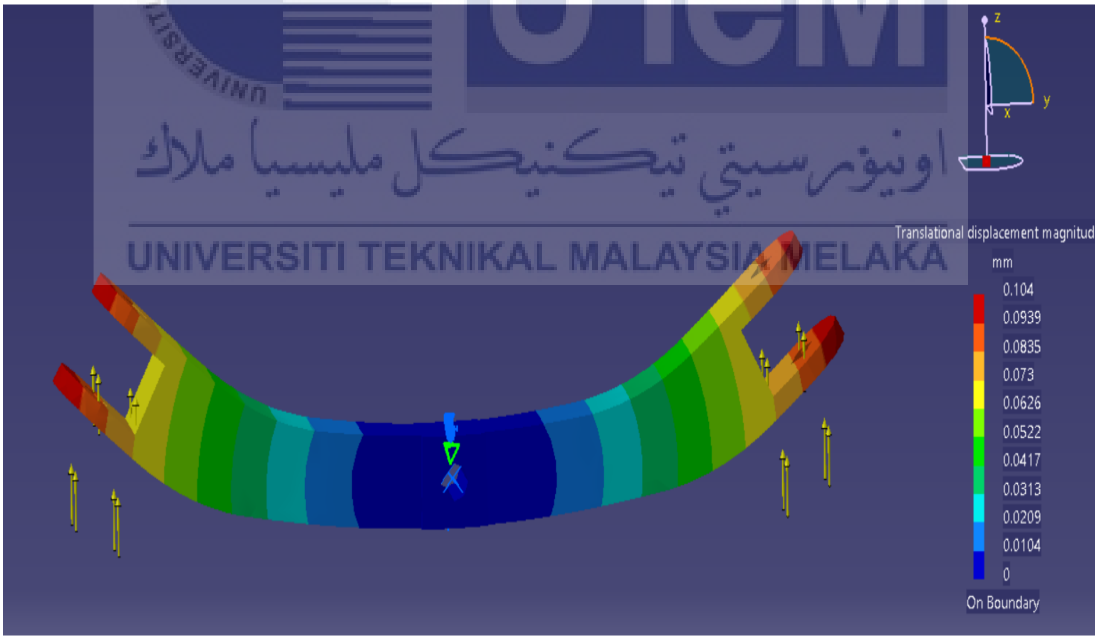

Figure 4.12: Analysis for 8mm thickness.

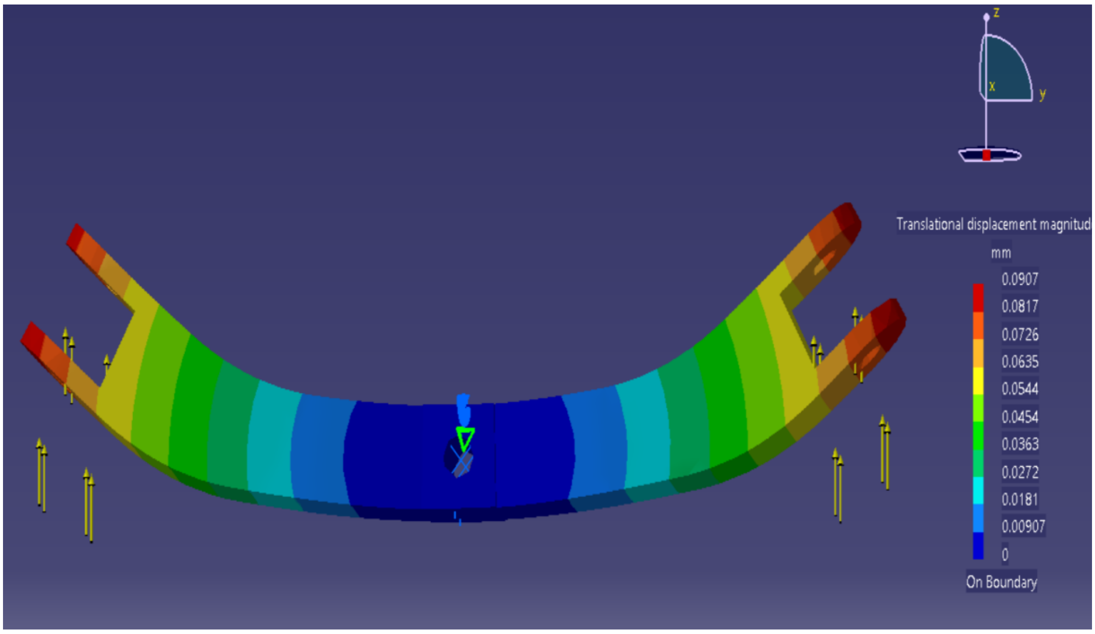

Figure 4.13: Analysis for 10mm thickness.

Table 4.3: Displacement analysis of the rear cradle.

Thickness (mm)	Displacement (mm)
6	0.1280
8	0.1040
10	0.0907

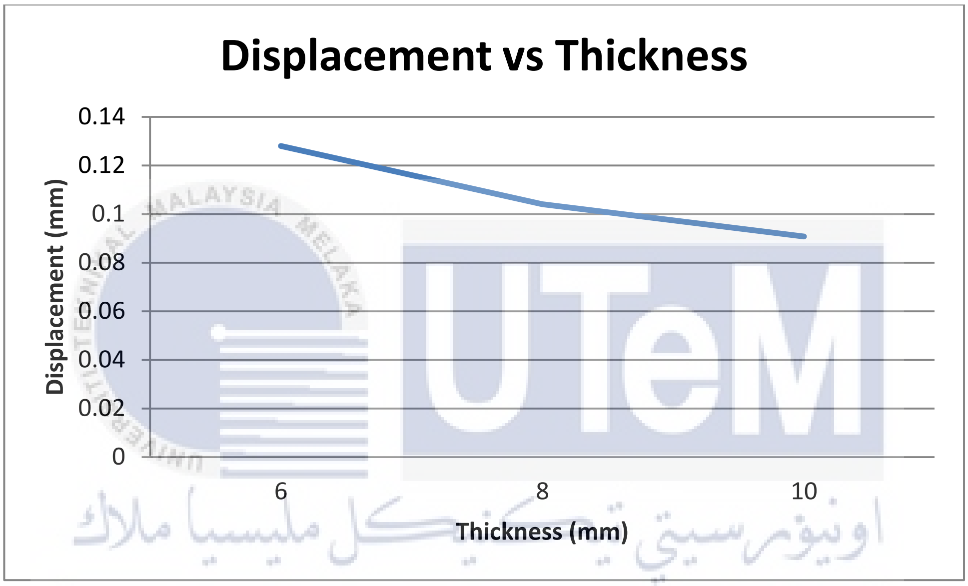

Figure 4.14: Graph of displacement against thickness.

4.3 Analysis of front cradle

This is the analysis that has been done on the front cradle. The analyses are Von Mises stress, displacement, and principle stress analysis. The amount of distributed force applied on the front cradle is 442N. It is applied for both left and right side of the cradle.

4.3.1 Von Mises stress

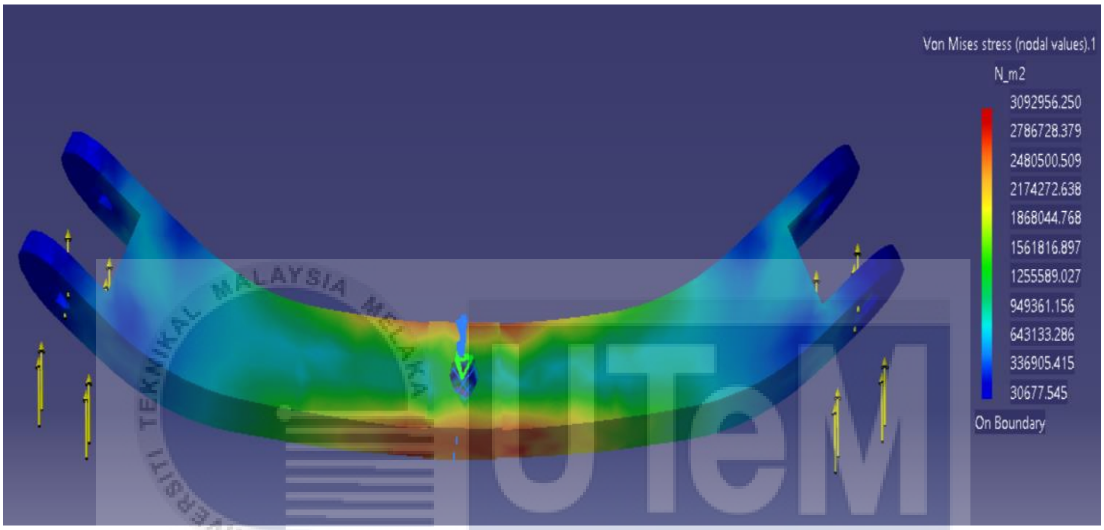

Figure 4.15: Analysis for 6mm thickness.

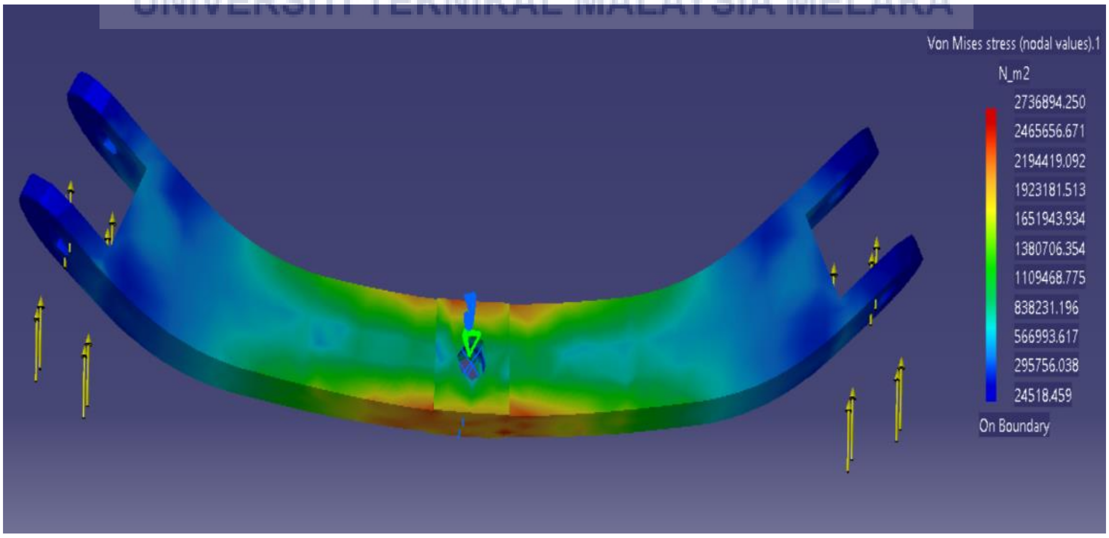

Figure 4.16: Analysis for 8mm thickness.

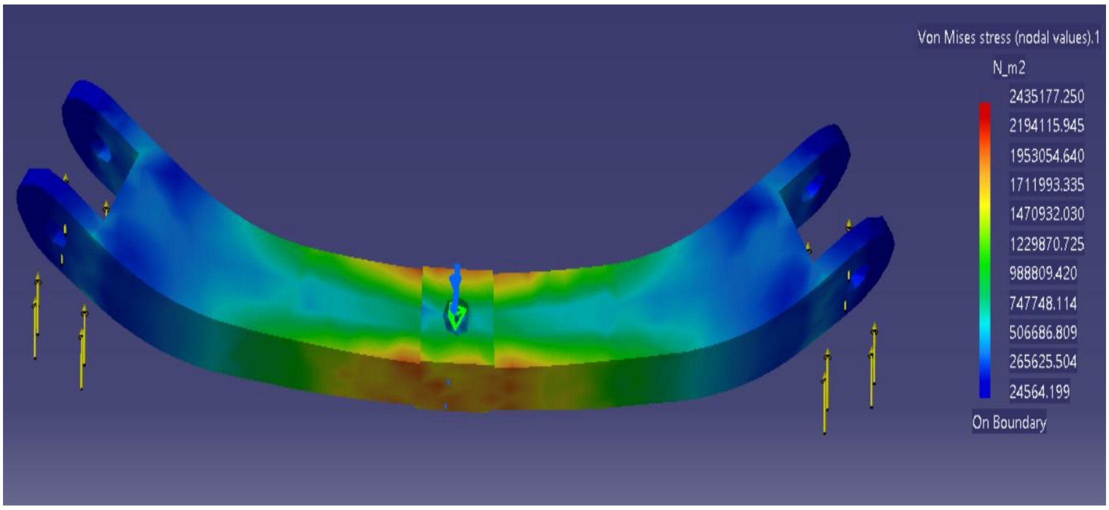

Figure 4.17: Analysis for 10mm thickness.

Table 4.4: Von Mises analysis of front cradle.

Thickness (mm)	Maximum Von Mises (N/m²)	Minimum Von Mises (N/m²)
6	3092956.250	30677.545
8	2736894.250	24518.459
10	2435177.250	24564.199

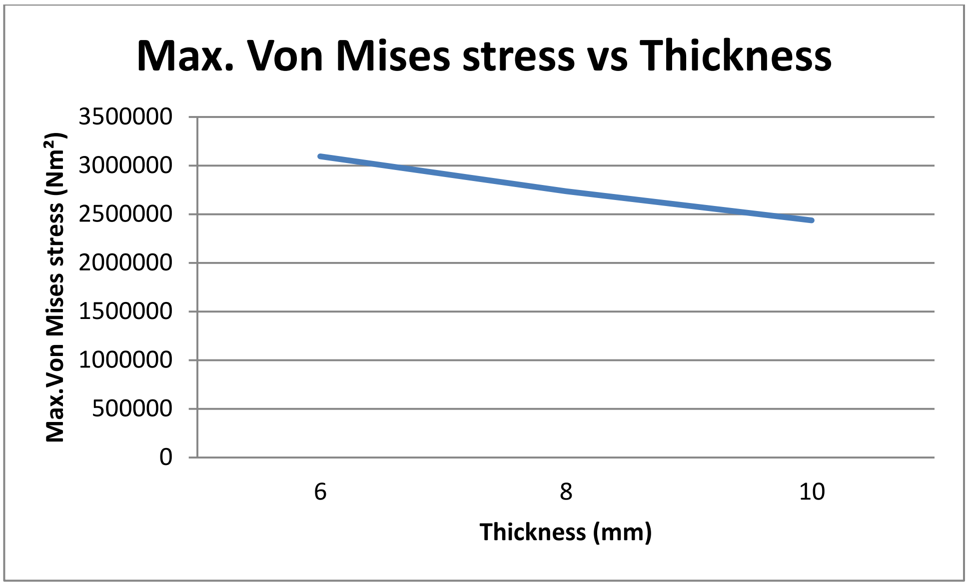

Figure 4.18: Graph of maximum Von Mises stress against thickness.

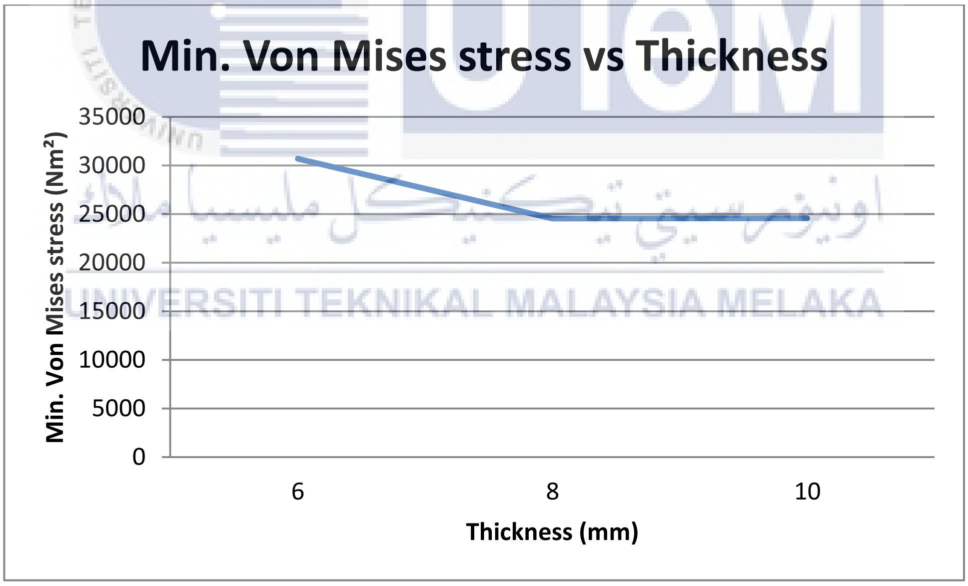

Figure 4.19: Graph of minimum Von Mises stress against thickness.

4.3.2 Principle stress

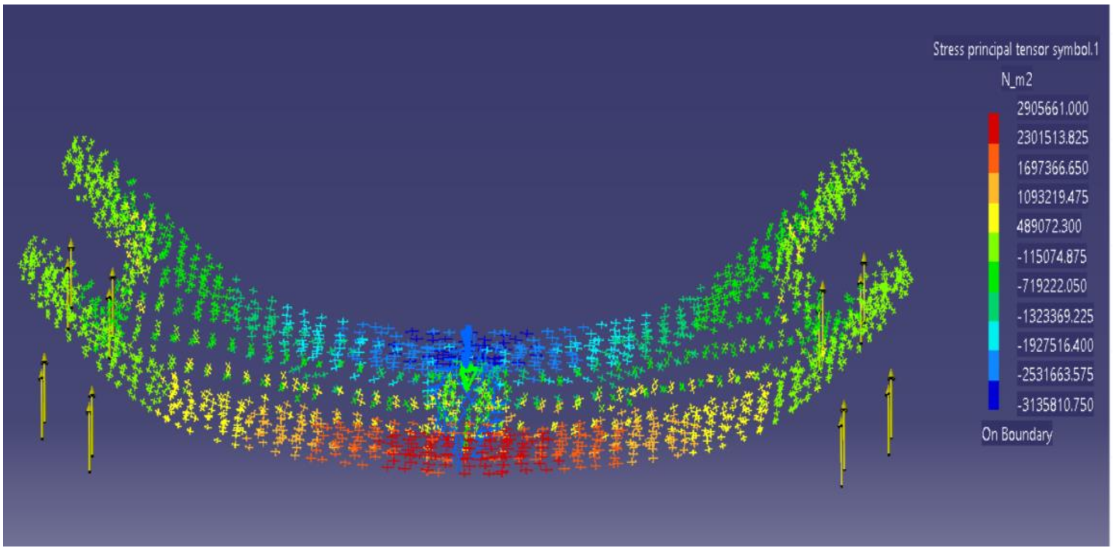

Figure 4.20: Analysis for 6mm thickness.

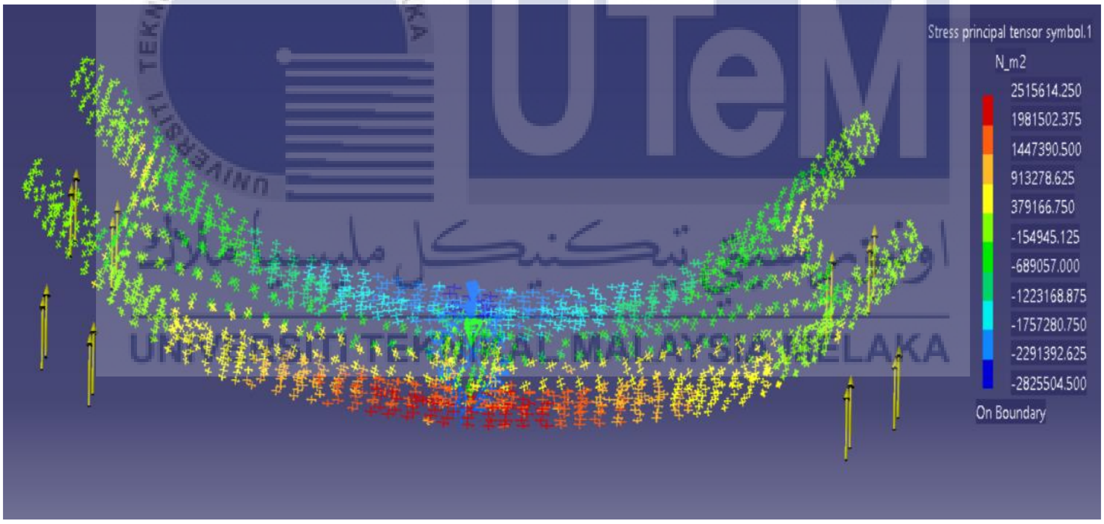

Figure 4.21: Analysis for 8mm thickness

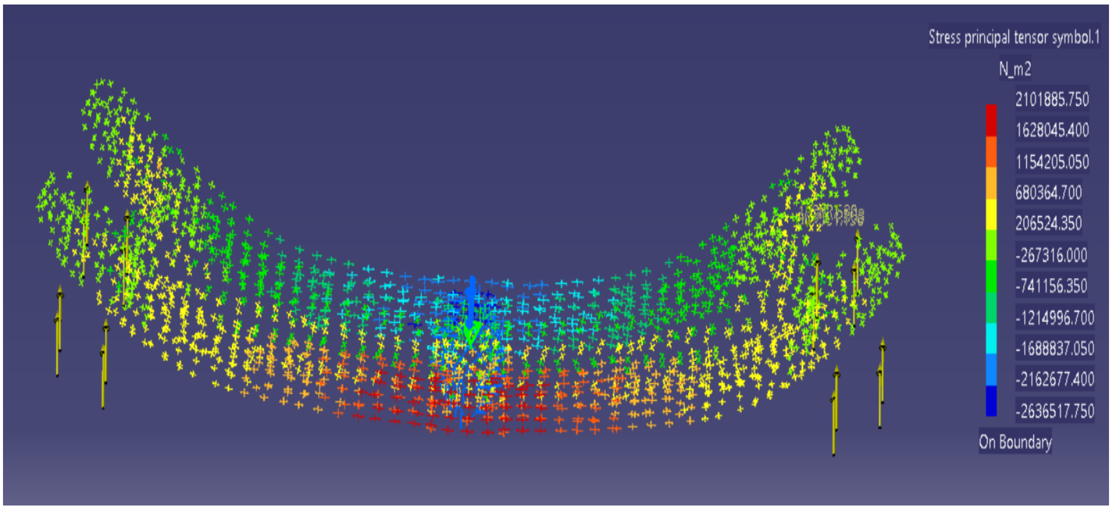

Figure 4.22: Analysis for 10mm thickness

Table 4.5: Principle stress analysis of the front cradle.

Thickness	Max. principle stress (N/m²)	Min. principle stress (N/m²)
6	2905661.000	-3135810.750
8	2515614.250	-2825504.500
10	2101885.750	-2636517.750

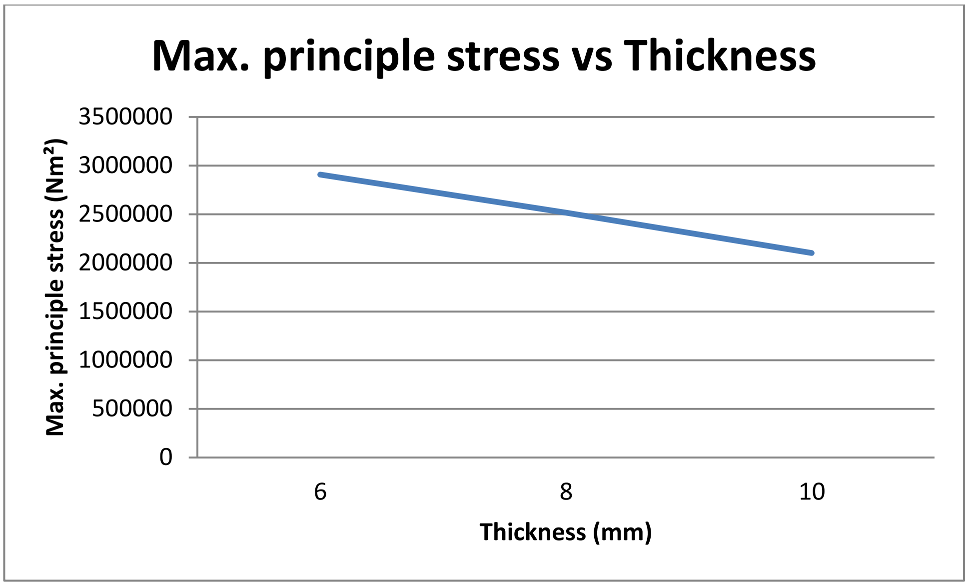

Figure 4.23: Graph of maximum principle stress against thickness.

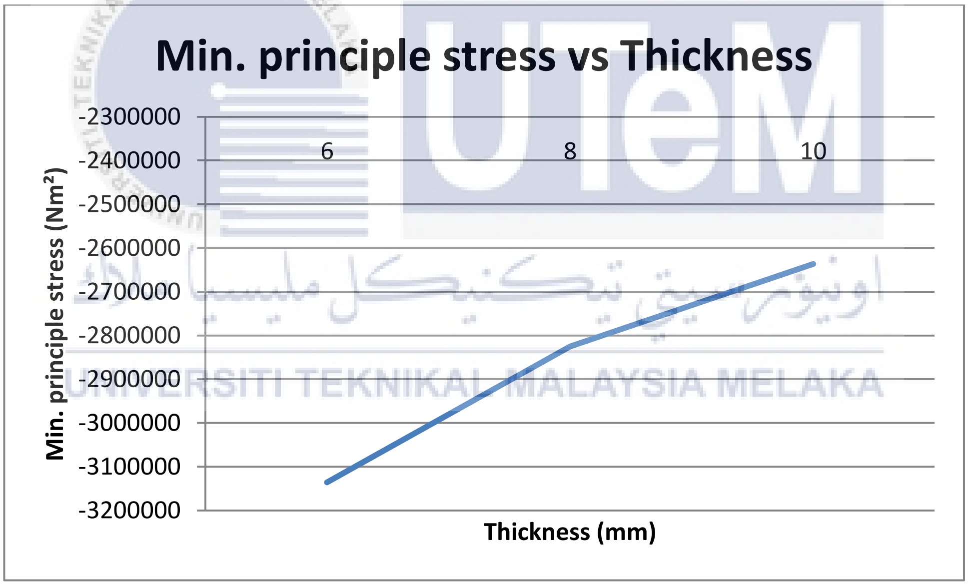

Figure 4.24: Graph of minimum principle stress against thickness.

4.3.3 Displacement

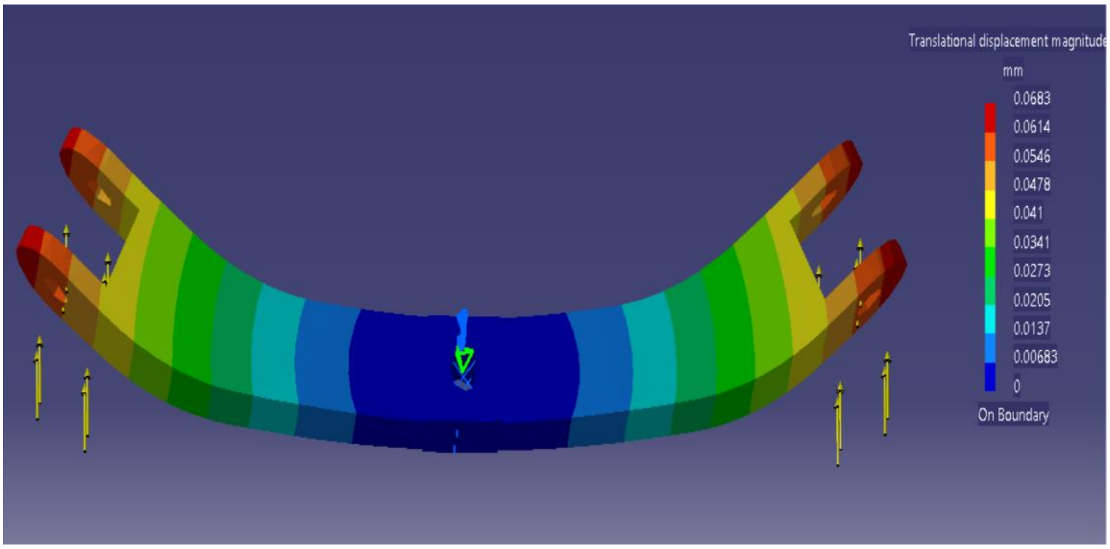

Figure 4.25: Analysis for 6mm thickness

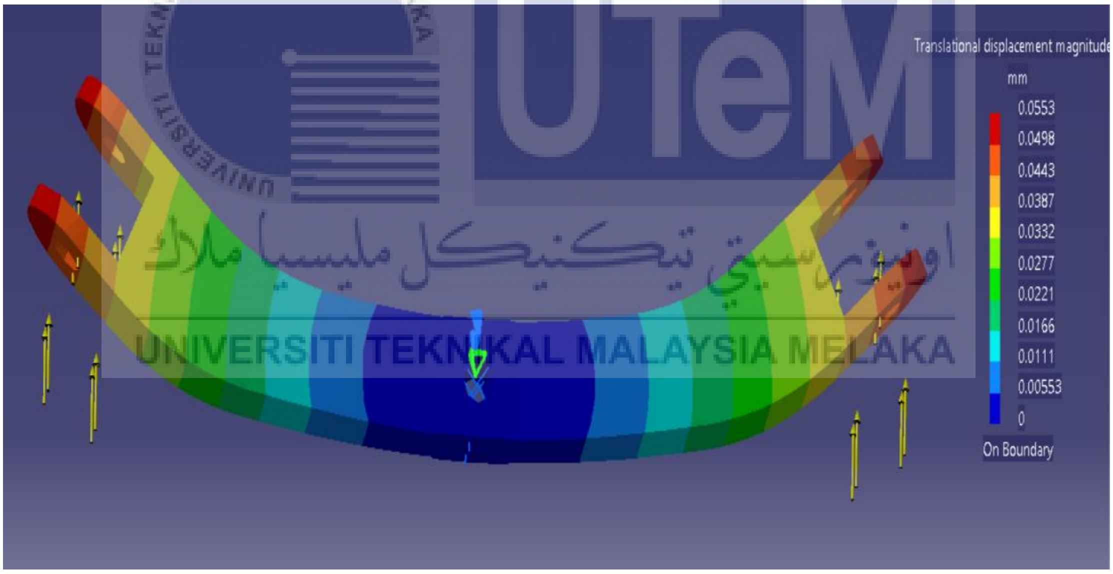

Figure 4.26: Analysis for 8mm thickness

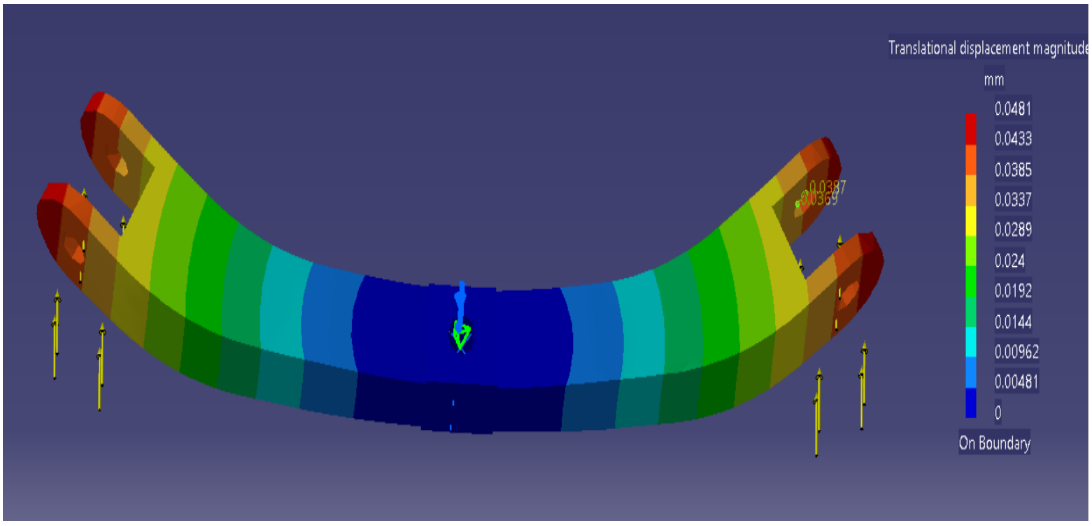

Figure 4.27: Analysis for 10mm thickness

Table 4.6: Displacement analysis of the front cradle.

Thickness (mm)	Displacement (mm)
6	0.0683
8	0.0553
10	0.0481

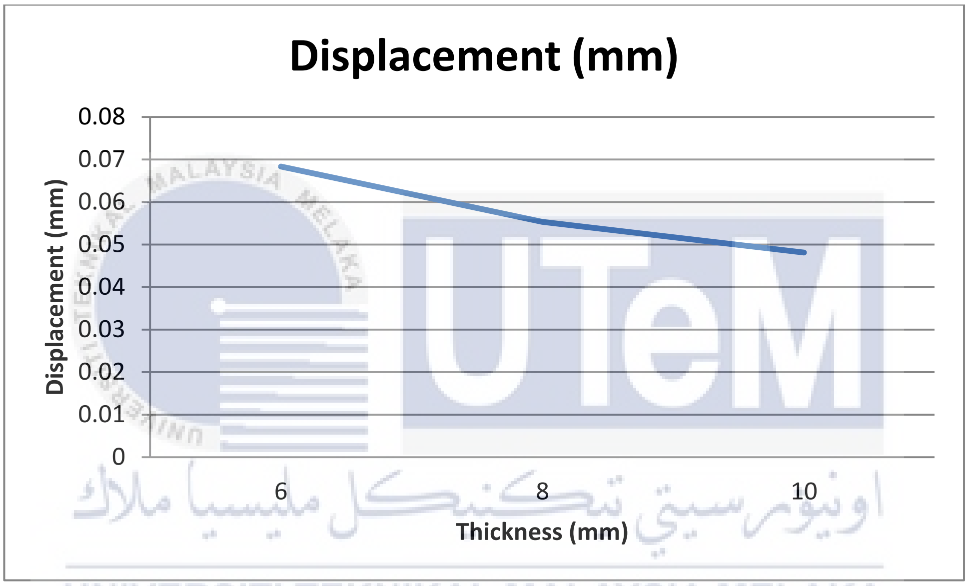

Figure 4.28: Graph of displacement against thickness.

4.4 Analysis of Von Mises stress

In the Figure 1, Figure 2, Figure 3, Figure 15, Figure 16, and Figure 17, the red colour on the cradle represent the maximum Von Mises stress acting on the cradle. It is situated in the middle of the cradle where the body of swimcar connected to the cradle. As the colour change from red to blue, that indicates that the stresses are decreasing and the minimum Von Mises stress is at the end of the cradle at left and right side of the cradle.

The graphs of maximum and minimum Von Mises stress against thickness in Figure 4 and Figure 5 that are represent the rear cradle show that the stresses acting on the cradle decrease as the thickness of the cradle increase. For the lowest thickness which is 6mm, the maximum Von Mises stress is 5848605.500N/m^2. For 8 mm thickness, the maximum Von Mises stress is 5172022.500N/m^2. Lastly, for the highest thickness which is 10mm, the maximum Von Mises stress is 4558881.000N/m^2. For the thickness of 6mm, 8mm and 10mm, the minimum Von Mises stress are 60350.715N/m^2, 47836.94 N/m^2, and 47115.777N/m^2 respectively.

The graphs of maximum and minimum Von Mises stress against thickness in Figure 18 and Figure 19 that are represent the front cradle show that the stresses acting on the cradle decrease as the thickness of the cradle increase. For the lowest thickness which is 6mm, the maximum Von Mises stress is 3092956.250N/m^2. For 8 mm thickness, the maximum Von Mises stress is 2736894.250N/m^2. Lastly, for the highest thickness which is 10mm, the maximum Von Mises stress is 2435177.250N/m^2. For the thickness of 6mm, 8mm and 10mm, the minimum Von Mises stress are 30677.545N/m^2, 24518.459N/m^2, and 24564.199N/m^2 respectively. It is shown in the Table 1 for rear cradle and Table 4 for the front cradle.

From this analysis we can say that the Von Mises stress analysis on both front and rear cradle had the same results based on the shape of the graphs. Even though the shape of the graphs is quite similar, the amount of stresses acting on the cradle is not the same due to the different amount of distributed force which are 883N for front cradle and 442N for rear cradle.

4.5 Analysis of principle stress

The red coloured dots indicate the maximum principle stress and the blue coloured dot for the minimum principle stress acting on the cradle as shown as in the Figure 6 until Figure 8 for the rear cradle and Figure 20 until 22 for the front cradle. The red coloured dots are at the bottom position where all the force from the body focusing on. On the top position of the cradle, only a little force acting on it, so it is coloured as blue dots.

For the rear cradle with 6mm, 8mm, and 10mm thickness, the maximum principle stresses are 5485483.500N/m^2, 4724683N/m^2 and 4008806N/m^2 respectively. The minimum principle stresses are -5906661.000N/m^2 for 6mm, -5333151.500 N/m^2 for 8mm, and -4823670.500 N/m^2 for 10 mm thickness. For the front cradle with the thickness of 6mm, 8mm, and 10mm, the maximum principle stresses are 2905661.000N/m^2, 2515614.250N/m^2, and 2101885.750N/m^2 respectively. The minimum principle stresses are -3135810.750N/m^2, -2825504.500N/m^2 and -2636517.750N/m^2 for the thickness of 6mm, 8mm, and 10mm respectively. It is shown in Table 2 for the rear cradle and Table 5 for the front cradle.

From the graph in Figure 9 and Figure 23, we can conclude that the principle stress decrease when the thickness of the cradle increase. Due to the increasing of thickness that making the cradle a lot stronger compared to the lower thickness. From the graph in Figure 10 and Figure 24, we can see that it is in negative value. The graphs are increasing due to its negative value. The minimum principle stress decreasing as the thickness increasing.

4.6 Analysis of displacement

From the Figure 11 until Figure 13 for the rear cradle and from Figure 25 until Figure 27 for the front cradle, we can see that the maximum displacement is where the red coloured regions which are at the left and right side of the cradle. The blue coloured regions are where the minimum displacement situated which is at the centre of the cradle. The ends of each side of the cradle are maximum displacement because that is the place where it is connected to the suspension.

The maximum displacement for the rear cradle at the thickness of 6mm, 8mm, and 10mm are 0.128mm, 0.104mm, and 0.0907mm respectively. As for the front cradle, the maximum displacements are 0.0683mm for 6mm thickness, 0.0553mm for 8mm thickness, and 0.0481mm for 10mm thickness. The results are shown in the Table 3 for rear cradle and Table 6 for the front cradle.

From both graphs in Figure 14 and Figure 28, it show that the displacement decrease as the thickness of the cradle increase. This is because the cradle becomes more sturdy and stronger as the thickness increase.

4.7 Mass of the cradle

All the figures below showed the mass of the cradle for the different thickness for both rear and front cradle. The mass for rear and front for certain thickness are the same because the dimension for both cradle are the same and identical.

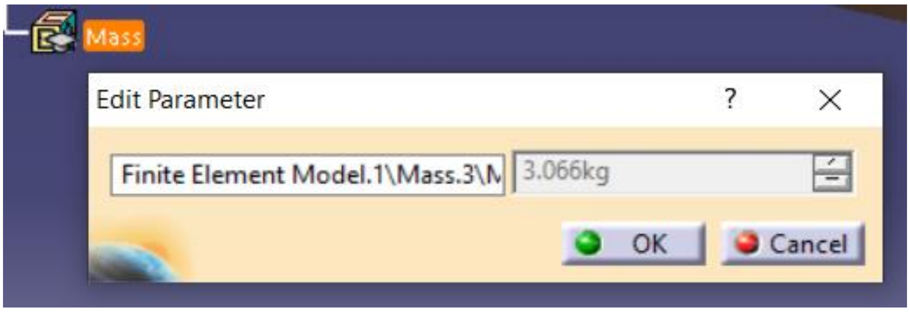

Figure 4.29: Mass of the cradles for 6mm thickness.

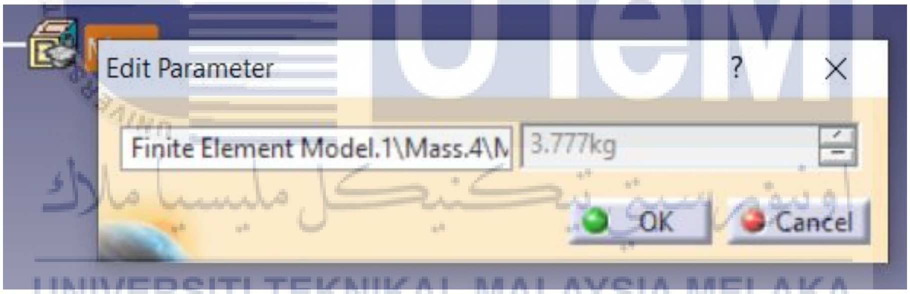

Figure 4.30: Mass of the cradles for 8mm thickness.

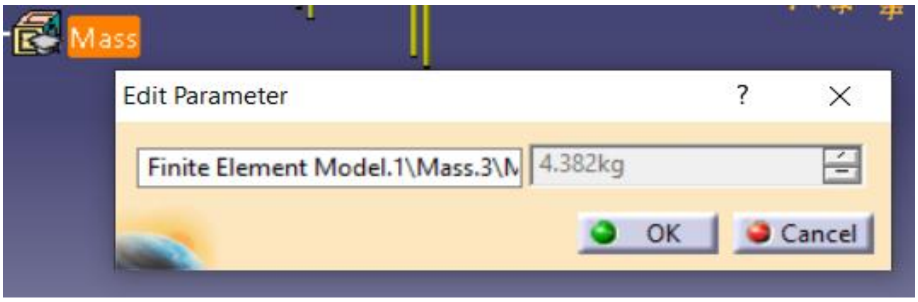

Figure 4.31: Mass of the cradles for 10mm thickness.

4.8 Calculation the force for the rear and front cradle.

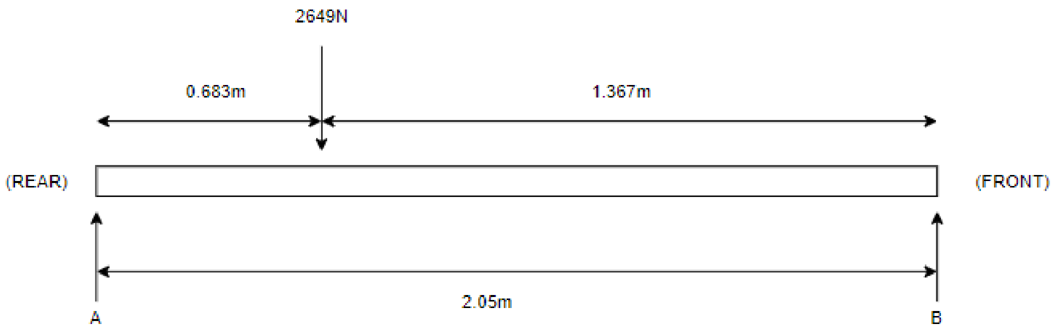

Figure 4.32: Free body diagram of the swimcar

$$Weight\ of\ the\ body = 180kg$$

$$Average\ weight\ of\ human = 90kg$$

$$(180 + 90) \times 9.81 = 2649N$$

$$+\circlearrowleft M_A : -2649(0.683) + B(2.05) = 0$$

$$B\ (2.05) = 2649\ (0.683)$$

$$B = 883N\ (Front)$$

$$+\circlearrowleft M_B : 2649(1.367) - A(2.05) = 0$$

$$A\ (2.05) = 2649\ (1.367)$$

$$B = 1766N\ (Rear)$$

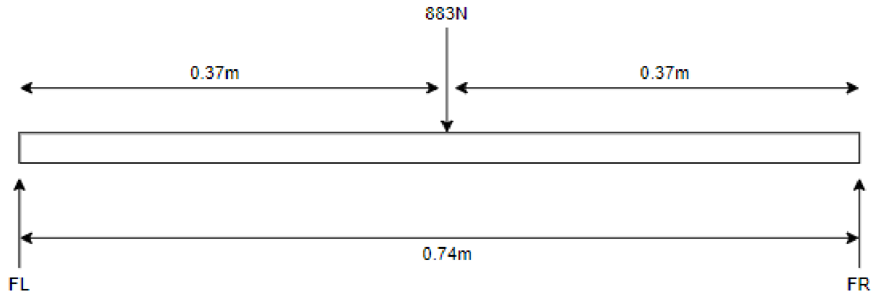

Figure 4.33: Free body diagram of front cradle.

Front Cradle:

$+\circlearrowleft M_{FL}: -883\,(0.37) + FR\,(0.74) = 0$

$$FR\,(0.74) = 883\,(0.37)$$

$$FR = 442N = FL$$

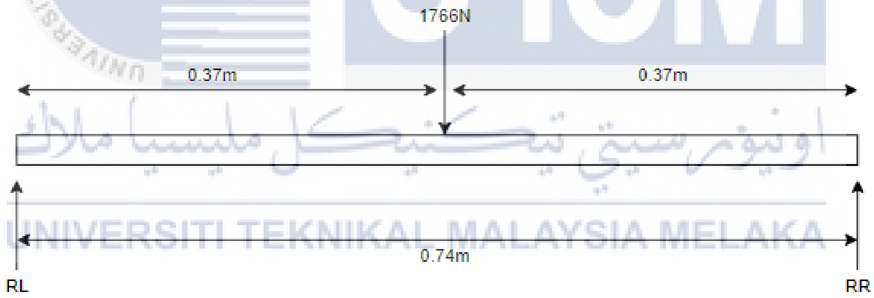

Figure 4.34: Free body diagram of the rear cradle.

Rear Cradle:

$+\circlearrowleft M_{RL}: -1766\,(0.37) + RR\,(0.74) = 0$

$$RR\,(0.74) = 1766\,(0.37)$$

$$RR = 883N = RL$$

4.9 Calculation for the safety factor of Von Mises Stress.

- **Factor of safety of rear cradle for 6mm thickness.**

$$Factor\ of\ Safety = \frac{Yield\ Strength}{Maximum\ Stress}$$

$$\text{FOS} = \frac{9.5 \times 10^7}{5848605.500}$$

FOS = 16.2 > 5 (theoretical safety factor)

- **Factor of safety of rear cradle for 8mm thickness.**

$$Factor\ of\ Safety = \frac{Yield\ Strength}{Maximum\ Stress}$$

$$\text{FOS} = \frac{9.5 \times 10^7}{5172022.500}$$

FOS = 18.4 > 5 (theoretical safety factor)

- **Factor of safety of rear cradle for 10mm thickness.**

$$Factor\ of\ Safety = \frac{Yield\ Strength}{Maximum\ Stress}$$

$$\text{FOS} = \frac{9.5 \times 10^7}{4558881.000}$$

FOS = 20.8 > 5 (theoretical safety factor)

- **Factor of safety of front cradle for 6mm thickness.**

$$Factor\ of\ Safety = \frac{Yield\ Strength}{Maximum\ Stress}$$

$$\text{FOS} = \frac{9.5 \times 10^7}{3092956.250}$$

FOS = 30.7 > 5 (theoretical safety factor)

- **Factor of safety of front cradle for 8mm thickness.**

$$Factor\ of\ Safety = \frac{Yield\ Strength}{Maximum\ Stress}$$

$$\text{FOS} = \frac{9.5 \times 10^7}{2736894.250}$$

FOS = 34.7 > 5 (theoretical safety factor)

- **Factor of safety of front cradle for 10mm thickness.**

$$Factor\ of\ Safety = \frac{Yield\ Strength}{Maximum\ Stress}$$

$$\text{FOS} = \frac{9.5 \times 10^7}{2435177.250}$$

FOS = 39.0 > 5 (theoretical safety factor)

4.10 Calculation for the safety factor of principle stress.

- **Factor of safety of rear cradle for 6mm thickness.**

$$Factor\ of\ Safety = \frac{Yield\ Strength}{Maximum\ Stress}$$

$$\text{FOS} = \frac{9.5 \times 10^7}{5485483.500}$$

FOS = 17.3 > 5 (theoretical safety factor)

- **Factor of safety of rear cradle for 8mm thickness.**

$$Factor\ of\ Safety = \frac{Yield\ Strength}{Maximum\ Stress}$$

$$\text{FOS} = \frac{9.5 \times 10^7}{4724683.000}$$

FOS = 20.1 > 5 (theoretical safety factor)

- **Factor of safety of rear cradle for 10mm thickness.**

$$Factor\ of\ Safety = \frac{Yield\ Strength}{Maximum\ Stress}$$

$$\text{FOS} = \frac{9.5 \times 10^7}{4008806.000}$$

FOS = 23.7 > 5 (theoretical safety factor)

- **Factor of safety of front cradle for 6mm thickness.**

$$Factor\ of\ Safety = \frac{Yield\ Strength}{Maximum\ Stress}$$

$$\text{FOS} = \frac{9.5 \times 10^7}{2905661.000}$$

FOS = 32.7 > 5 (theoretical safety factor)

- **Factor of safety of front cradle for 8mm thickness.**

$$Factor\ of\ Safety = \frac{Yield\ Strength}{Maximum\ Stress}$$

$$\text{FOS} = \frac{9.5 \times 10^7}{2515614.250}$$

FOS = 37.8 > 5 (theoretical safety factor)

- **Factor of safety of front cradle for 10mm thickness.**

$$Factor\ of\ Safety = \frac{Yield\ Strength}{Maximum\ Stress}$$

$$\text{FOS} = \frac{9.5 \times 10^7}{2101885.750}$$

FOS = 45.2 > 5 (theoretical safety factor)

4.11 Minimum thickness for the cradle.

- **Factor of safety for 2mm thickness of Von Mises stress.**

$$Factor\ of\ Safety = \frac{Yield\ Strength}{Maximum\ Stress}$$

$$\text{FOS} = \frac{9.5 \times 10^7}{13746068}$$

FOS = 6.91 > 5 (theoretical safety factor)

- **Factor of safety for 2mm thickness of principle stress.**

$$Factor\ of\ Safety = \frac{Yield\ Strength}{Maximum\ Stress}$$

$$\text{FOS} = \frac{9.5 \times 10^7}{13319890}$$

FOS = 7.13 > 5 (theoretical safety factor)

- **Factor of safety for 1mm thickness of Von Mises stress.**

$$Factor\ of\ Safety = \frac{Yield\ Strength}{Maximum\ Stress}$$

$$\text{FOS} = \frac{9.5 \times 10^7}{31024348}$$

FOS = 3.06 < 5 (theoretical safety factor)

- **Factor of safety for 1mm thickness of principle stress.**

$$Factor\ of\ Safety = \frac{Yield\ Strength}{Maximum\ Stress}$$

$$\text{FOS} = \frac{9.5 \times 10^7}{24510798}$$

FOS = 3.88 < 5 (theoretical safety factor)

Based on the calculated factor of safety for the 2mm thickness and the 1mm thickness above, it show that the 2mm thickness is the minimum thickness that can be chosen to manufacture the cradle as the safety factor is greater than the theoretical safety factor which is 5. Both safety factor of Von Mises stress and principle stress for 2mm is above 5 and that indicates that it is safe to be used.

As for the 1mm thickness, the calculated safety factor shows that they are below the theoretical value of safety factor which is 5. Both safety factor for Von Mises and principle stress for 1mm thickness are below 5 and this indicates that it is not safe to use the thickness of 1mm to manufacture the cradle.

4.12 Chapter summary

The results indicate that the aluminium is a suitable material to be used for manufacture the cradle. All the thickness used in this analysis which are 6mm, 8mm, and 10 mm are safe to be used. This is because all the maximum stress is not exceed the yield strength of the aluminium that is 9.5 x 10^7N/m2.

The results show that when the thickness of the cradle increased, the stress acting on it decreased. But as the thickness increase, the mass of the cradle also increase. Increasing in mass will give the disadvantages to the swimcar as it can affect the battery consumption. It is also not practical for this type of vehicle which needs to be as light as possible for going through rough terrain. The one that have lightest mass is the cradle that used 6mm thickness which is 3.066kg and this is the most suitable thickness in the aspect of mass.

Based on the safety factor of Von Mises Stresses and the principle stresses calculated, we can see that the ratio is much greater from the theoretical value which is 5.We can say that the part is safe due to bigger factor of safety but this also indicates that the part is over-engineered. Which is mean that the thickness used is not suitable because it is too thick and will contribute to wasting of the material and also increase the cost. The minimum thickness that can be used is the 2mm.

CHAPTER 5

CONCLUSION & FUTURE WORK

5.1 Introduction

An analysis of the cradle from the swimcar, which is an all - terrain vehicle (ATV), is conducted to investigate which thickness is the most suitable for the cradle using Finite Element Analysis (FEA). The thicknesses to be chosen are 6mm, 8mm, and 10mm. From this analysis we can know whether it is safe or not and the performance of the car.

It can be concluded that the cradle with the thickness of 6mm is the most suitable compared to cradle with 8mm and 10mm thickness. Even though the 6mm thickness has the highest stress compared to others, it can still withstand the applied stress. The maximum Von Mises stress and the principle stress of both front and rear cradle also did not exceed the yield strength of the aluminium which is $9.5\text{x}10^7$ N/m2. The 6mm thickness is considered safe after the factor of safety on Von Mises stress and principle stress calculated.

One more factor of choosing 6mm thickness as the most suitable thickness is because it has the lightest mass which is 3.066kg. Mass is one of the critical criteria that needs to be taken into account because it can affects the performance of the vehicle. When the vehicle is heavier, the performance of the vehicle will decline compared to the much lighter vehicle. The 10mm thickness has a mass of 4.382kg and it is way heavier compared to 6mm thickness which is only 3.066kg. The minimum thickness that can be used to manufacture this cradle is 2mm because the 1mm thickness is concluded not safe to be used based on the safety factor. This type of vehicle needs to be light in order to go through rough terrain. Choosing the suitable thickness is one of the factors to boost the performance of this vehicle.

At the end, aluminium is not the most suitable material that can be used for manufacturing this part or this vehicle. The aluminium can be made stronger depending on the alloy and processing technique used. It can be forged to be as strong if not stronger than some steel.

5.2 Future work

As extension of the works which may be appropriate in investigating the most suitable thickness of the cradle for the swimcar to make sure the results of the project more accurate are by using ANSYS software together with CATIA software in order to obtain more accurate results of the analysis of the cradle.

Another recommendation is that by using different material other than aluminium or using aluminium alloy in order to increase the strength of the cradle to withstand the stresses way better than in this project. Lastly, modify the structural design of the cradle especially at the end of both right and left side of the cradle where most of the stresses applied.

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