DESIGN AND ANALYSIS OF A LIGHTWEIGHT CHASSIS FOR HUMAN POWERED VEHICLE

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DESIGN AND ANALYSIS OF A LIGHTWEIGHT CHASSIS FOR HUMAN POWERED VEHICLE

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This report is submitted
in fulfillment of the requirement for the degree of
Bachelor of Mechanical Engineering (Automotive)

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DECLARATION

I declare that this project report entitled "Design and Analysis of a Lightweight Chassis for Human Powered Vehicle" is the result of my own work except as cited in the references

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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 (Automotive).

Signature : …………………………..
Name of Supervisor: Assoc. Prof. Dr. Mohd Azman Bin Abdullah
Date : …………………………..

DEDICATION

To my beloved family, respected supervisor, lecturers and friends,
thank you for everything.

ABSTRACT

Human powered vehicle (HPV) is a transportation powered by muscular strength. A typical HPV weighted between 30 kg to 50 kg, which is quite heavy for racing and recreation. Thus, most of the HPV have difficulties and require more efforts to move. This is because the chassis of the HPV is too heavy. Therefore, this thesis aims to design a lightweight chassis with ideal stiffness through acceleration and cornering analysis. The selection of the design and material for the chassis are crucial to make sure that the HPV is strong, lightweight and rigid. There are four designs with different size of structural beam that will be analysed using Finite Element Analysis (FEA) in ANSYS Workbench. Furthermore, three different materials are applied to each design in the analysis. The analysis cover acceleration, cornering and torsional analysis in a static condition. Next, the analysis is conducted by applying loads and fix supports to some parts of the chassis. The loads represent the weight of the driver; will be applied at the centre of the chassis where the driver would be seated. Whereas, the fix supports are applied at all points which have tyres. From the analysis, ANSYS Workbench will produce total deformation, mass, Von-mises stress and safety factor results. Later, some calculations are performed to obtain ideal bending and torsional stiffness. After that, the design with desirable mass will be tested with safety factor to make sure it is within a suitable range. Meanwhile, the Von-mises stress will be compared with yield stress of each material to identify the toughness of the chassis. Then, the results will be compared with benchmarks from another sources to achieve the objectives of this study. Finally, the best chassis design that provide low weight, better stiffness and ideal safety factor is selected through weight decision matrix analysis.

ABSTRAK

Kenderaan bertenaga manusia (HPV) adalah sebuah kenderaan yang menggunakan kekuatan fizikal dan otot badan manusia. Kebiasaannya, HPV mempunyai berat di antara 30 kg hingga 50 kg, di mana ia adalah agak berat untuk perlumbaan dan kegunaan rekreasi. Oleh itu, kebanyakkan HPV mempunyai kesukaran dan memerlukan tenaga yang lebih untuk bergerak. Ini disebabkan rangka HPV tersebut yang sangat berat. Sehubungan itu, tesis ini mensasarkan reka bentuk rangka HPV yang ringan beserta kekukuhan yang terbaik melalui analisis pecutan dan belokan. Pemilihan reka bentuk dan bahan untuk rangka HPV adalah sangat penting untuk mendapatkan HPV yang kuat, ringan dan tegar. Terdapat empat reka bentuk yang berlainan saiz struktur besi yang akan diuji menggunakan '*Finite Element Analysis'* (FEA) dalam perisian ANSYS *Workbench*. Selain itu, tiga bahan berlainan akan digunakan dalam setiap reka bentuk untuk setiap analisis. Analisis tersebut merangkumi analisis pecutan, belokan dan pusingan di mana ianya adalah dalam keadaan statik. Seterusnya, analisis diteruskan dengan mengenakan daya dan sokongan kekal pada bahagian tertentu pada rangka HPV. Daya yang kenakan mewakili berat pemandu dan ianya dikenakan di pusat rangka di mana tempat untuk pemandu tersebut akan duduk. Manakala, sokongan kekal dikenakan pada semua tempat yang mempunyai tayar. Daripada analisis tersebut, perisian ANSYS *Workbench* akan mengeluarkan hasil jumlah pesongan, jisim, tekanan Von-mises dan faktor keselamatan. Selepas itu, beberapa kiraan akan dilakukan untuk mencari kadar kekerasan bengkokan dan kadar kekerasan pusingan yang terbaik. Seterusnya, rekabentuk yang mempunyai jisim yang terbaik akan diuji tahap faktor keselamatannya supaya berada dalam keadaan yang sesuai dan selamat. Kemudian, tekanan Von-mises akan dibandingkan dengan tekanan kekuatan bahan tersebut untuk menentukan kekuatan rangka kenderaan. Selepas itu, hasil keputusan akan dibandingkan dengan penanda aras daripada hasil kajian atau sumber lain untuk mencapai objektif kajian. Akhir sekali, rekabentuk rangka yang ringan, lebih keras dan mempunyai ciri-ciri keselamatan terbaik akan dipilih berdasarkan '*weight decision matrix analysis*'.

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TABLE OF CONTENT

CHAPTER	TOPIC		PAGE
	DECLARATION		ii
	APPROVAL		iii
	DEDICATION		iv
	ABSTRACT		v
	ABSTRAK		vi
	ACKNOWLEDGEMENTS		vii
	TABLE OF CONTENT		viii
	LIST OF FIGURES		x
	LIST OF TABLES		xiv
	LIST OF ABBREVIATIONS		xv
	LIST OF SYMBOLS		xvi
1	**INTRODUCTION**		1
	1.1	Background	1
	1.2	Problem Statement	3
	1.3	Objectives	3
	1.4	Scope of Project	3
2	**LITERATURE REVIEW**		4
	2.1	Introduction	4
	2.2	Human Powered Vehicle	4
	2.3	Frame	6
	2.4	Chassis	7
	2.5	Ladder Chassis	7
	2.6	Backbone Chassis	8
	2.7	Space Frame Chassis	9

	2.8	Monocoque Chassis	10
	2.9	Materials	11
	2.10	Finite Element Analysis of ANSYS Software	15
3	**METHODOLOGY**		16
	3.1	Introduction	16
	3.2	Flow Chart of Project Methodology	17
	3.3	Benchmarking	18
	3.4	Conceptual Design	19
	3.5	Analysis	21
4	**RESULTS AND DISCUSSION**		32
	4.1	ANSYS Analysis Results	32
	4.2	Bending and Torsional Stiffness	42
	4.3	Safety Factor	49
	4.4	Weight Decision Matrix	61
	4.5	Discussion	65
5	**CONCLUSION AND FUTURE WORK**		71
	5.1	Conclusion	71
	5.2	Future Work	72
	REFERENCES		74
	APPENDICES		79

LIST OF FIGURES

FIGURE	TITLE	PAGE
1.1	Frame structured in HPV (Das, 2013).	1
2.1(a)	Aerodynamic shell HPV.	5
2.1(b)	Structural frame HPV.	5
2.2	Body measurement parameters (Allen et al., 2015).	6
2.3	Model of ladder chassis (Singh et al., 2014).	8
2.4	Model of backbone chassis (Ludd, 2013).	9
2.5	Model of space frame chassis (Das, 2013).	10
2.6	Model of monocoque chassis (Carello et al., 2014).	11
3.1	Flow chart of the methodology.	17
3.2	Sketched conceptual design.	20
3.3	CAD model of final design.	20
3.4	Rendering model of final design.	21
3.5	Idealization of the chassis using line element.	23
3.6	Model visualization with cross-sections.	23
3.7	L-shaped cross-sectional beam.	24
3.8	Circular cross-sectional beam.	24
3.9	Rectangular cross-sectional beam.	25

3.10	Computational model featuring elements.	25
3.11	Computational model featuring constraints for torsional analysis.	26
3.12	Computational model featuring loads for torsional analysis.	27
3.13	Computational model featuring fixed support for bending loads analysis.	28
3.14	Computational model featuring downwards loads.	29
3.15	Computational model featuring front loads for acceleration analysis.	29
3.16	Computational model featuring side loads for cornering analysis.	30
4.1	Fourth design of aluminium alloy chassis for cornering analysis.	33
4.2	Fourth design of structural steel chassis for cornering analysis.	34
4.3	Fourth design of stainless steel chassis for cornering analysis.	34
4.4	Total deformation for cornering analysis.	35
4.5	Fourth design of aluminum alloy chassis for acceleration analysis.	36
4.6	Fourth design of structural steel chassis for acceleration analysis.	37
4.7	Fourth design of stainless steel chassis for acceleration analysis.	37
4.8	Total deformation for acceleration analysis.	38

4.9	Fourth design of aluminum alloy chassis for torsional analysis.	39
4.10	Fourth design of structural steel chassis for torsional analysis.	40
4.11	Fourth design of stainless steel chassis for torsional analysis.	40
4.12	Total deformation for torsional analysis.	41
4.13	Bending stiffness for cornering analysis.	44
4.14	Bending stiffness for acceleration analysis.	45
4.15	Free body diagram of the chassis structure with respect to frontal view.	46
4.16	Overall torsional stiffness analysis.	47
4.17	Overall mass of the chassis design.	48
4.18	Von-mises stress of structural steel chassis for cornering analysis.	50
4.19	Safety factor of structural steel chassis for cornering analysis.	51
4.20	Von-mises stress of stainless steel chassis for cornering analysis.	51
4.21	Safety factor of stainless steel chassis for cornering analysis.	52
4.22	Von-mises stress of aluminium alloy chassis for cornering analysis.	52
4.23	Safety factor of aluminium chassis for cornering analysis.	53
4.24	Von-mises stress of structural steel chassis for acceleration analysis.	54
4.25	Safety factor of structural steel chassis for acceleration analysis.	54

4.26	Von-mises stress of stainless steel chassis for acceleration analysis.	55
4.27	Safety factor of stainless steel chassis for acceleration analysis.	55
4.28	Von-mises stress of aluminium alloy chassis for acceleration analysis.	56
4.29	Safety factor of aluminum alloy chassis for acceleration analysis.	56
4.30	Von-mises stress of structural steel chassis for torsional analysis.	57
4.31	Safety factor of structural steel chassis for torsional analysis.	58
4.32	Von-mises stress of stainless steel chassis for torsional analysis.	58
4.33	Safety factor of stainless steel chassis for torsional analysis.	59
4.34	Von-mises stress of aluminum alloy chassis for torsional analysis.	59
4.35	Safety factor of aluminum alloy chassis for torsional analysis.	60

LIST OF TABLES

TABLE	TITLE	PAGE
2.1	Material properties (Prajwal et al., 2014).	11
2.2	Material properties for typically used frame design materials (Porter et al., 2014).	13
2.3	Comparison of material properties (Kamaruddin et al., 2016).	14
3.1	Overall geometries of cross-sectional beams.	31
4.1	Overall total deformation for cornering analysis.	35
4.2	Overall total deformation for acceleration analysis.	38
4.3	Overall total deformation for torsional analysis.	41
4.4	Overall bending stiffness for cornering analysis.	43
4.5	Overall bending stiffness for acceleration analysis.	45
4.6	Overall torsional stiffness.	46
4.7	Overall mass of the chassis design.	47
4.8	Yield strength and ultimate strength from ANSYS Workbench.	49
4.9	Overall Von-Mises stress and safety factor.	60
4.10	Decision matrix for overall mass of the chassis designs.	62
4.11	Decision matrix for the material selection.	64

LIST OF ABBREVIATIONS

HPV	Human Powered Vehicle
FEA	Finite Element Analysis
TIG	Tungsten Inert Gas
GPU	Graphic Processing Units
3D	3-Dimensional
CAD	Computer Aided Design
ANSYS	Analysis System

LIST OF SYMBOLS

K = Stiffness (N/m)

F = Force (N)

δ = Deformation (m)

M_t = Twisting Moment (Nm)

θ = Angle of rotation (rad)

σ = Stress (Pa)

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

There are many types of pollution occurred on earth such as water pollution, thermal pollution, noise pollution and air pollution. Air pollution can be considered as one of the main hazards to the health of human being. The air pollution is due to the increasing number of vehicles used by human that also contribute to global warming. Many incentives have been made to solve these problems. One of the efforts is a Human Powered Vehicle (HPV) creation, which can be popularized as a viable form of green technology and sustainable transportation. This transportation is powered only by muscular-strength (Abdullah et al., 2016). HPV systems consist of many main components sub-system such as drivetrain system, steering system, brake system, chassis and tires. This project will cover the chassis sub-system. There are three chassis structures in a passenger car namely frame, underbody and sub-frame structures. However, most HPV design used the frame structure as shown in **Figure 1.1**.

Figure 1.1: Frame structured in HPV (Das, 2013).

Supposedly, chassis supports the HPV components and payload mounted upon it including all the sub-systems mentioned earlier (Kumar & Deepanjali, 2008). When the HPV travel along the road, its chassis is subjected to a stress, bending moment and vibration induced by road roughness. Stress that acting on the chassis varies with the displacement and each part of the chassis. Because of the behavior of the chassis that is always subjected to a stress, a weak structurally designed part will collapse. Therefore, there are factors that need to be considered in this project in order to produce a strong and lightweight chassis. The factors are mass, bending and torsional stiffness (Galolia & Patel, 2011), total deformation and Von-mises stress.

For the weight of the HPV, there are four elements or characteristics that need to be considered which are material, parameter of frame structure, shape of frame structure, and design of the chassis. These elements will affect the mass of the chassis in order to get a lightweight chassis. As for the toughness of the chassis, those elements also play an important role to produce the value of bending and torsional stiffness, total deformation and Von-mises stress in static analysis. Static analysis will determine displacement, stress or component that do not cause significant damping effect and inertia (Anurag et al., 2016). The Von-mises stress is used by engineers and designers to check whether their design can withstand the applied loads or not. When the value of Von-mises stress in particular material is higher than the yield stress of the material, the design is considered failed.

Design of the chassis was analysed using computerized software. A computer based numerical stress analysis methods such as Finite Element Analysis (FEA) has permitted the complex distributions of stress in engineering to be more deliberate. The FEA provided a better solution to analyze impact of load on the chassis body including the critical part which experiences a high value of stress or load on it. The analysis was performed using ANSYS software. ANSYS will show the maximum total deformation and Von-mises stress (Choubey, 2016). The Von-mises stress need to be calculated in order to get the safety factor of the chassis design. Next, the safety factor is used to determine whether the design structure is safe or not. An ideal chassis is the one that provide low weight, better stiffness and ideal safety factor.

1.2 PROBLEM STATEMENT

The Faculty of Mechanical Engineering of Universiti Teknikal Malaysia Melaka has organized a competition for engineering students themed “Human Powered Vehicle Competition.” Although the design of HPV is important for this competition, speed must also be given major priority because the competition is a race event. One of the main problems for the design is the weight of the HPV. The HPV is having difficulties to speed up because the chassis is too heavy. Some efforts must be put to decrease the weight of the HPV. A lightweight HPV may increase the speed of the HPV and probably win the competition. Thus, the chassis, which represent the major sub-system of the HPV, must be lightweight. The selection of material and the design of the chassis are therefore crucial to ensure that the HPV is strong, lightweight and rigid.

1.3 OBJECTIVES

The objectives of this project are as follows:

a) To design a lightweight chassis with ideal stiffness through acceleration and cornering analysis.
b) To select the best chassis through weight decision matrix analysis.

1.4 SCOPE OF PROJECT

The scope of this project are:

a) The design of chassis is based on static analysis with acceleration and cornering condition in finding total deformation, mass, bending and torsional stiffness and lastly, maximum Von-mises stress.
b) The selection of the best analysis with various material, dimension and size of structural beam structure is chosen with the aid of FEA using ANSYS software.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter discusses previous research and sources collected to find related information regarding this project. The sources include journals, articles, reports, Internet, books and web sites. The main purpose of this chapter is to convey the knowledge and ideas from other researchers as a guideline to complete this project. The information obtained is selected based on the objectives of the project. For example, the information about chassis frame, materials, stiffness and factor of safety are required to achieve the objectives.

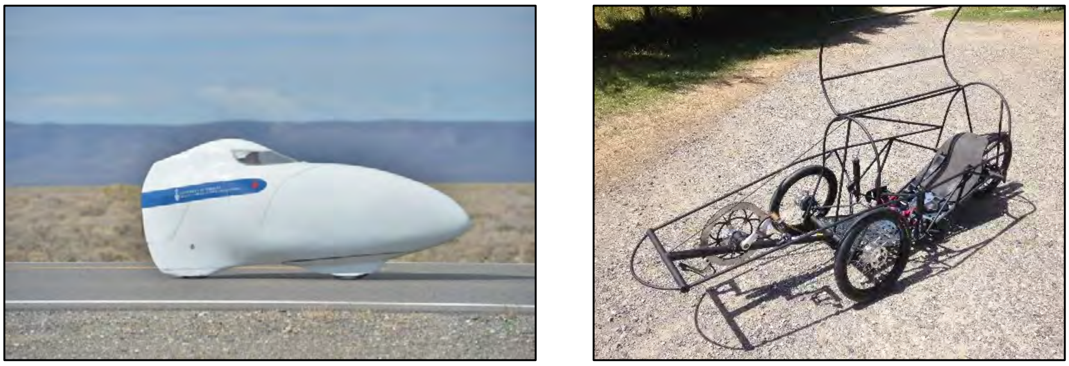
This chapter is organized as follows. The next section covers human powered vehicle. Section 2.3 continues with the discussion of the frame while Section 2.4 describes the chassis. Section 2.5, 2.6, 2.7 and 2.8 explain ladder chassis, backbone chassis, space frame chassis and monocoque chassis, respectively. Section 2.9 looks into materials. Finally, Section 2.10 examines Finite Element Analysis of ANSYS Software.

2.2 HUMAN POWERED VEHICLE

Human powered vehicles (HPV) can be classified into three categories, which are human-powered watercraft vehicles, land vehicles and aircraft vehicles (Abbott

& Wilson, 1995). For land HPV, traditionally it consists of two parts structure which are aerodynamic shell called a fairing or recumbent, and the structural frame as shown in **Figure 2.1**(a) and **Figure 2.1**(b) respectively, that supports the rider and other vehicle systems. These two components can be combined or separated. However, both structures must be presented in some form for a vehicle to be considered as a HPV (Allen et al., 2015). HPV also vary widely in design, shape, size and scope, but the fundamental ideas behind each vehicle remains the same. That is to apply human power and energy efficiently to create a viable form of sustainable transportation.

In this era, human power is one of important criteria for local distance and long distance transportation, thus civilizations decided to use the human power in the most effective way. Human power has been researched in many different capacities, although none so significantly as upright bicycling. Bicycle is almost unique among human-powered machines in that it uses human muscles in a near-optimum way (Wilson, 2004). From the beginning to modern day of bicycles and skateboards, human power has been a cheap mode but relatively ineffective mode of transportation for long distance travel. Hence, modern transportation of long distance travel is no longer dominated by human power. However, HPV offers a viable alternative to automobiles for recreation and commuting purposes. Therefore, it serves specific purposes and ease of human life to seek comfortable yet affordable short distance mode of transportation.



(a) (b)

Figure 2.1: (a) Aerodynamic shell HPV and
(b) Structural frame HPV.

2.3 FRAME

There are several choices in term of frame geometry in the design space defined by the conventional, forward-facing, recumbent rider position. For all this time, this rider position is the most mainstream design in use today for good reason as it eases the riding and optimizes rider's comfort. However, many of HPV designs are not considering the effects on the rider's comfort and cycling effectiveness when the rider seating position was impunity chosen. Plus, the seating position is not confirmed for which it will relate to maximum power output or not (Lei et al., 1993). Some of criteria used for comparisons are aerodynamics of frontal area, ergonomics and rider comfort, stability, experience with frame type and innovation of frame geometry (Darvirris et al., 2009). Besides that, fit and ergonomics have huge impacts on power and confidence of the rider especially on a new racer. Thus, it is crucial that each of the team's riders can pedal effectively and achieve their full capabilities without any obstacle. Body measurement parameters as shown in **Figure 2.2** are becoming important criteria in designing a HPV.

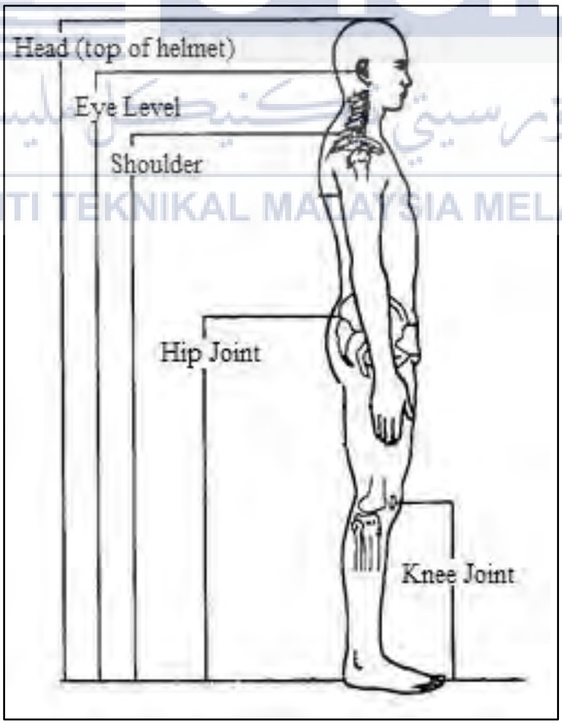


Figure 2.2: Body measurement parameters (Allen et al., 2015).

2.4 CHASSIS

A vehicle without body is called chassis. Chassis was initially used to indicate the frame parts or basic structure of a vehicle. It is the structural backbone of any vehicle. The main function of the chassis frame is to withstand the body, parts and components, and payload placed upon it. The chassis has to detain the stresses developed, deformation, shock, twist vibration and other stresses (Francis et al., 2014). Chassis is also a skeletal frame that possesses some mechanical parts such as engine, tires, axle, assemblies, brake and steering joined together. It is the most crucial element that gives strength and stability to the vehicle under different conditions which keep the automobile rigid, stiff and unbending. Usually, it is made of a steel frame. There are four major types of chassis frames viz. ladder chassis, backbone chassis, space frame chassis and monocoque chassis (Gadagottu & Mallikarjun, 2015). Each type is explained in the subsequent section.

2.5 LADDER CHASSIS

Ladder chassis frame is one of the oldest forms of automotive chassis. As its name connotes, ladder chassis as shown in **Figure 2.3** resembles a shape of a ladder having two longitudinal rails inter-linked by several lateral and cross braces (Singh et al., 2014). The longitudinal members are the main stress members. They deal with the load and also the longitudinal forces caused by acceleration and braking. The lateral and cross member provide resistance to lateral forces and further increase torsion rigidity. Since it is a two-dimensional structure, torsional rigidity is very much lower compared to other chassis especially when dealing with vertical load or bumps. In term of design, ladder chassis looks like a ladder-two longitudinal rails interconnected by several lateral and cross braces. On the other hand, the disadvantage this ladder chassis is its strength is less compared to other chassis due to its one-dimensional frame. Nonetheless, the maintenance and repair for the ladder chassis is inexpensive and quite affordable. Besides, ladder chassis is easy to repair.

Figure 2.3: Model of ladder chassis (Singh et al., 2014).

2.6 BACKBONE CHASSIS

Backbone chassis is a type of chassis that is similar to a body-on-frame design. It consists of a strong tubular backbone and not always rectangular in cross section (Birajdar & Mule, 2015). Usually this backbone chassis is made up of glass fibre that is used for joining front and rear axle together. This type of automotive chassis or automobile chassis is strong and powerful enough to provide support for smaller sports car. Backbone chassis is easy to make and cost effective. In terms of design, the body will be placed on this structure. Inside backbone there is a space for the drive shaft in case of front engine, rear wheel layout. The whole drive train, engine and suspension are both connected to both ends of the backbone. Backbone chassis is known for its strength that is strong and powerful in order to provide support for a smaller car. For the maintenance, backbone chassis is easy to repair and maintain. The price is also inexpensive and affordable. **Figure 2.4** shows an example of a backbone chassis model.

Figure 2.4: Model of a backbone chassis (Ludd, 2013).

2.7 SPACE FRAME CHASSIS

Space frame is a truss–like and lightweight rigid structure constructed from interlocking struts in a geometric pattern. It can be used to span large areas with few interior supports. Space frame chassis as shown in **Figure 2.5** is strong due to the inherent rigidity of the triangle. Flexing loads or bending moments are transmitted as tension and compression loads along the length of each strut. Its construction consists of steel or aluminum tubes placed in a triangulated format, to support the loads from suspension, driver and aerodynamics. The design of a space frame chassis is simple compared to other types of chassis. Space frame chassis is easy to assemble and dissemble. The maintenance is low and cheap. Besides that, when a space frame chassis undergoes an accident, the damaged part or critical part can be detected easily. Only the damage part is removed. In term of strength, the space frame chassis is stronger because its capability to support stronger material and larger weight. A tubular space frame chassis should be strong enough to absorb energy when back, side, front and torsional loads are applied if they meet the high-performance racing car criteria. The criteria are minimizing the weight to stiffness ratio, maintain low centre of gravity, reasonable material and manufacturing cost, create a solid base chassis and aesthetically pleasing design (Das, 2013).

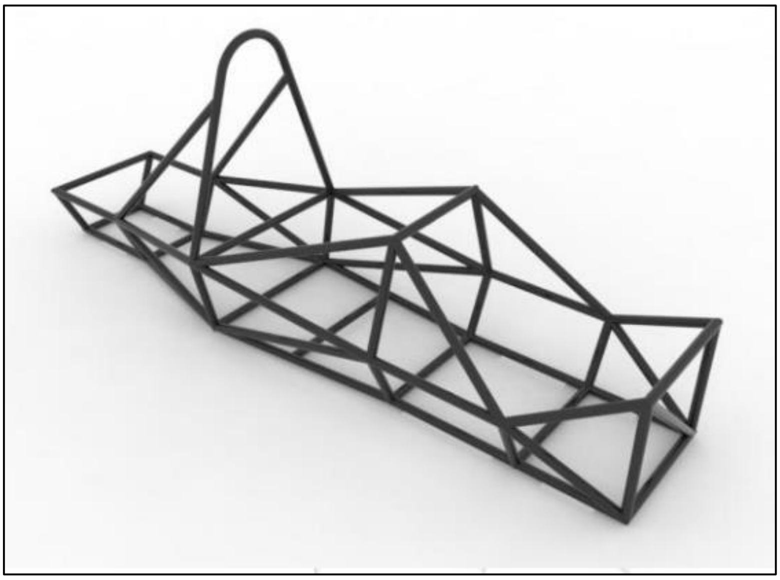


Figure 2.5: Model of a space frame chassis (Das, 2013).

2.8 MONOCOQUE CHASSIS

Monocoque is a one-piece structure built by welding number of pieces together which gives overall shape of the car (Shreepathi et al., 2015). Since monocoque chassis as shown in **Figure 2.6** is cost-effective and suitable for robotized production, most of the vehicles today make use of steel plated monocoque chassis. Monocoque chassis design is beneficial for crash protection. This is because this chassis uses a lot of steel, crumple zone that can be built into the structure. Another advantage of this chassis is space efficiency. In term of design, monocoque chassis is difficult to build and operate. In addition, the structure is also complicated. For the maintenance, monocoque chassis is hard to repair; difficult to detect damaged part when undergoes an accident; and need to change the whole surface even though the damaged area or crack is small. On the other hand, the advantage of monocoque chassis is in term of strength - it is lighter and stronger. A space frame with monocoque structure is quite heavy, but its manufacturing is cost-effective, requires simple tools and damages to the chassis can be easily fixed (Prajwal et al., 2014).

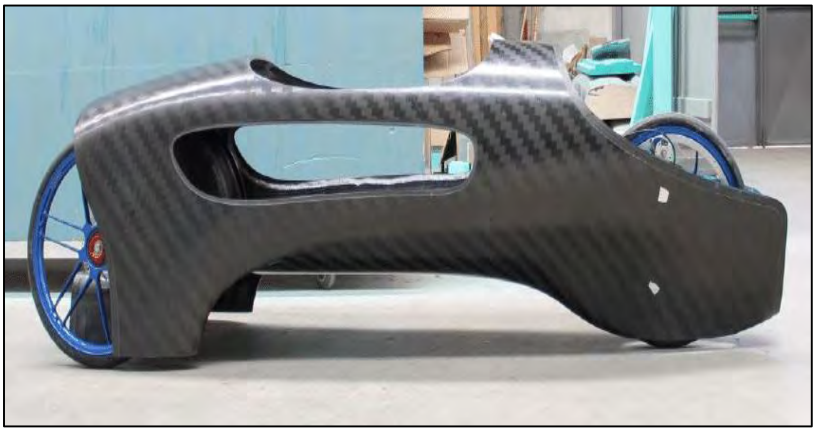


Figure 2.6: Model of a monocoque chassis (Carello et al., 2014).

2.9 MATERIALS

Chassis structure will undergo many kinds of forces during movement, so it has to remain intact without yielding, stiff to absorb vibrations and lastly, it should resist high temperatures. The material selection is an important criterion while designing and manufacturing a car. The two very commonly used materials for making the space frame chassis are Chromium Molybdenum steel which is known as Chromoly 4130 steel and SAE-AISI 1018. SAE-AISI 1018 grade steel is better in terms of thermal properties but weaker than Chromoly 4130 in terms of strength. But the main preference of design is the safety of the driver. Hence, the material with better stiffness and strength must be chosen. The material should not cause any failure even under extreme conditions of driving. Chromoly Steel 4130 exhibits better structural property than SAE 1018 Grade steel. Even though the cost of Chromoly 4130 steel is marginally higher than that of SAE 1018 grade steel, the safety of the driver remains the utmost priority (Prajwal et al., 2014). **Table 2.1** shows the comparison of material properties between SAE AISI 1018 steel and Chromoly 4130 steel.

Table 2.1: Material properties (Prajwal et al., 2014).

Properties	SAE AISI 1018	Chromoly 4130 Steel
Yield Strength (MPa)	360	480
Ultimate Strength (MPa)	420	590

A composite material is a material composed of two or more elements combined on a microscopic scale by mechanical and chemical bonds. Fibre reinforced composites material has a high internal damping capacity which lead to a better absorption of vibration energy within the material. The excellent of fatigue strength weight ratios and fatigue damage tolerances of many composite laminates leads to exchange with metal in many weight-critical components in aerospace, automotive and other industries (Chandra et al., 2012).

Aluminium is a light, conductive, corrosion-resistant metal with a strong affinity for oxygen. This combination of properties has made it a widely used material, with applications in the aerospace, architectural construction and marine industries, as well as many domestic uses. It is also the second most widely used in the world today. Plus, it is also one of the most important metals used in modern societies. Aluminium's strength, light weight, and workability have led to increased use in transportation systems, including light vehicles, railcars, and aircraft in efforts to reduce fuel consumption. The choice of a material will depend on its price, its mechanical properties and its impact on vehicle production costs. Many of vehicle manufacturers must constantly improve their performance at minimum costs. Due to its low weight, good formability and corrosion resistance, aluminium is the material of choice for many automotive applications, such as the chassis, auto body and many structural components. In short, considering the entire life-cycle of an automobile, from the extraction of materials to the final disposal, including recycling and reuse applications, aluminium proved to be a potential alternative to steels in future automotive applications (Gandara, 2012). Another material is titanium, which is hard to fabricate and is an expensive material, but has some similarities with aluminium which are lightweight and quite easy to manufacture but troublesome in welding process.

Next is carbon composite. Usually it is lightweight in structure and defies fatigue phenomenon. However, it is also quite expensive and it can break under huge impact. Lastly, Aluminium 6061 T6 is the best choice of materials selection. It is strong, lightweight aluminium alloy which contains magnesium and silicon, and smooth for tungsten inert gas (TIG) welding (Porter et al., 2014). **Table 2.2** shows the material properties for typically used frame design materials. Meanwhile, **Table 2.3** lists the material properties of a standard steel, fibre and aluminium.

Table 2.2: Material properties for typically used frame design materials (Porter et al., 2014).

Material	Yield Stress (Psi)
Aluminium 6061 T6	11 to 59 10^3

Table 2.3: Comparison of material properties (Kamaruddin et al., 2016).

TYPE OF MATERIAL		
Steel	Fibre reinforced plastic	Aluminium
• Not affected by welding heat and do not require post-welding heat treatment. • 4130 chromyl grade, while stronger than mild steel, does require post-welding heat treatment to restore its mechanical properties. • Good from a metal fatigue perspective and due to the vibration and oscillating loads. • Long chassis life and dependable strength.	• The fibre can be anything from fiberglass to carbon fibre, depending on the requirement to save weight.	• It can provide weight savings. • It may or may not be weldable (Cannot assemble & dissemble after welded). • Expensive material.

2.10 FINITE ELEMENT ANALYSIS OF ANSYS SOFTWARE

Finite Element Analysis (FEA) is a type of computer program that uses the finite element method to analyze a material or object and to find how applied stresses will affect the material or design. The FEA can help determine any points of weakness in a design before it is manufactured. In addition, it is an effective way of determining the static performance of structures for three reasons which are saving in design time, cost effective in construction and increase the safety of the structure. ANSYS Workbench software is one of the tools for FEA. ANSYS Workbench combines the strength of their core product solvers with the project management tool necessary to manage the project workflow. In ANSYS, analyses are built as systems that can be combined into a project. ANSYS Workbench also consists of many analyses; explicit dynamic, static structural, fluid flow, random vibration and others (Southpointe, 2009). In a static structural analysis, ANSYS Workbench is capable of producing Von-mises stress and total deformation of the structure estimations (Choubey, 2016). Graphic Processing Units (GPU) are effective accelerators to diagnose the compute-intensive parts of a program. Their huge number of cores, speed memory and improved programming models allow researchers to study their use for linear algebra. The highest degree of the run time of a direct sparse solver is used in the factorization of dense matrices and their assembly and for this caused; this decomposition was transmitted to GPUs. For ANSYS's case, the matrices are symmetrical and factorized by using generalized Cholesky decomposition (Krawezik & Poole, 2009). Furthermore, the sparse solver is real and complex, symmetric and non-symmetric, positive definite and indefinite, support block Lanczos method and others. For torsional stiffness, FEM simulations are done in order to estimate the value of torsional stiffness for the body-in-white, vehicle body's sheet metal parts without any other sub-assemblies, doors, fenders and others. An estimation range can be set between 17 kNm/deg to 40 kNm/deg for most common car manufacturers and vehicle segments (Danielsson & Cocana, 2015).

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

The actions that need to be carried out to achieve the objectives of this project include literature review, benchmarking, Finite Element Analysis (FEA), results and report writing. This chapter will describe the methodology used in this project to obtain the desired results. Benchmarking is a process in which the findings of the present project are compared to existing data from other sources. This process involved information and data about existing chassis and HPV in the market such as mass, material, strength, type of frame and others. Hence, the results will indicate whether the research objectives have been achieved. The main FEA method for this project employs ANSYS Workbench software to analyze the chassis. Various materials, dimensions and parameters are analyzed and tested in the ANSYS Workbench.

This chapter contains five sections. After the Introduction, the next section delineates the flow chart of project methodology. Section 3.3 discusses benchmarking process while Section 3.4 explains the conceptual design. Section 3.5 looks into the analysis of the project.

3.2 FLOW CHART OF PROJECT METHODOLOGY

The methodology of this project covered the whole semester. It is summarized in the flow chart as shown in **Figure 3.1**.

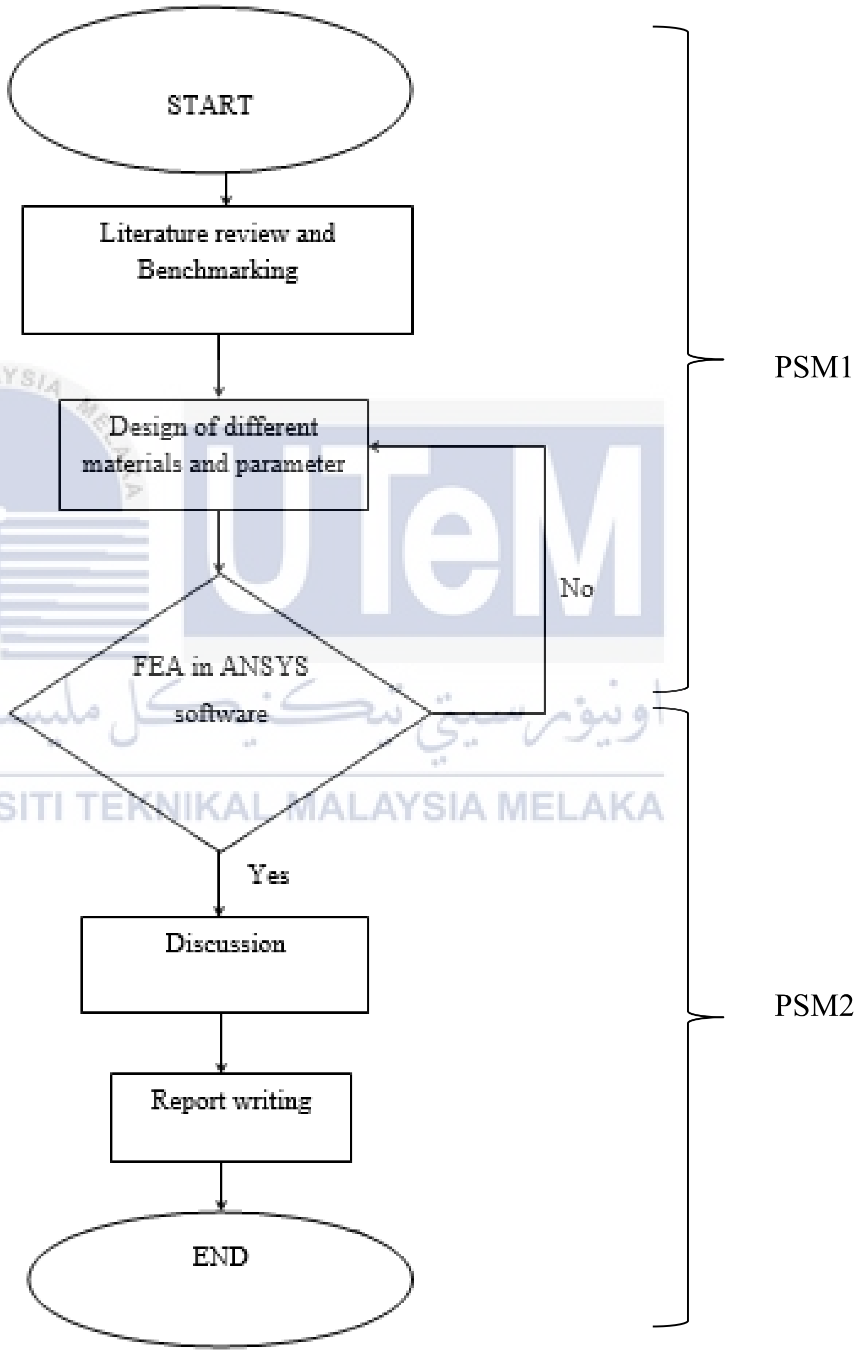


Figure 3.1: Flow chart of project methodology.

3.3 BENCHMARKING

Essential design parameters for a HPV must include weight, speed, cost, rider ergonomics, reliability and easy maintenance. Bike monocoque is able to reduce weight when the changing process of hand sketches to a 3D model takes place. A chromoly steel material in steering and tubing frame contribute to a heavy weight. The material is reliable for costing and easy for assembling process. Even so, carbon fibre, aluminium, magnesium or titanium is examples of better materials to reduce overall weight. A selection of a steel material for frame structure produced a total of 40 lbs which is equivalent to 18.14 kg or less (Knaus et al., 2010). The test description of the HPV involves measuring the weight of all parts and components except for fairing and fairing attachments in a laboratory surrounding. The main goal of a HPV is to transfer its rider safely and efficiently. In order to ensure the safety of the rider, lots of criteria need to be considered such as total deformation or deflection of some particular beams of the chassis structure, stiffness, torsional and bending stiffness, and safety factor of the chassis structure. The deformation of a beam depends on its cross-sectional shape, its length, material selection, constraints and loads distribution to the beams (Elliot, 2000). Deflection is a level to which a structural element is displaced with a certain distance or angle under a force, pressure or load. Deflection is also the limit factor in beam structure design, beams must also be able to withstand the required maximum load to avoid excessive deflection. One of the researches about HPV found that their maximum deflection of AISI 1015 steel chassis structure is 0.08066 mm which is obtained from FEA by using ANSYS Workbench. However, the weight of the frame is 20 kg without considering other components resulting to a total weight of 50 kg (Abhilash & Sri, 2014).

Safety factor is interpreted as how much of an object or structure can withstand loads. In other words, it is defined as how much stronger the structure is than it normally needs to be for a desired load. There are two types of materials which are ductile and brittle material. When a structure material is ductile, deformation or yielding will occur corresponding to the force or pressure exerted upon it before breaking. Meanwhile, if the material is brittle, possibly it will fracture or break after having its maximum load applied upon it. An example of ductile material is steel which allows it to mold and bend along with the direction of the force applied. Glass is an example of a brittle material.

There are two types of strength within the field of a ductile material. First is yield strength and second is ultimate strength. Yield strength is the point of applied load causing the material to deflect or bend with stress. This is referred to as a process of yielding phenomenon. Whereas ultimate strength is the point at which the material will break or fracture when the maximum load is applied. Engineers and designers often used Von-mises stress to check whether the material can withstand the load or otherwise. When the Von-mises stress exceed the yield stress of the particular material, it is considered failed. Safety factor can be obtained from the ratio of yield stress to Von-mises stress as shown in Equation (3.1). FEA was performed for various loading cases to verify the frame. The cases are front wheel landing, rear wheel landing, four-wheel landing, side impact, front impact and rollover. All these cases proved that the frame was safe and obtained the lowest safety factor of 1.5 (Colone et al., 2008). Therefore, it can be concluded that a chassis design with safety factor of more than 1.5 is acceptable.

$$\text{Factor of Safety, FOS} = \sigma_{yield} / \sigma_{von\text{-}mises} \quad (3.1)$$

3.4 CONCEPTUAL DESIGN

Figure 3.2 shows the sketched design of chassis where single rear tire and double front tires attached to the chassis for weight reduction of the chassis to achieve lightweight which is the goal of this project. There are some features and benefits in designing this chassis which are:

a) Single rear wheel drive requires no traction control and gives less traction loss.
b) Three-dimensional design chassis to provide better torsional stiffness.

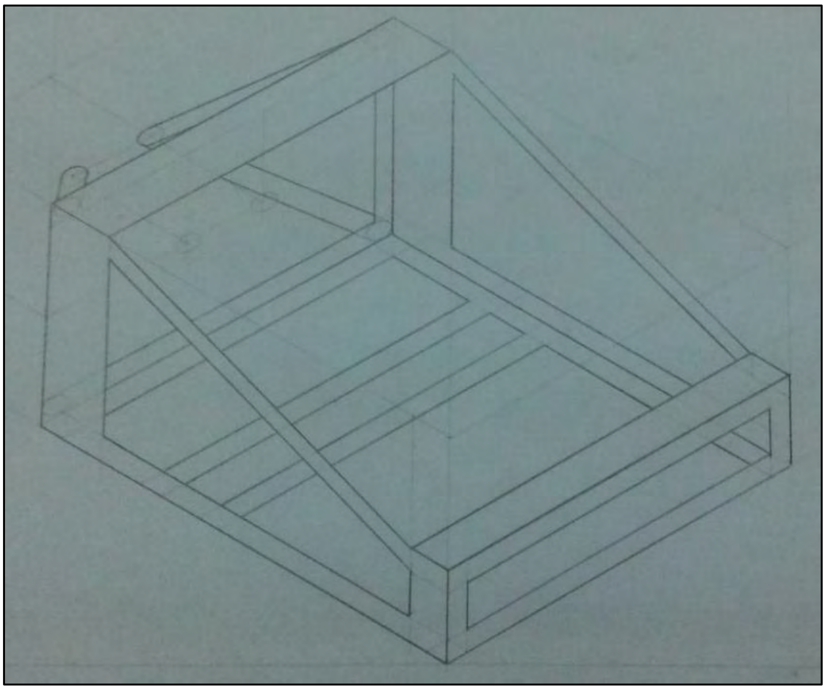


Figure 3.2: Sketched conceptual design.

For the aforementioned reasons, conclusion can be made from this design which provides better stability, flexibility and distribution force during acceleration, deceleration and cornering. Therefore, it enhances the quality of the HPV. **Figure 3.3** and **Figure 3.4** show a CAD model and rendering model of the final design, respectively.

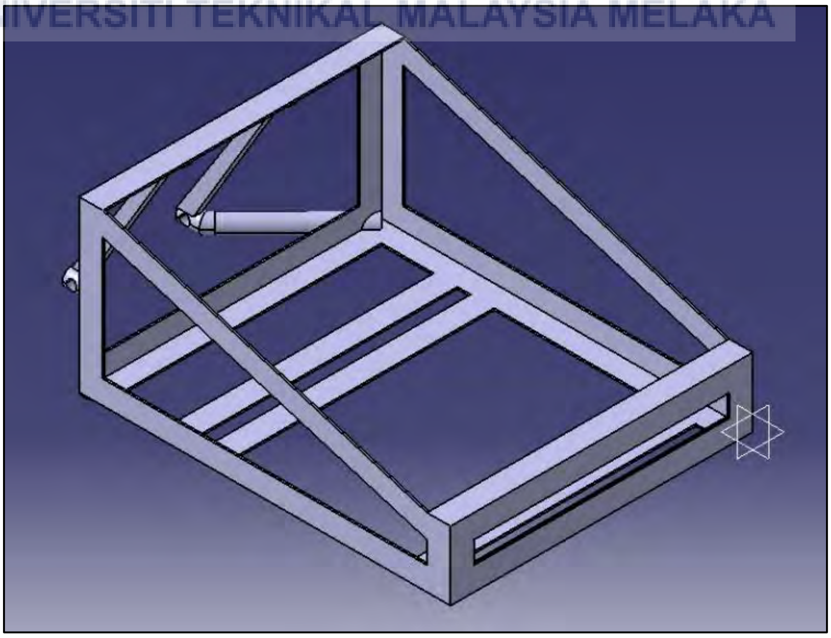


Figure 3.3: CAD model of final design.

Figure 3.4: Rendering model of final design.

3.5 ANALYSIS

CAD is an abbreviation for Computer-Aided Design. It is a software that uses computational system to assist in design, creation, analysis, modification or optimization of a design. CAD software is used to widen the productivity of the designers and engineers, increase the quality of design and to extract a database for manufacturing. Before the CAD drawing process takes place, the design of the chassis was conceptually sketched as shown in **Figure 3.2**. Afterwards, the designed was drawn again in the CAD software. ANSYS Workbench is the chosen software for this project to evaluate the FEA process. It uses the FEA method to solve the underlying governing equations and the related problem-specific boundary condition. Moreover, ANSYS is also able to import CAD data and build geometry with its pre-processing abilities. Besides, it can also run out advanced engineering analyses safely, quickly and practically by its variety of contact algorithms, time based loading features and nonlinear material models.

For structural analysis, FEA has been made to verify the toughness and suitability of the chassis design. There are two types of analysis for this project which are acceleration analysis and cornering analysis. Various materials and shape size or frame dimension will be tested in ANSYS to produce the weight, total deformations, Von-mises stress and safety factor results. Modification of the design is suggested in this chapter to come out with desired results. Hence, there will be several designs to meet the required design of the chassis to meet the research objectives.

Based on the conceptual design section, there are few beams installed to the chassis design. It consists of three types of structural shape beams which are L-shaped, circular shape and rectangular shape. For the materials selection, there are three materials: structural steel, stainless steel and aluminium alloy. These materials have their own characteristics and properties neither physical properties nor chemical properties. It is expected that results would differ when FEA is tested because the material properties will affect the result of the analysis.

The step of drawing the chassis design in ANSYS Workbench started with selecting static structural analysis in the software. The beam structure for the chassis is assumed as a straight line in ANSYS. Every joint part will be plotted using points of coordinate, then the points were joint together with a straight line as shown in **Figure 3.5**. Next, every line will be defined as a particular cross-section. Majorities of the lines are defined as a L-shaped beam, and others are defined as a circular beam and rectangular beam as shown in **Figure 3.6**. Rectangular beam cross-sectional is defined at the specific line which will hold the load of the rider. The cross-sectional geometries of L-shaped, circular shape and rectangular shape are shown in **Figure 3.7**, **Figure 3.8** and **Figure 3.9,** respectively. After that, meshing process take place, ANSYS separated mesh evenly on the drawing as shown in **Figure 3.10**.

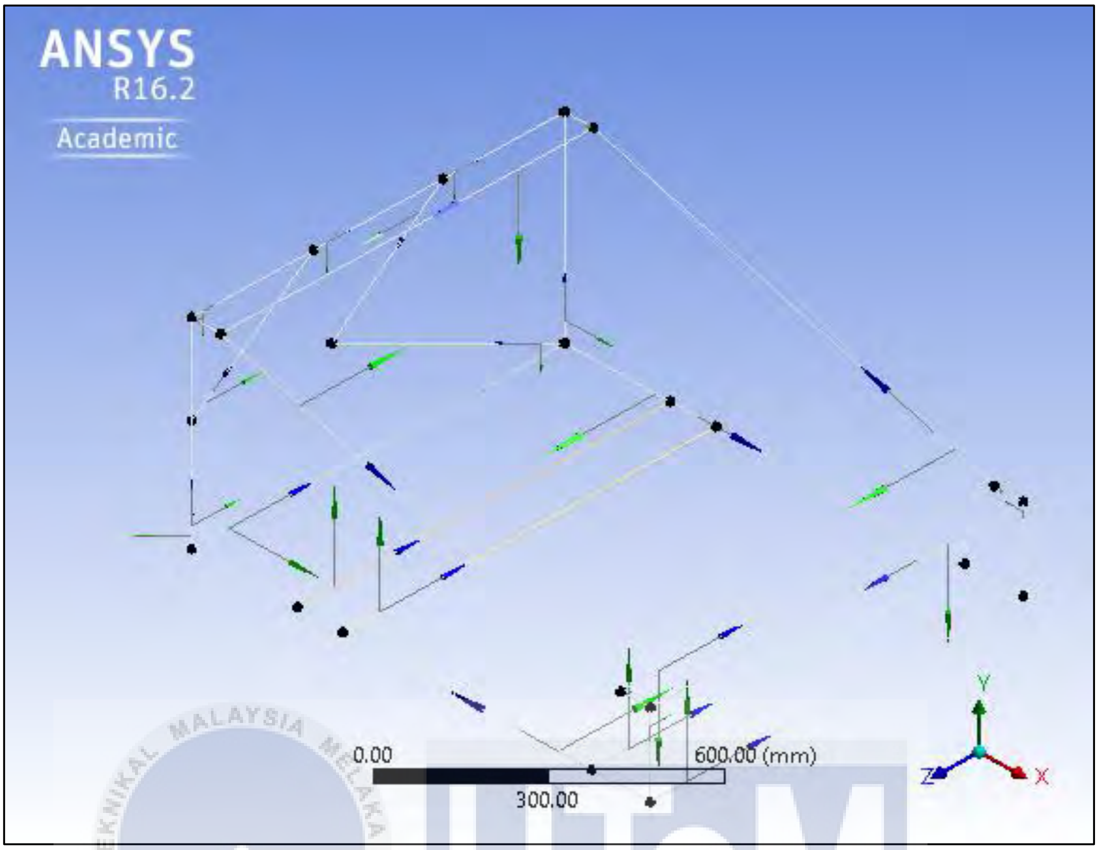


Figure 3.5: Idealization of the chassis using line element.

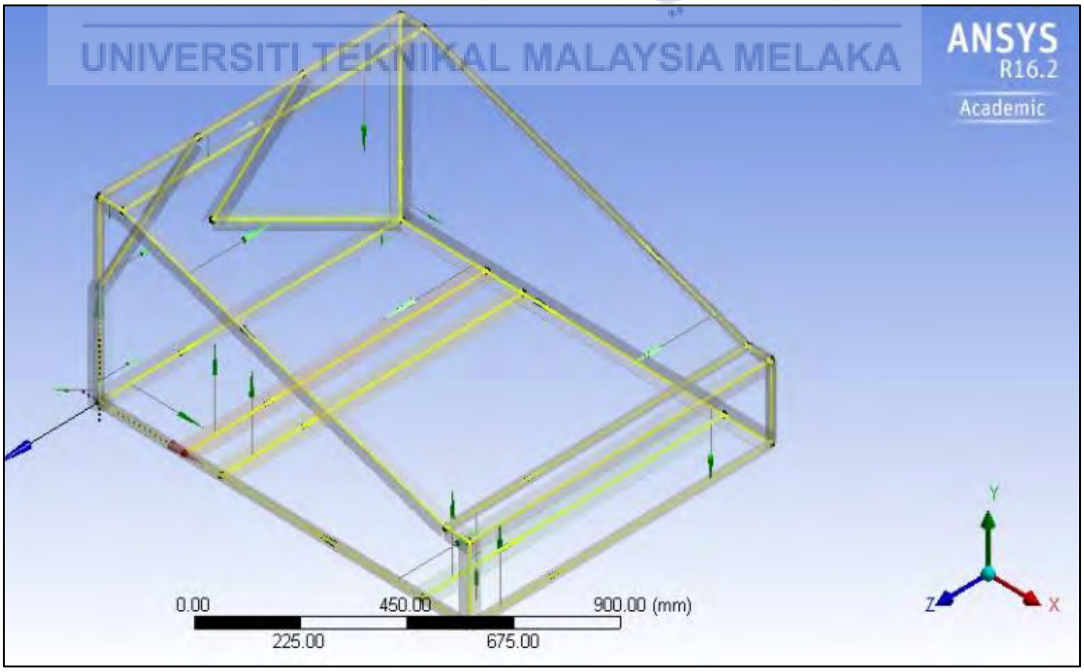


Figure 3.6: Model visualization with cross-sections.

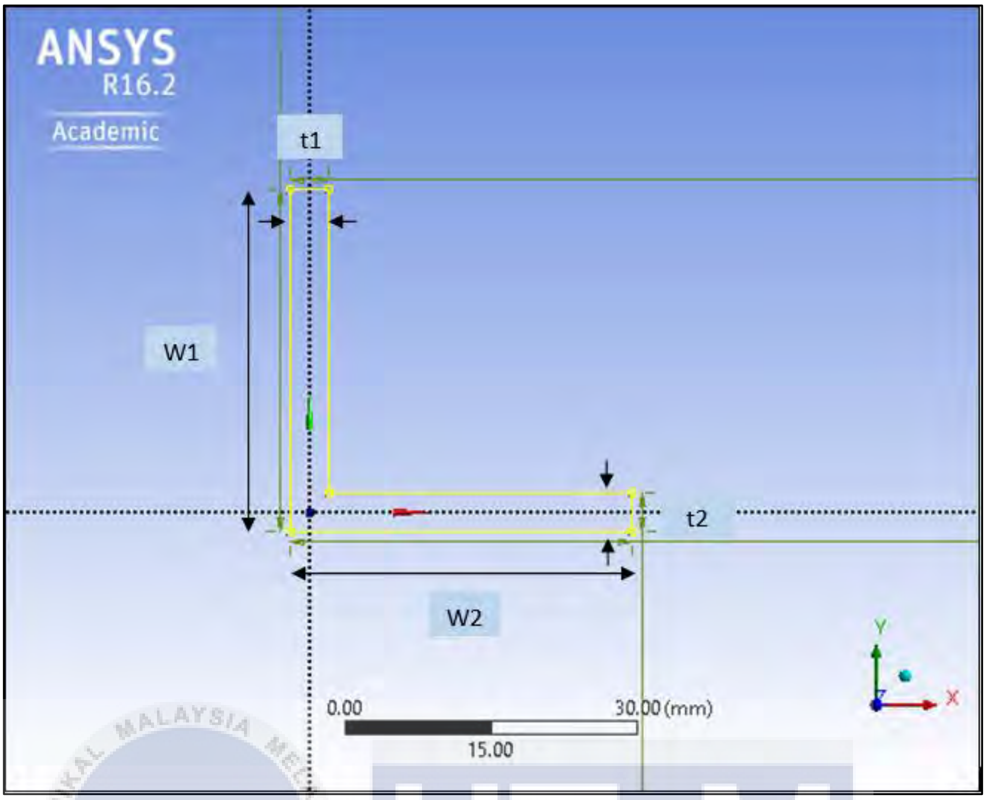


Figure 3.7: L-shaped cross-sectional beam.

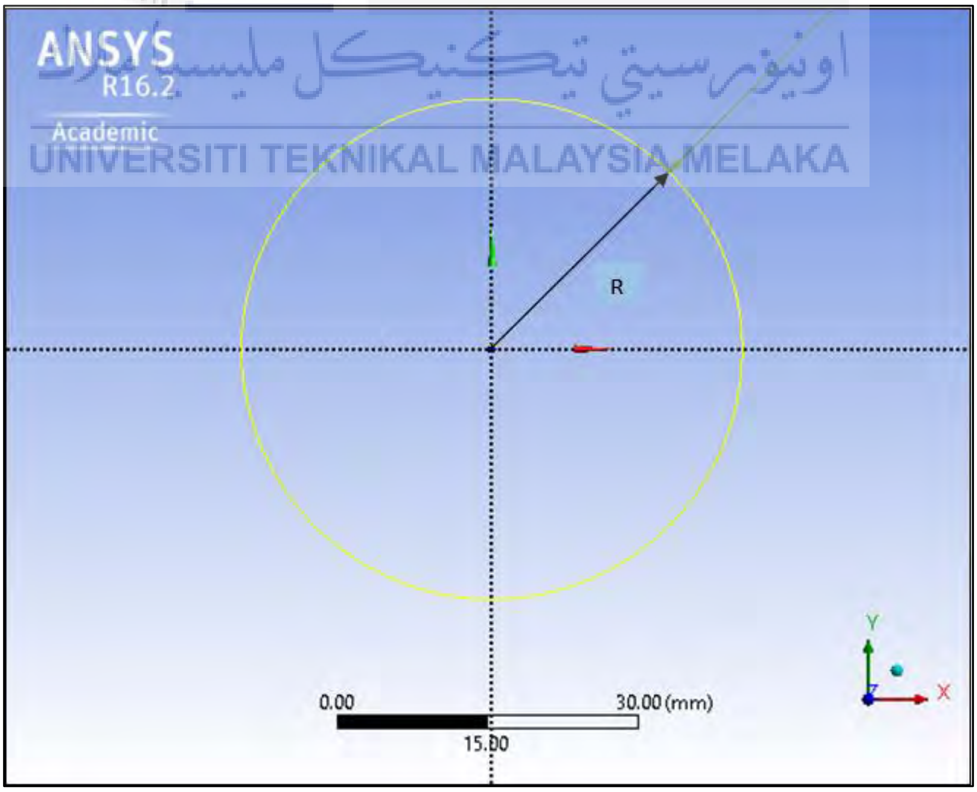


Figure 3.8: Circular cross-sectional beam.

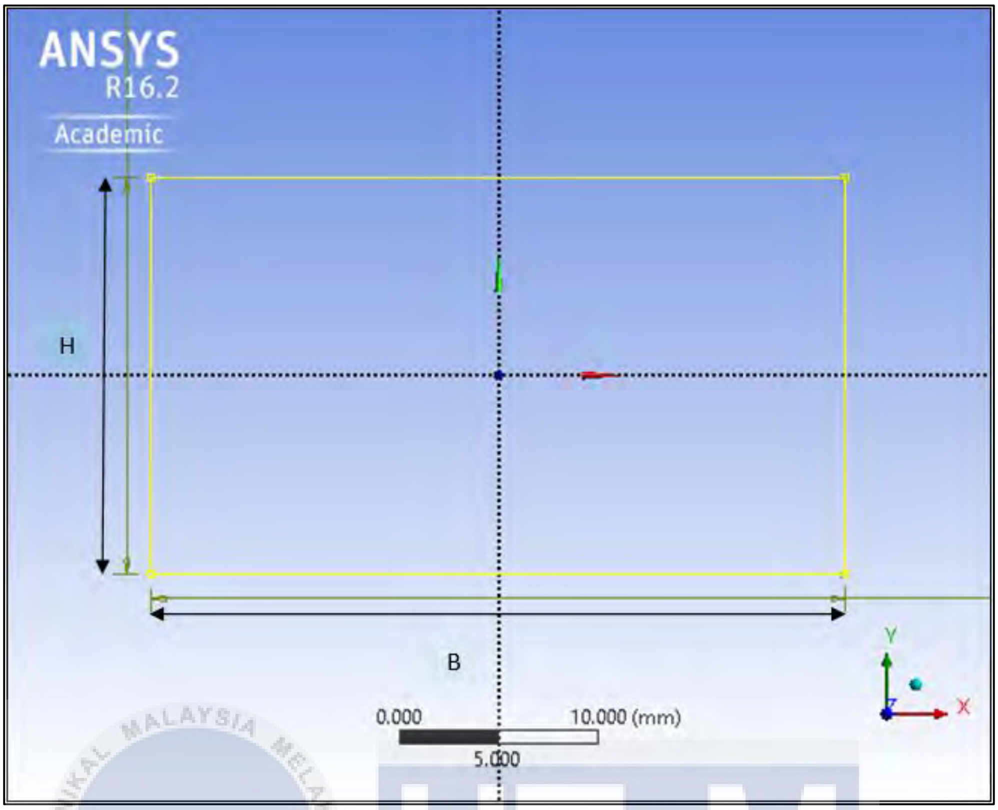


Figure 3.9: Rectangular cross-sectional beam.

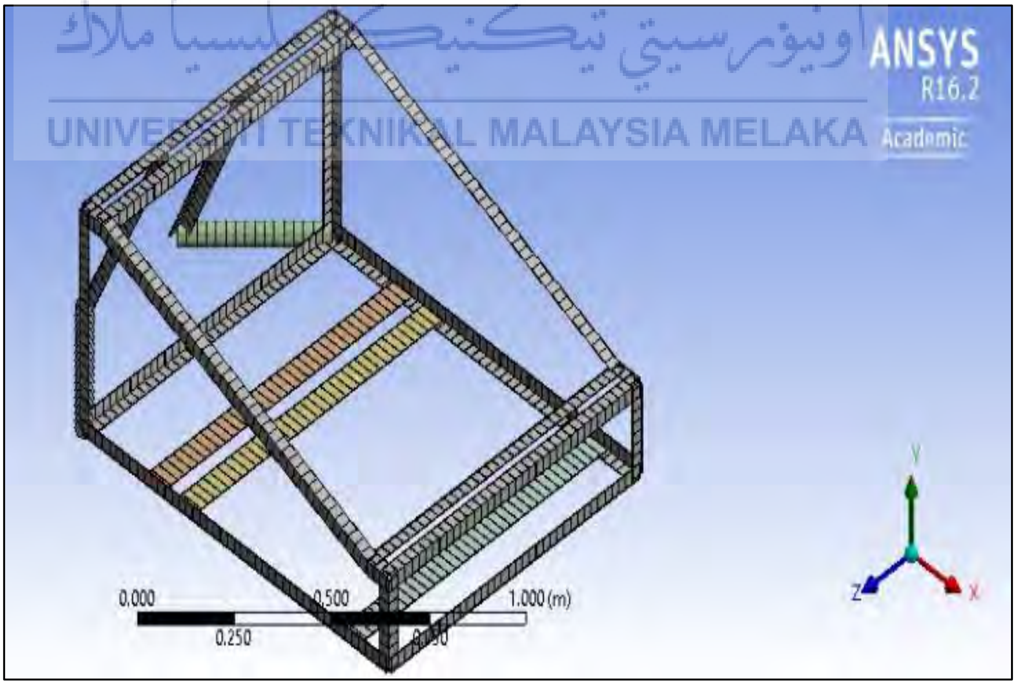


Figure 3.10: Computational model featuring elements.

There are two elements or parameters that need to be considered namely bending loads and torsional loads. The bending loads analyses were analysed through acceleration and cornering analysis. Meanwhile, the torsional loads analysis only covers static analysis. For torsional loads analysis, three points were set as fixed supports as shown in **Figure 3.11**. These points represent the position of two tyres out of three tyres which are the single rear tyre and the right front tyre. Then, a single force with 490.5 N downwards was applied at the left front tyre as shown in **Figure 3.12** since all the other point of the tyres was considered as a fixed supported. This torsional analysis was analysed only to the final design of the chassis which already achieved the most lightweight design and acceptable maximum total deformation. The value of maximum total deformation will be used to calculate torsional stiffness of the structure. Hence, the value of the torsional stiffness will be compared with existing value from another source. After that, the design is analysed again in the ANSYS Workbench to gain Von-mises stress and the safety factor of the design. Finally, the design is considered successful if the safety factor is equal to or exceed 2.0.

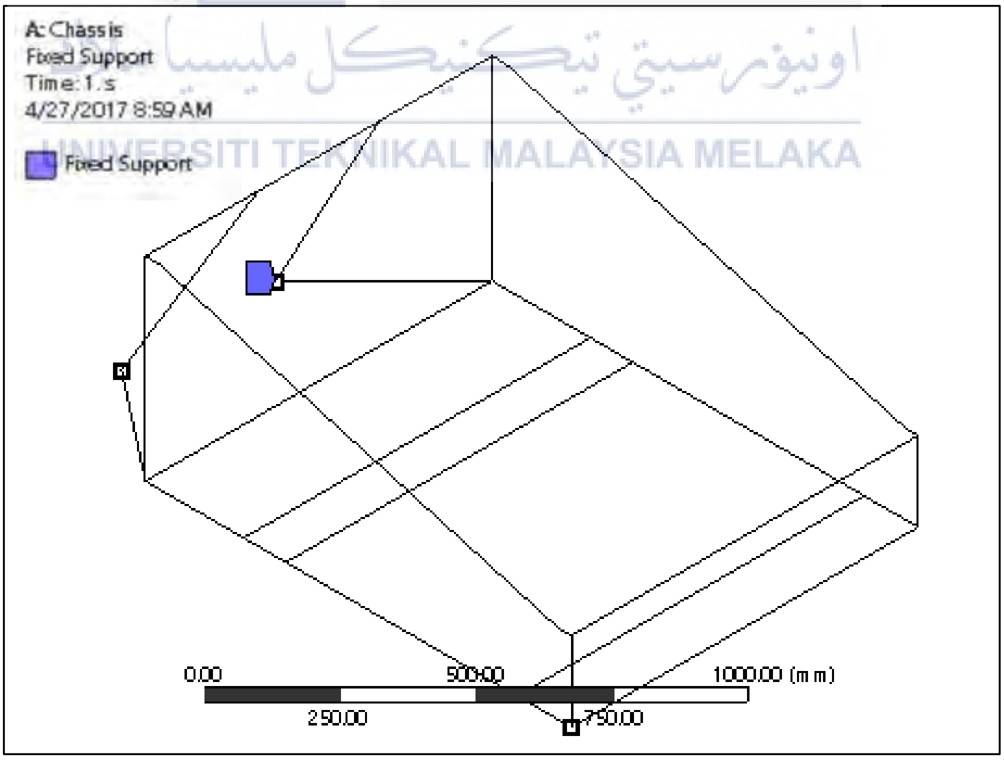


Figure 3.11: Computational model featuring constraints for torsional analysis.

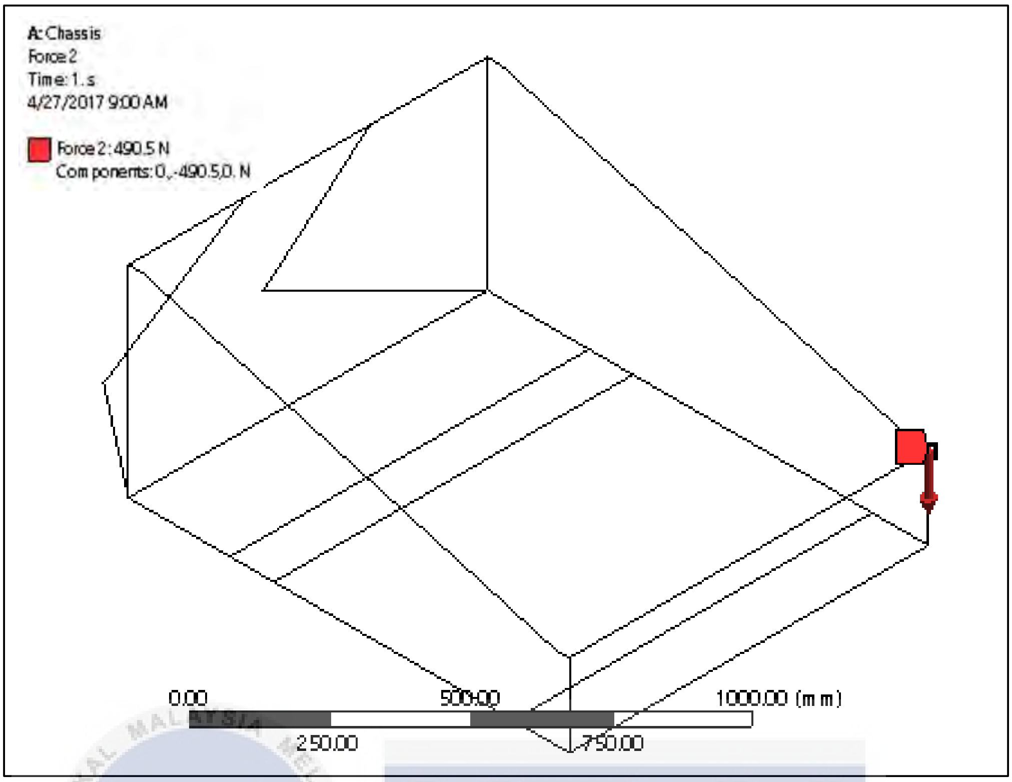


Figure 3.12: Computational model featuring loads for torsional analysis.

Bending loads analysis consists of acceleration and cornering analysis. The bending moment occurred at the beam structure where the rider will be seated. The maximum mass of the rider is assumed to be 100 kg, thus the maximum loads will be 981 N. In this project, the analysis is still in static analysis. But for the acceleration and cornering analysis, the assumption is it is in acceleration and cornering condition with static structure. Thus, the vehicle will not move and it is not considered as a fully dynamic analysis. The analysis for the acceleration and cornering condition is affected by the way of force applied or distributed to the beam structure. All the points which are located and hooked with the tyres of the chassis were considered as a fixed support as shown in **Figure 3.13**.

There will be two forces applied to the chassis structure for each bending loads analysis. The first force was applied at the middle of the chassis where the driver would be seated with the force of 981 N downwards in the direction as shown in **Figure 3.14**. This force represents the driver who is in a sitting position with his weight towards downwards direction. The same force also covers for acceleration and cornering analysis.

The second force will differentiate between acceleration and cornering analysis condition. While the first force is applied on the structure, the second force for acceleration analysis was applied as another force at the same beam structure but is applied from frontal direction of the chassis as shown in **Figure 3.15,** which is known as front loads. The same goes for cornering analysis. The only difference is the direction of the force which is from the right side of the chassis as shown in **Figure 3.16**. This force is known as the side force or side loads.

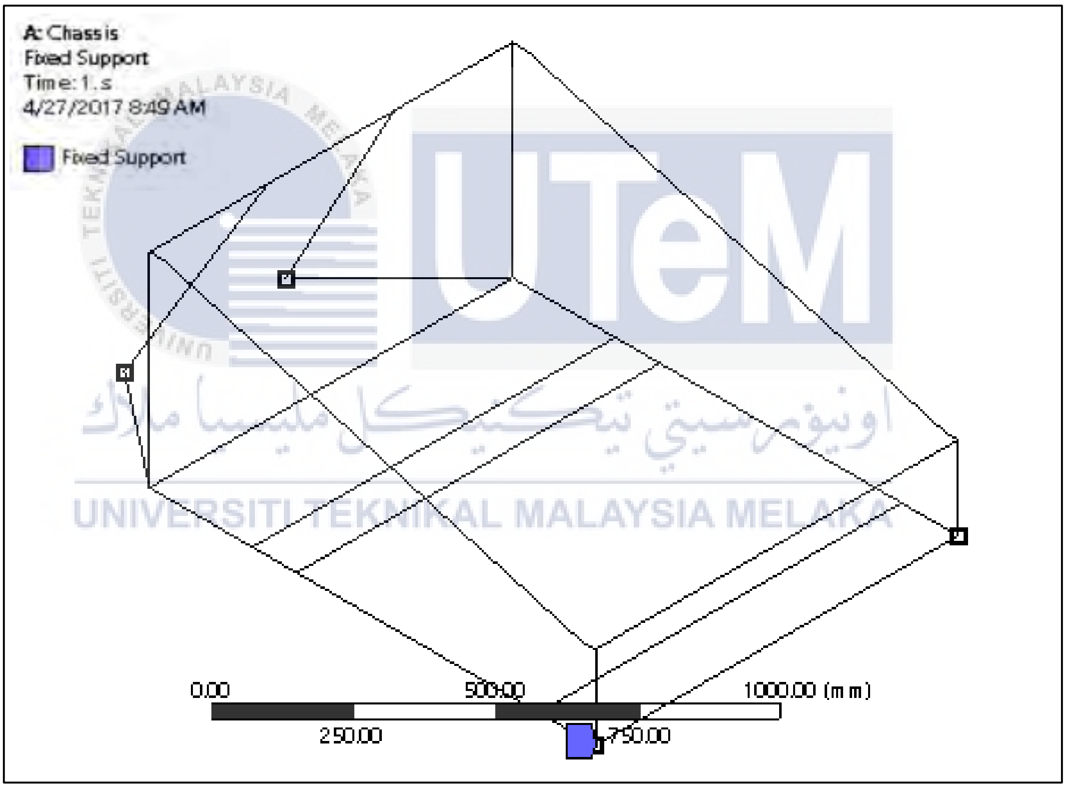


Figure 3.13: Computational model featuring fixed support for bending loads analysis.

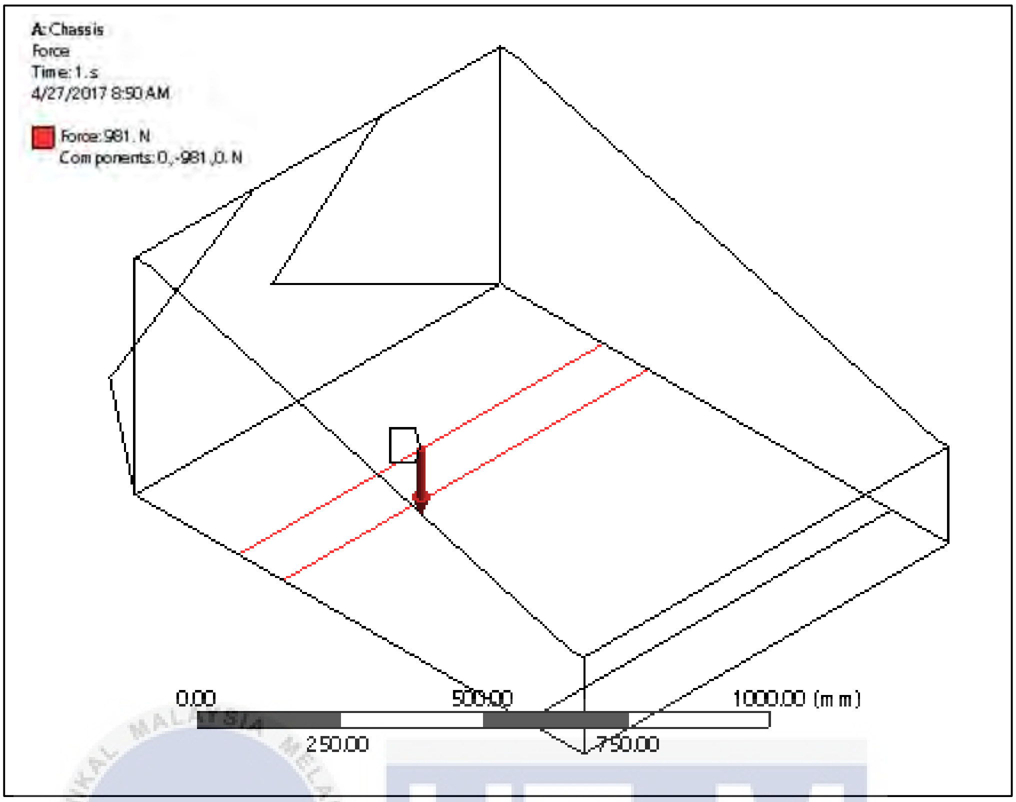


Figure 3.14: Computational model featuring downwards loads.

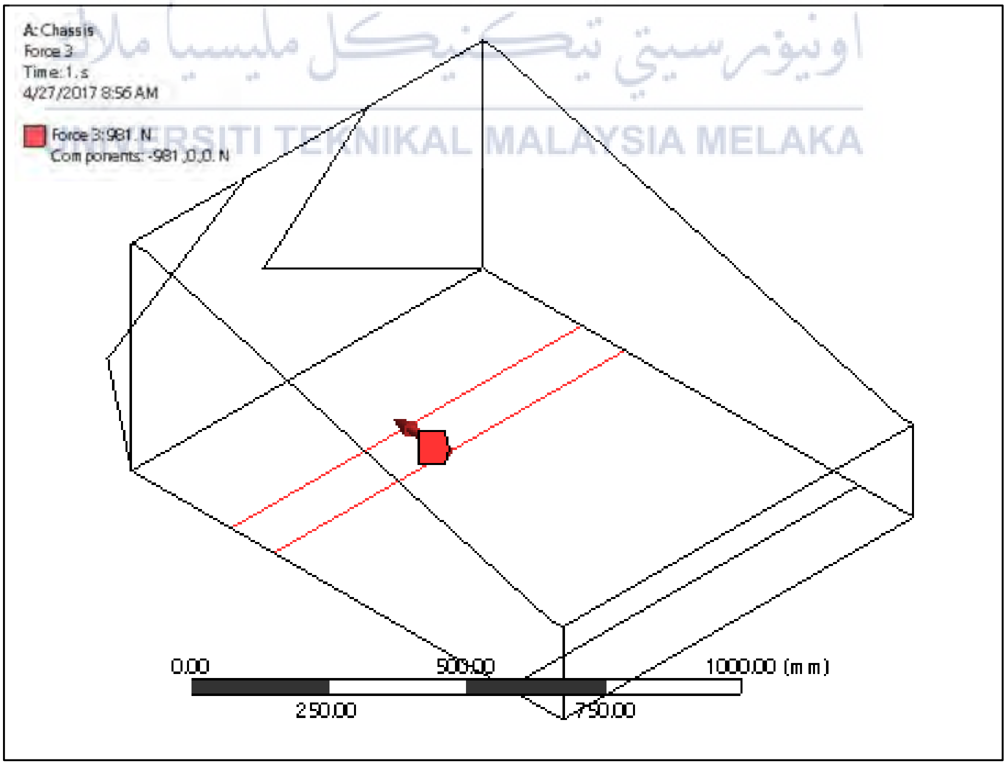


Figure 3.15: Computational model featuring front loads for acceleration analysis.

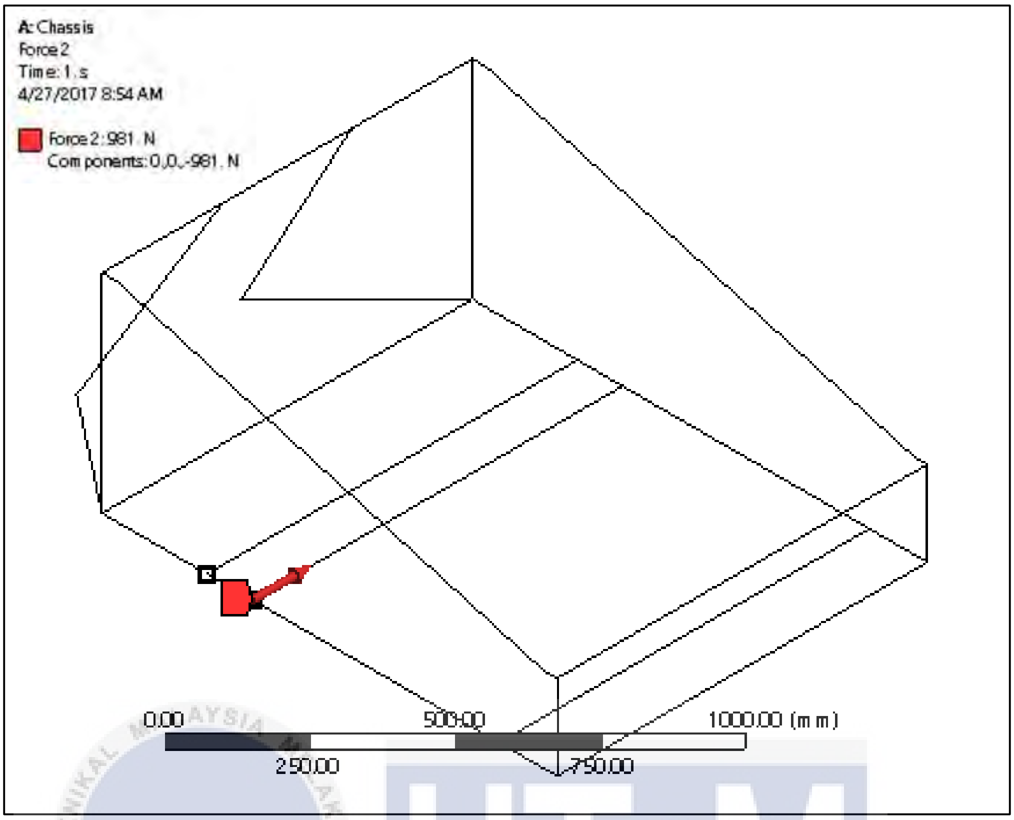


Figure 3.16: Computational model featuring side loads for cornering analysis.

When the drawing of the chassis has been completed, the next step will ensure the feasibility of the project. The materials selection mentioned earlier were applied to the drawing of the chassis in ANSYS Workbench to analyse the design. The three materials tested (structural steel, stainless steel and aluminium alloy) yield different results. The main objective for this step is to compare and analyse the weight of the chassis for each material. Based on the findings of the analysis, the most lightweight chassis will be chosen to continue to the next stage of the project.

It should be noted that cost of the materials will not be covered and considered for the existing project. Hence, the selection of the materials is irrespective of their cost and/or the cost of the total project. The project will continue with the selected material that display the most lightweight chassis regardless of the cost of acquiring it. Finally, the selected chassis design was tested and analyzed by using different size of shape structures and cross-sectional beam geometries. **Table 3.1** shows the overall geometries of cross-sectional beams for the chassis structure from the first design to the fourth design. This stage will produce desirable weight with acceptable maximum deflection, Von-mises stress and safety factor. The results will be discussed in the next chapter.

Table 3.1: Overall geometries of cross-sectional beams.

Design	L-shaped (mm)				Cylindrical (mm)	Rectangular (mm)	
	t1	t2	W1	W2	R	B	H
1	4	4	35	35	25	35	20
2	4	4	30	30	20	35	20
3	4	4	25	25	15	35	20
4	3	3	25	25	15	35	20

CHAPTER 4

RESULTS AND DISCUSSION

4.1 ANSYS ANALYSIS RESULTS

This chapter discusses the results of this project which contains total deformation for cornering, acceleration and torsional analysis, bending stiffness and torsional stiffness, mass of each design of the chassis and lastly the safety factor. The results are obtained from ANSYS software with various types of materials used. Specific calculations are performed to obtain bending stiffness and torsional stiffness as well as the safety factor measurements. The results for the fourth designed only are shown and discussed.

This chapter is divided into two sub-sections. Section 4.1 discusses total deformation for cornering analysis and Section 4.2 examines bending and torsional stiffness. The overall results are combined and grouped into tables. The graphical visualizations of the results are also made available. Next, results are discussed in the last section based on the theoretical framework of the analysis in order to answer the research objectives. For that purpose, a weight decision matrix method is used to identify which design and material works best. Lastly, the selected designs will be analysed based on safety factor to make sure the design is safe and usable.

4.1.1 TOTAL DEFORMATION FOR CORNERING ANALYSIS

There are three type of materials tested in this project namely aluminum alloy**,** structural steel and stainless steel. This section will show the total deformation for cornering analysis with respect to the fourth designs of aluminum alloy, structural steel and stainless steel as well as an overall table and a graphical illustration. **Figure 4.1**, **Figure 4.2 and Figure 4.3** show the total deformation of the fourth design of aluminium alloy, structural steel and stainless steel chassis, respectively for cornering analysis. Lastly, **Table 4.1** shows overall total deformation for cornering analysis followed by **Figure 4.4** which shows the graph of the total deformation for cornering analysis.

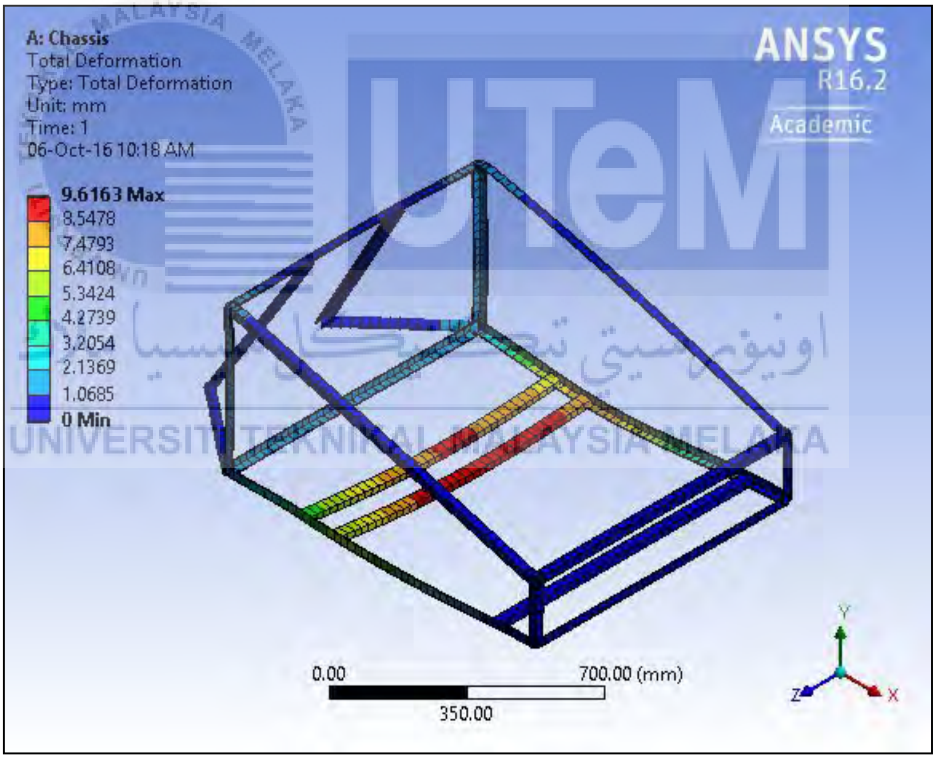


Figure 4.1: Fourth design of aluminium alloy chassis for cornering analysis.

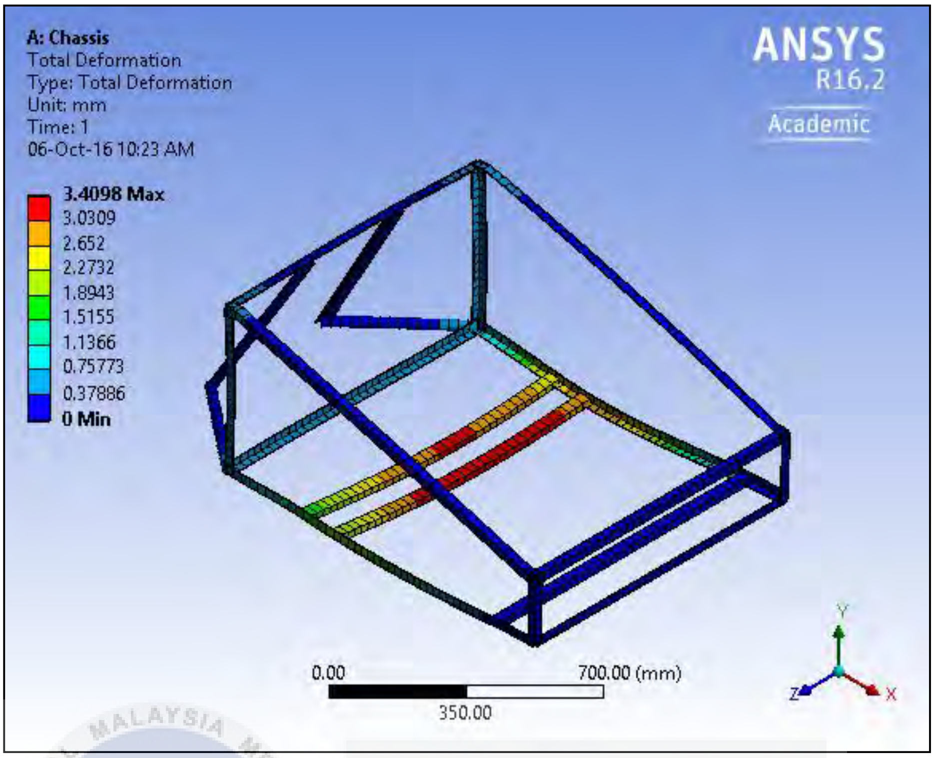


Figure 4.2: Fourth design of structural steel chassis for cornering analysis.

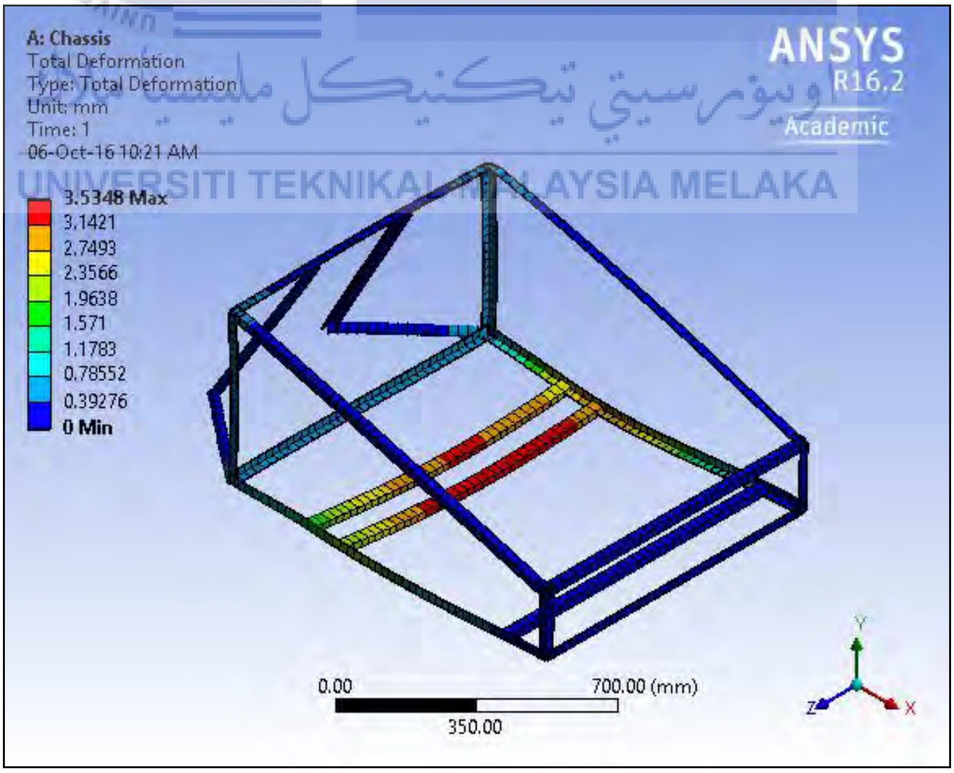


Figure 4.3: Fourth design of stainless steel chassis for cornering analysis.

Table 4.1: Overall total deformation for cornering analysis.

Design	Total deformation for cornering analysis (mm)		
	Structural Steel	Stainless Steel	Aluminium Alloy
1	1.6534	1.7139	4.6616
2	2.0492	2.1243	5.7784
3	2.9750	3.0841	8.3900
4	3.4098	3.5348	9.6163

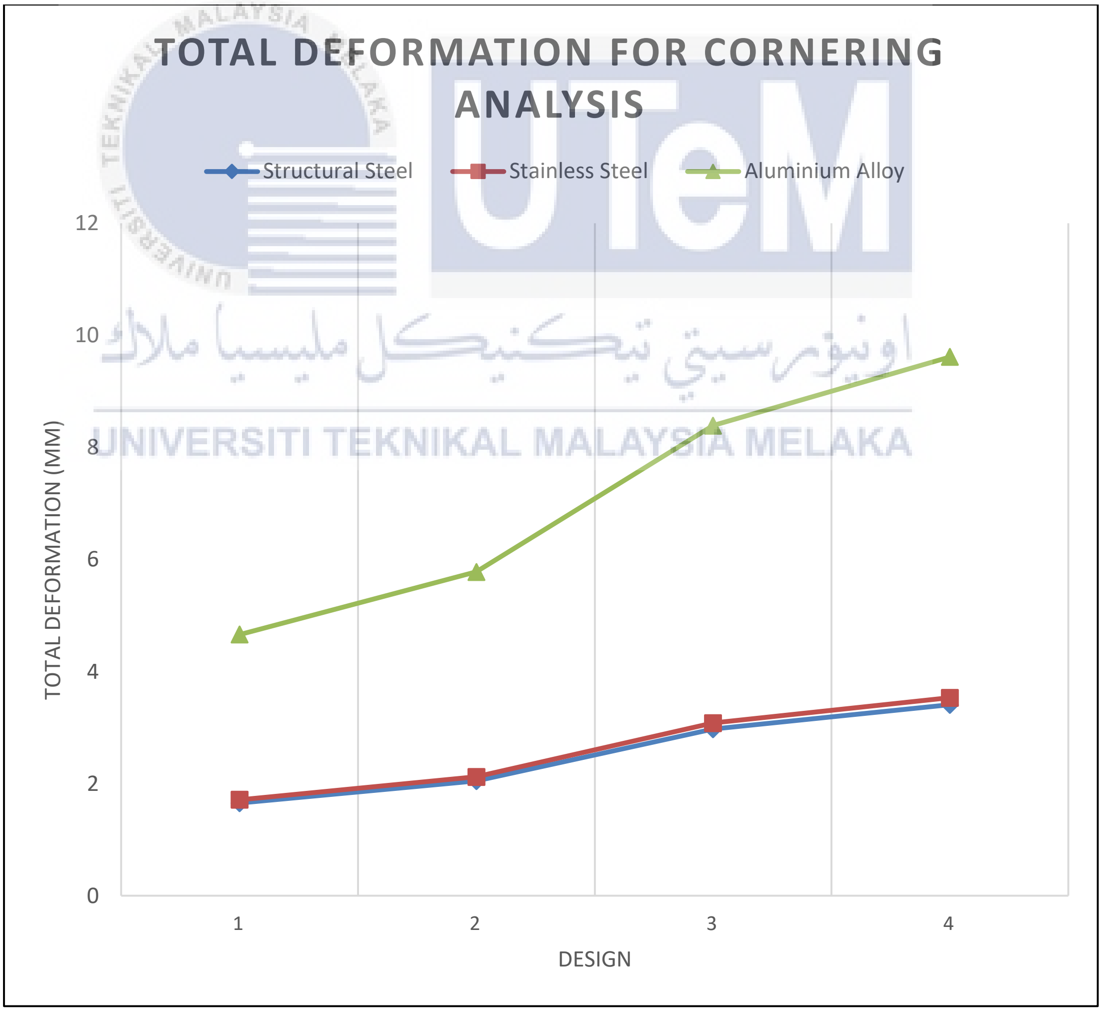


Figure 4.4: Total deformation for cornering analysis.

4.1.2 TOTAL DEFORMATION FOR ACCELERATION ANALYSIS

This section shows the total deformation for acceleration analysis with respect to fourth designs of aluminum alloy, structural steel and stainless steel including an overall table and a graphical illustration. **Figure 4.5**, **Figure 4.6 and Figure 4.7** show the total deformation of fourth design of aluminium alloy, structural steel and stainless steel chassis, respectively for acceleration analysis. **Table 4.2** shows overall total deformation for acceleration analysis followed by **Figure 4.8** which illustrates total deformation for acceleration analysis.

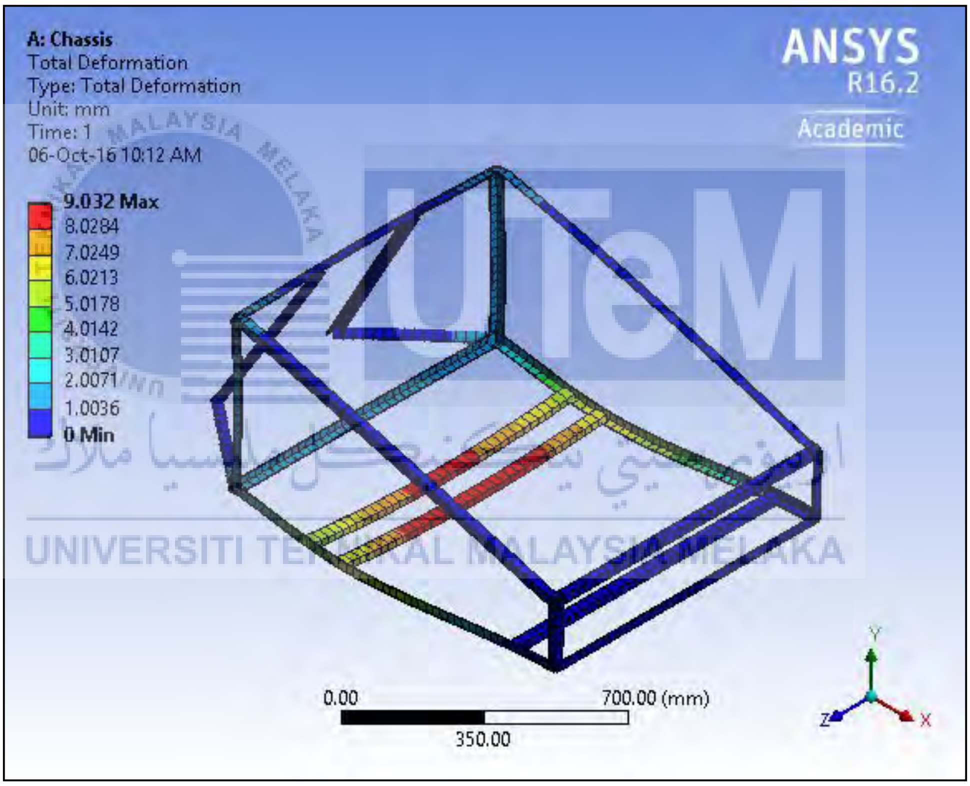


Figure 4.5: Fourth design of aluminum alloy chassis for acceleration analysis.

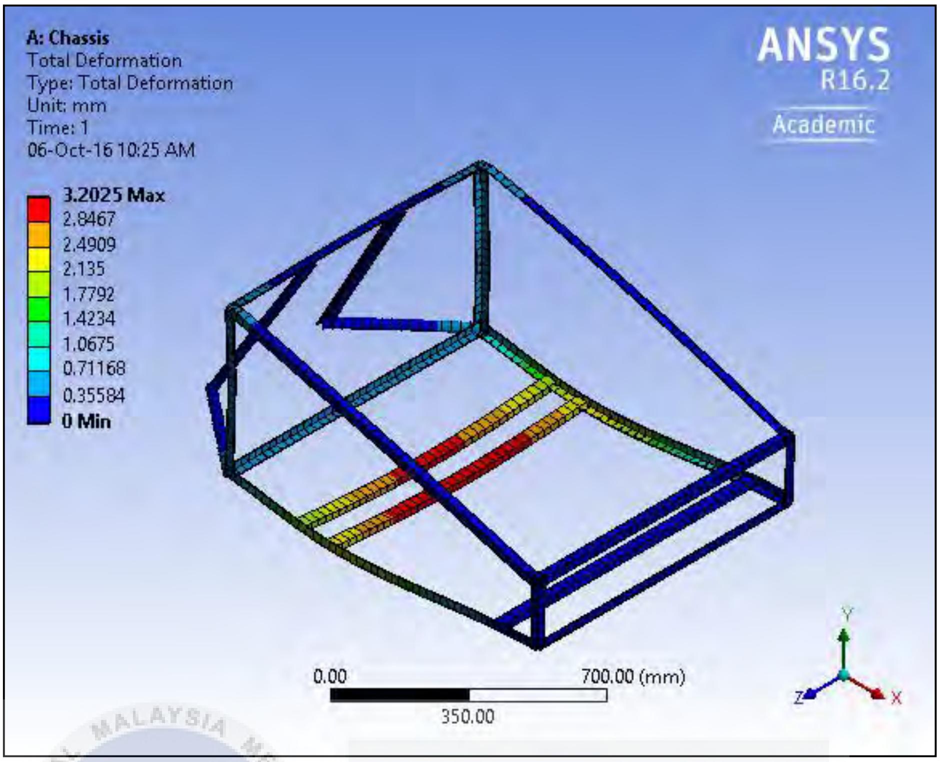


Figure 4.6: Fourth design of structural steel chassis for acceleration analysis.

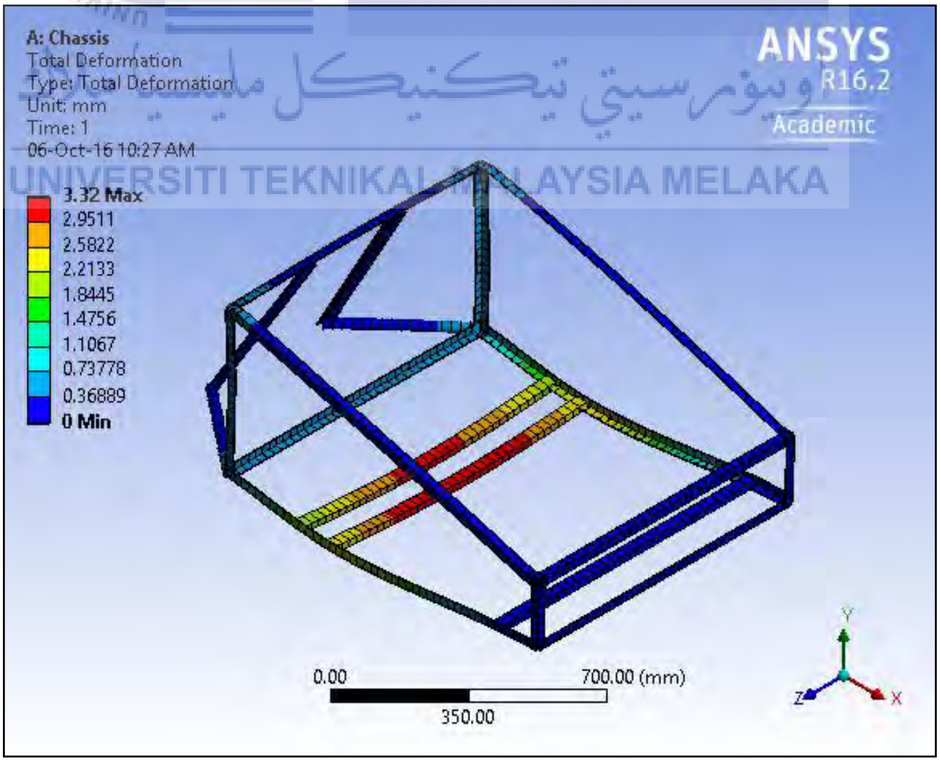


Figure 4.7: Fourth design of stainless steel chassis for acceleration analysis.

Table 4.2: Overall total deformation for acceleration analysis.

Design	Total deformation for acceleration analysis (mm)		
	Structural Steel	Stainless Steel	Aluminium Alloy
1	1.5571	1.6141	4.3899
2	1.9356	2.0064	5.4577
3	2.8155	2.9188	7.9402
4	3.2025	3.3200	9.0320

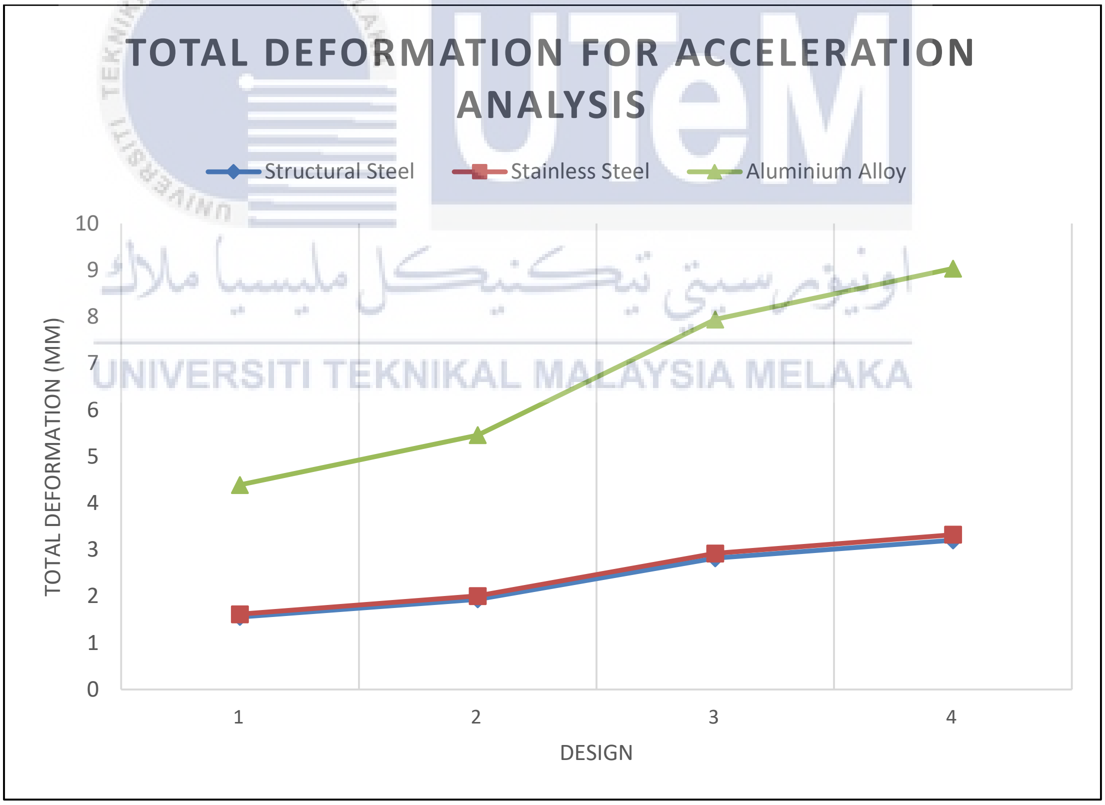


Figure 4.8: Total deformation for acceleration analysis.

4.1.3 TOTAL DEFORMATION FOR TORSIONAL ANALYSIS

Total deformation of the fourth design of aluminum alloy, structural steel and stainless steel chassis for torsional analysis are shown in **Figure 4.9**, **Figure 4.10** and **Figure 4.11** respectively. Finally, **Table 4.3** shows overall total deformation for torsional analysis followed by **Figure 4.12** which displays the total deformation for torsional analysis.

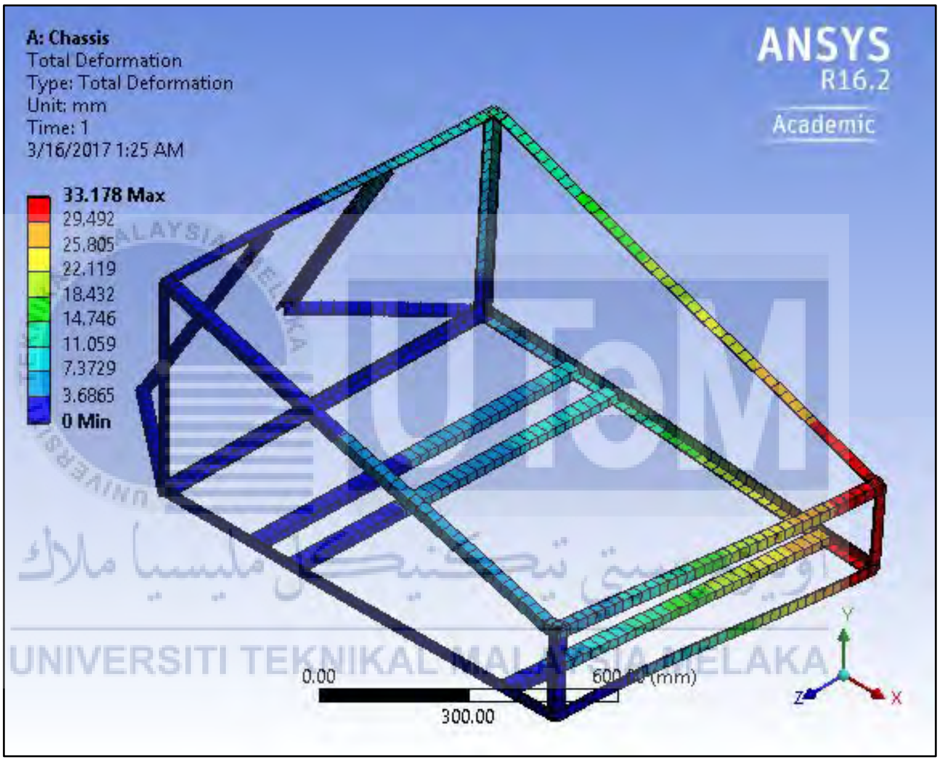


Figure 4.9: Fourth design of aluminum alloy chassis for torsional analysis.

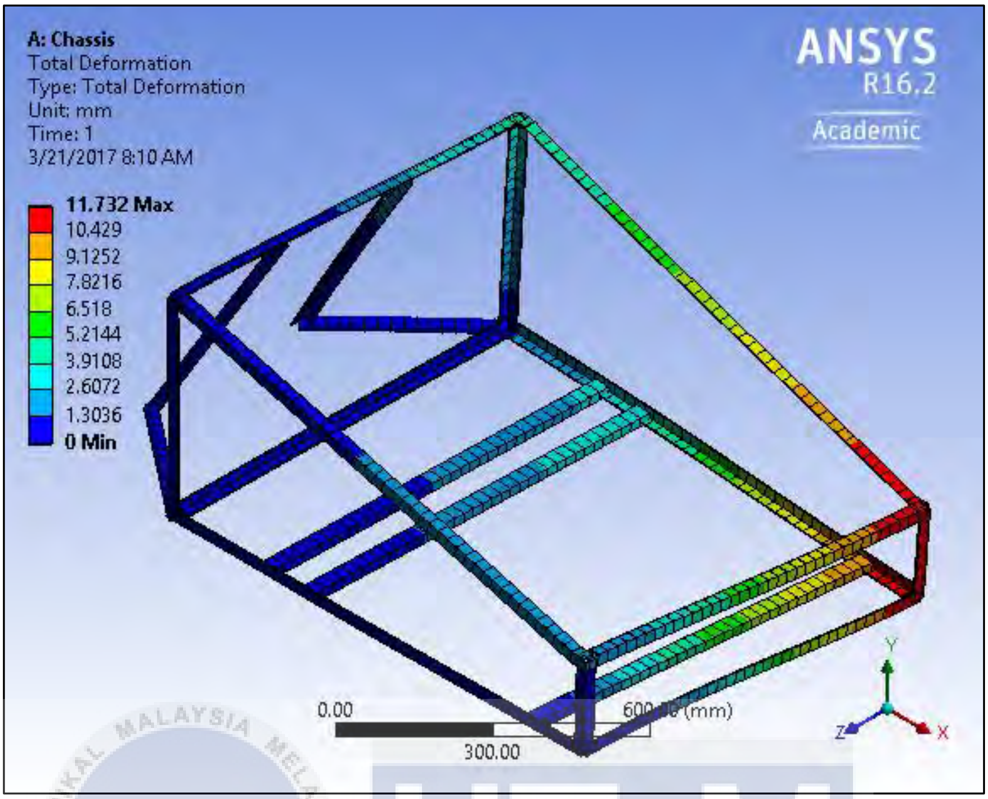


Figure 4.10: Fourth design of structural steel chassis for torsional analysis.

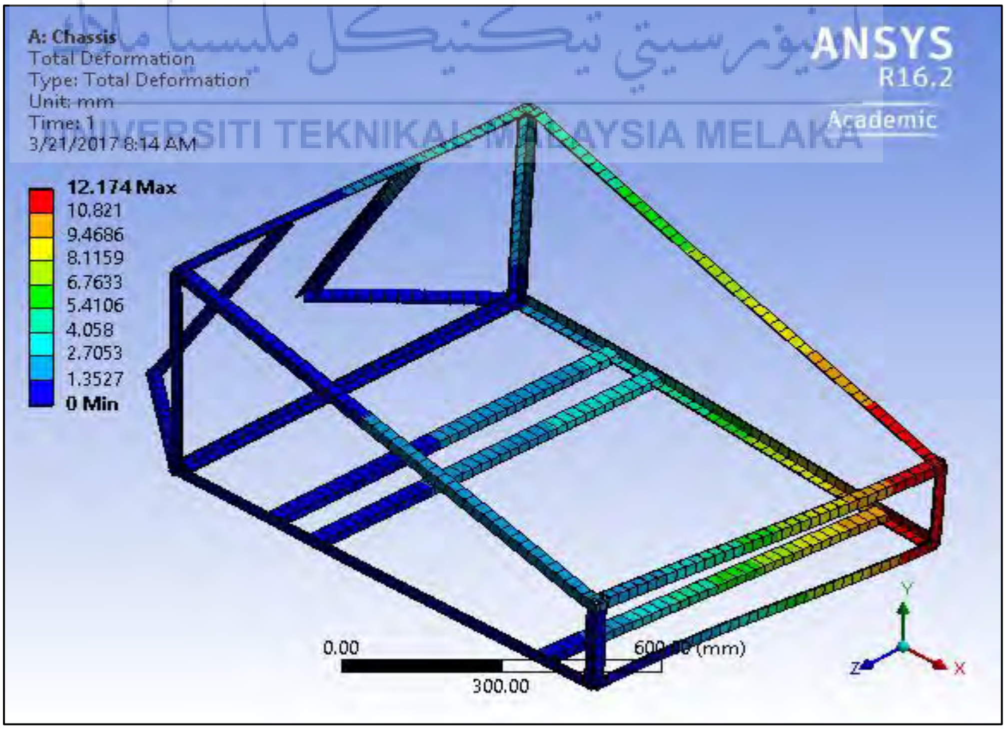


Figure 4.11: Fourth design of stainless steel chassis for torsional analysis.

Table 4.3: Overall total deformation for torsional analysis.

Design	Total deformation for torsional analysis (mm)		
	Structural Steel	Stainless Steel	Aluminium Alloy
1	3.3204	3.4440	9.3792
2	5.3805	5.5815	15.2040
3	9.5491	9.9076	26.9980
4	11.7320	12.1740	33.1780

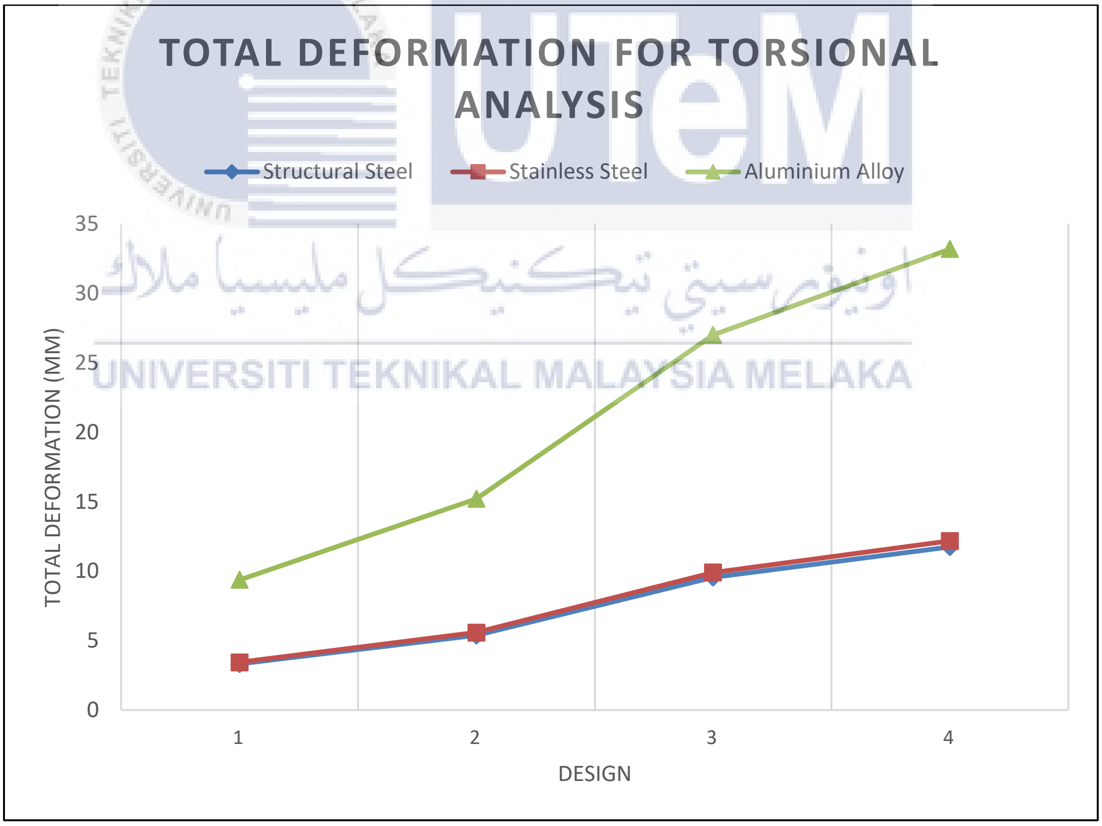


Figure 4.12: Total deformation for torsional analysis.

4.2 BENDING AND TORSIONAL STIFFNESS

Total deformation of a static structure may present the strength and toughness of a chassis with particular material and design. This can be shown by calculating the stiffness of the structure. It is important in designing products such as bridges, bicycles, furniture and others which can only be allowed to deflect by a certain amount. In transport applications for example aircraft, racing bicycles and HPV, stiffness is required at a minimum weight. The previous total deformation results are used to calculate the stiffness of the chassis structure.

Table 4.4 shows an overall bending stiffness for cornering analysis followed by **Figure 4.13** which shows bending stiffness for cornering analysis. Meanwhile, **Table 4.5** shows overall bending stiffness for acceleration analysis and **Figure 4.14** shows bending stiffness for acceleration analysis. In addition, **Table 4.6** and **Table 4.7** shows overall torsional stiffness and overall mass of the chassis design, respectively. Meanwhile, **Figure 4.15** shows a free body diagram of the chassis structure with respect to a frontal view. Lastly, **Figure 4.16** and **Figure 4.17** shows overall torsional stiffness analysis and overall mass of the chassis design, respectively. In these cases, materials with a large specific stiffness are the best. The stiffness can be expressed as:

$$k = F / \delta \tag{4.1}$$

where,

k = Stiffness (N/m)

F = Applied Force (N)

δ = Deformation (m)

Whereas, the stiffness formula for torsional moment can be expressed as:

$$k = M_t / \theta \tag{4.2}$$

Where,

M_t = Twisting Moment (Nm)

θ = Angle of rotation (rad)

Sample calculation of bending stiffness for cornering analysis is shown below:

$k = F / \delta$

$F = 100(9.81) = 981$ N

$k = 981$ N / 0.009616 m

$k = 102.02$ kN/m

Table 4.4: Overall bending stiffness for cornering analysis.

Design	Bending Stiffness (kN/m)		
	Structural Steel	Stainless Steel	Aluminium Alloy
1	594.55	573.68	210.52
2	478.54	462.74	169.72
3	329.19	318.51	116.92
4	287.68	277.90	102.02

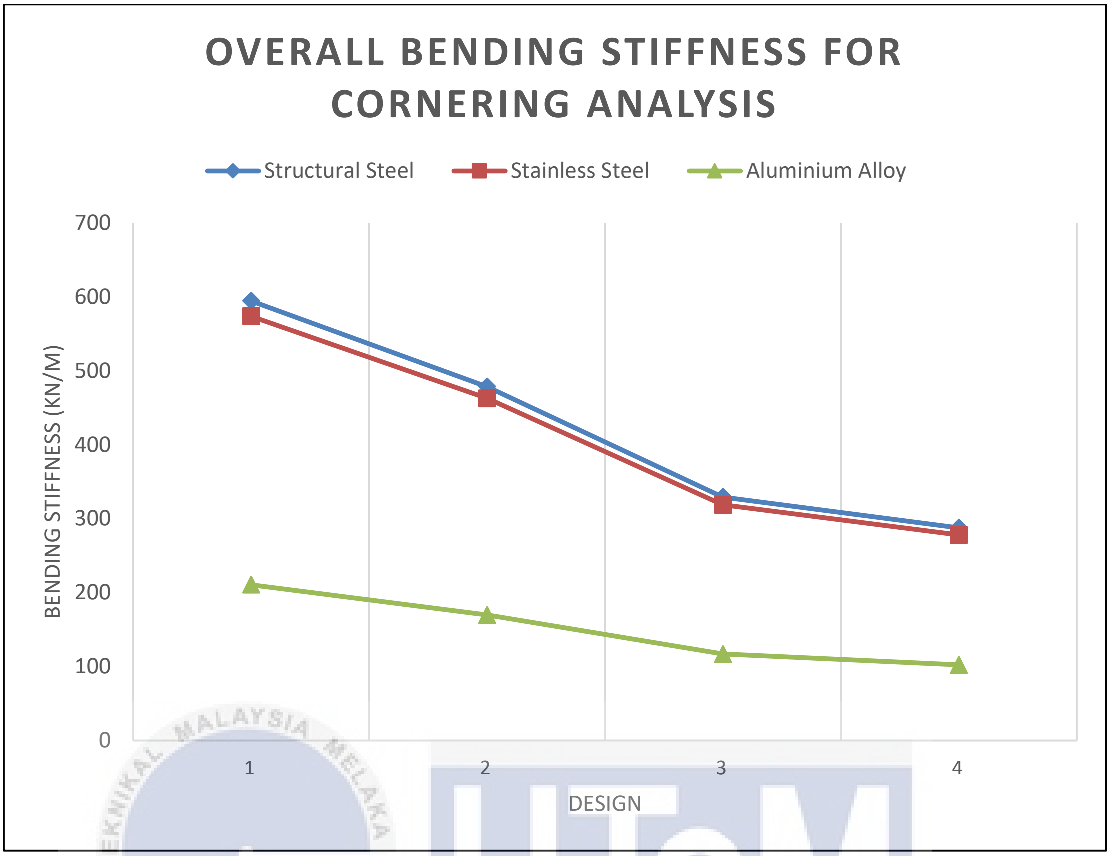


Figure 4.13: Bending stiffness for cornering analysis.

Sample calculation of bending stiffness for acceleration analysis is shown below:

$k = F / \delta$

$F = 100(9.81) = 981\ N$

$k = 981\ N / 0.00903\ m$

$k = 108.64\ kN/m$

Table 4.5: Overall bending stiffness for acceleration analysis.

Design	Bending Stiffness (kN/m)		
	Structural Steel	Stainless Steel	Aluminium Alloy
1	628.85	609.32	223.46
2	505.67	488.06	179.67
3	347.87	335.96	123.55
4	306.56	295.48	108.64

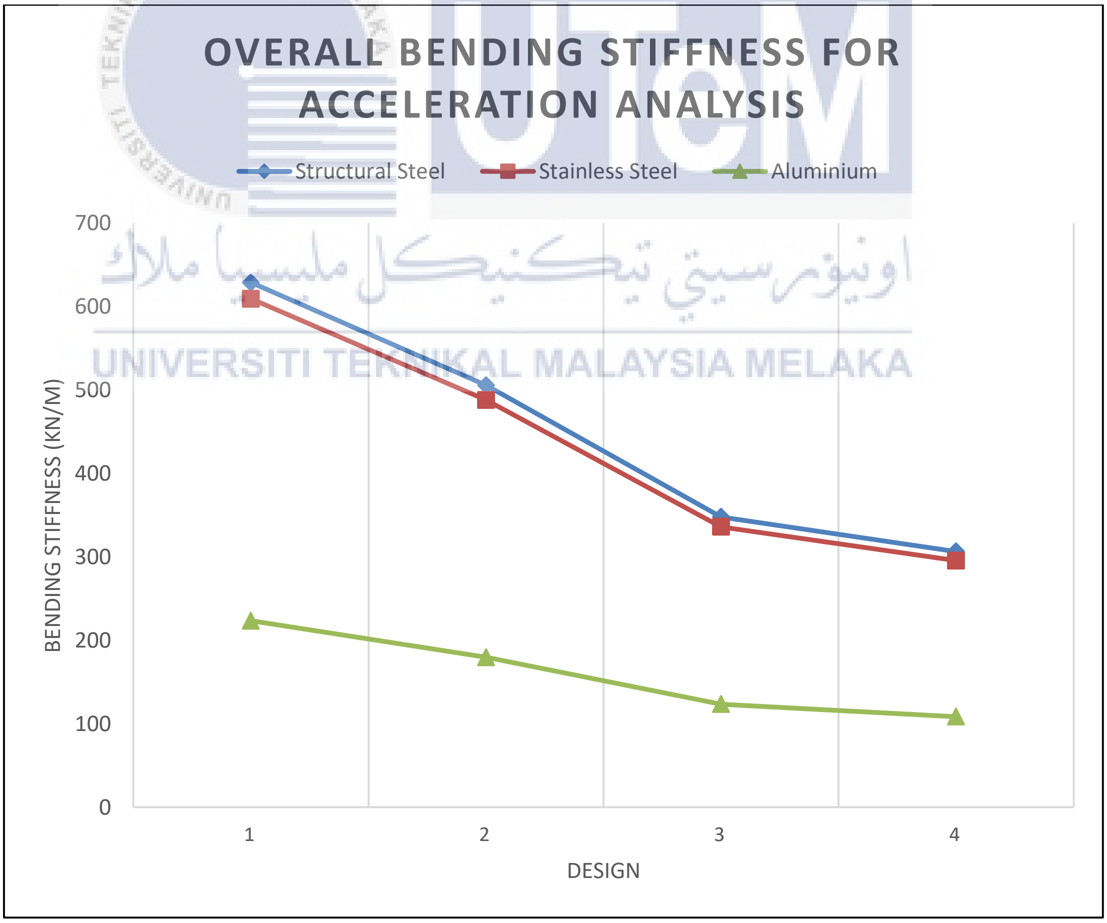


Figure 4.14: Bending stiffness for acceleration analysis.

Meanwhile, sample calculation for torsional stiffness analysis is as follows:

$k = M / \theta$

$\tan \theta = 0.03318 \text{ m} / 0.9 \text{ m}$

$\theta = 2.11 \text{ rad}$

$F = 50 \text{ kg } (9.81) = 490.5 \text{ N}$

$M_t = Fd = 490.5 \text{ N } (0.9 \text{ m})$

$= 441.45 \text{ Nm}$

$k = M / \theta$

$k = 441.45 \text{ Nm} / 2.11 \text{ rad}$

$= 209.2180 \text{ Nm/rad}$

$= 3.65 \text{ Nm/deg}$

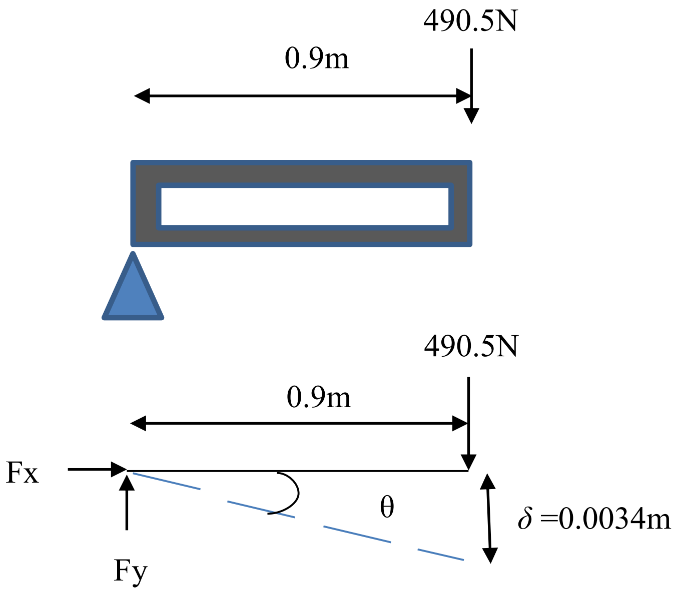


Figure 4.15: Free body diagram of the chassis structure with respect to frontal view.

Table 4.6: Overall torsional stiffness.

Design	Torsional Stiffness (Nm/deg)			Total
	Structural Steel	Stainless Steel	Aluminium Alloy	
1	36.69	35.02	12.84	84.55
2	22.66	21.40	7.94	52.00
3	12.63	12.23	4.48	29.34
4	10.27	10.01	3.65	23.93

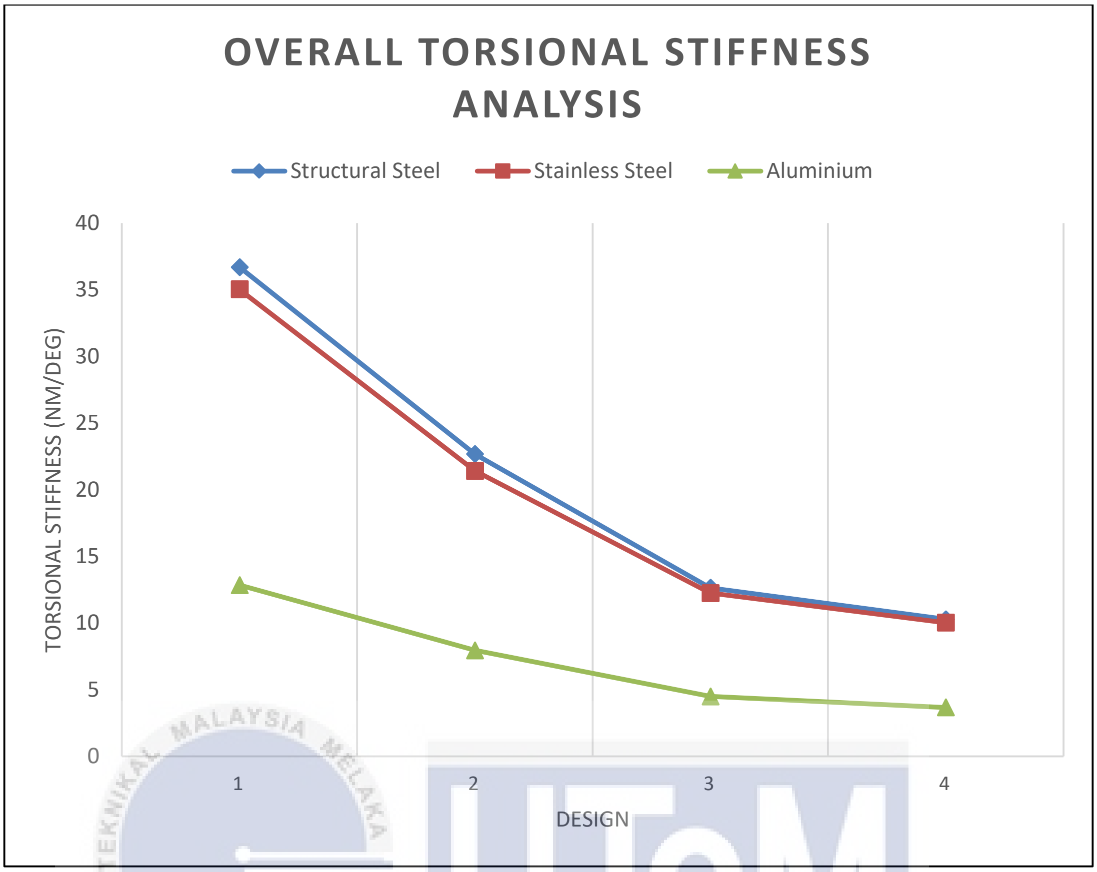


Figure 4.16: Overall torsional stiffness analysis.

Table 4.7: Overall mass of the chassis design.

Design	Mass (kg)		
	Structural Steel	Stainless Steel	Aluminium Alloy
1	48.596	47.977	17.148
2	41.064	40.541	14.490
3	34.459	34.020	12.159
4	30.849	30.456	10.885
Total	154.968	152.994	54.682

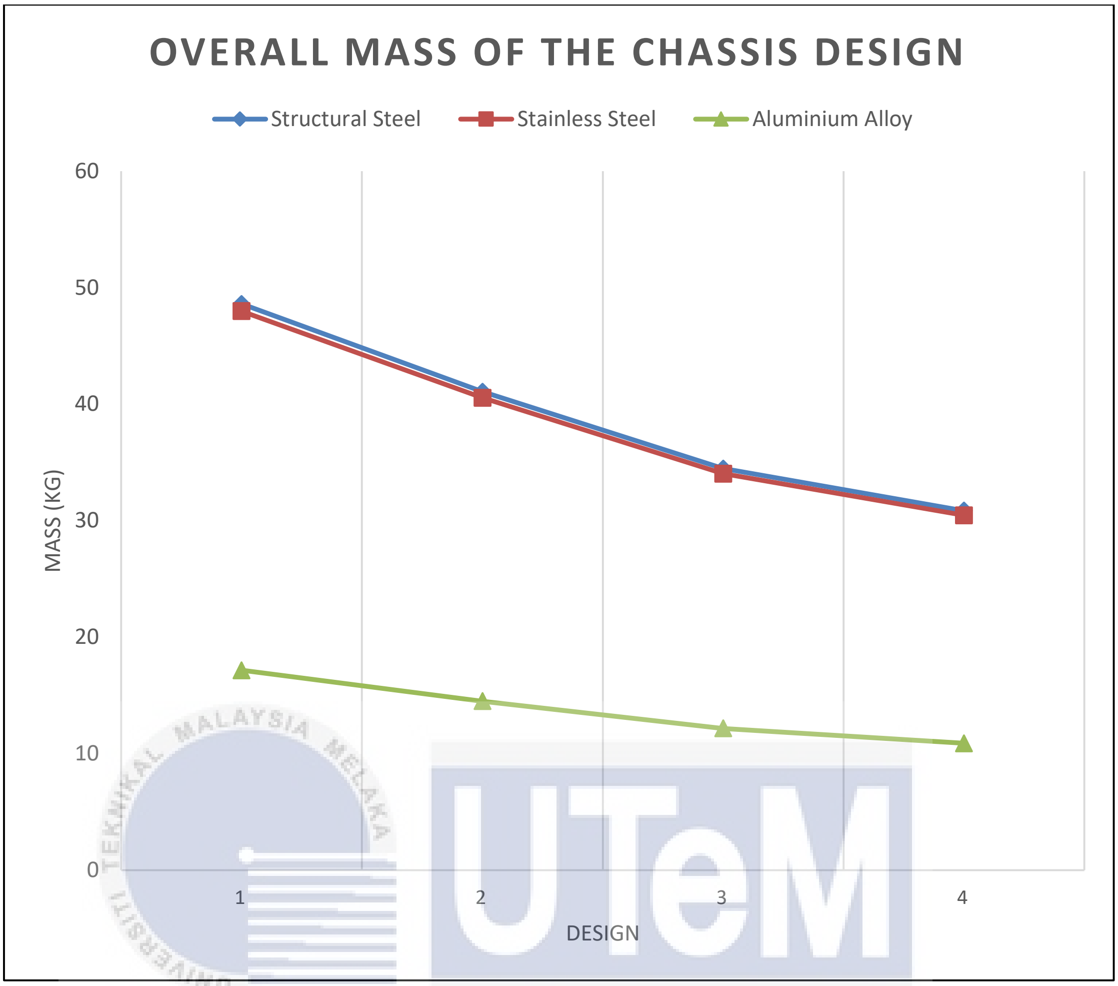


Figure 4.17: Overall mass of the chassis design.

From the ANSYS Workbench data in **Table 4.7**, it is proven that all the design of the chassis structural size and various materials have different mass. The fourth design shows that it has the lightest weight among all designs. The fourth design of aluminium alloy material has the lightest weight among the three materials. The illustration in **Figure 4.17** verified that aluminium alloy chassis and the fourth design have the lowest graph pattern. Therefore, the results indicate that the smaller the frame size, the lighter the chassis would be. Furthermore, it is also proven that aluminium alloy is a lightweight material as compared to structural steel and stainless steel. Thus, it is suitable to be used in a HPV chassis if it does not consider any other engineering criteria and the safety factor is within the safe range. In other study, a selection of a steel material for frame structure produced a total of 40 lbs which is equivalent to 18.14 kg or less (Knaus et al., 2010) which is heavier than the fourth design of aluminium alloy chassis. In short, the present project has achieved the objective of designing a lightweight chassis without considering any other engineering criteria.

4.3 SAFETY FACTOR

Safety factor is a very crucial criterion in designing process. It is understood as how much of an object or structure can withstand loads or simply defined as how strong the structure is. Without this safety factor, it is hard to verify whether the structure is strong or safe enough. Safety factor also can be obtained from the ratio of yield stress to Von-mises stress as shown in **Equation 3.1**. Engineers and designers often used Von-mises stress to check whether the material can withstand loads or otherwise. When the Von-mises stress exceed the yield stress of the particular material, then it is considered failed. **Table 4.8** shows the yield strength and ultimate strength of some particular materials from the ANSYS Workbench. Safety factor is the last criterion taken into account for the design of the project.

Table 4.8: Yield strength and ultimate strength data from ANSYS Workbench.

Material	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
Structural Steel	250	460
Stainless Steel	207	586
Aluminium Alloy	280	310

4.3.1 SAFETY FACTOR FOR CORNERING ANALYSIS

After Design 4 has been selected based on the previous section, it is analysed with safety factor to confirm the toughness, strength and safety measurements. This section contains Von-Mises stress and safety factor results of Design 4 for cornering analysis with various materials. **Figure 4.18**, **Figure 4.20** and **Figure 4.22** show the Von-Mises stress for structural steel, stainless steel and aluminium alloy chassis, respectively. Meanwhile, **Figure 4.19**, **Figure 4.21** and **Figure 4.23** show the safety factor of each materials mentioned earlier.

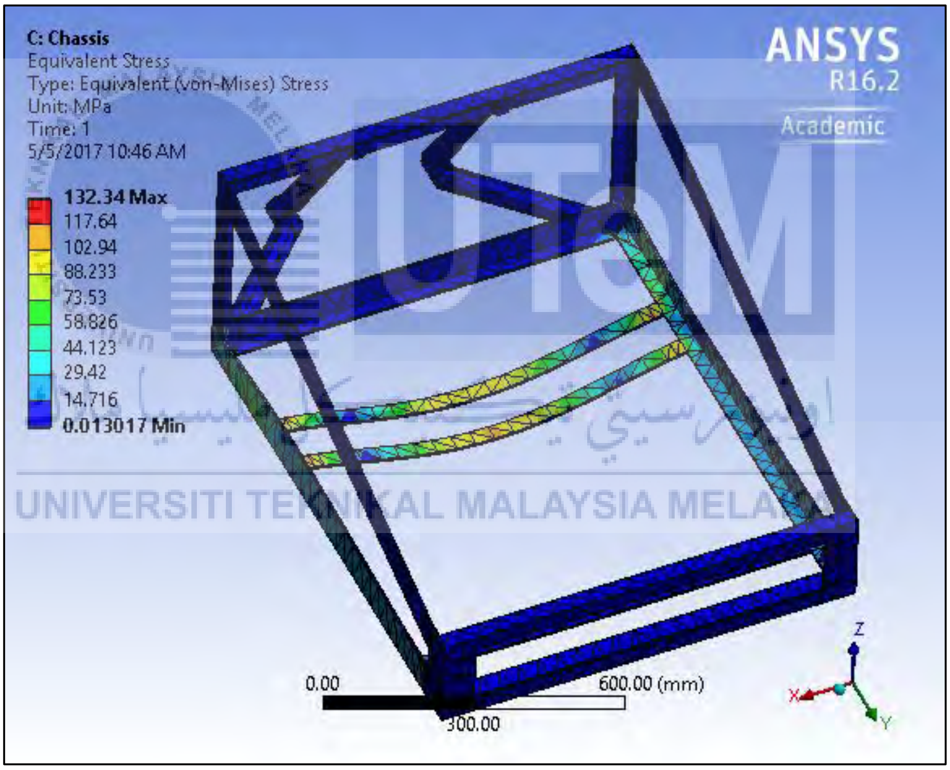


Figure 4.18: Von-Mises stress of structural steel chassis for cornering analysis.

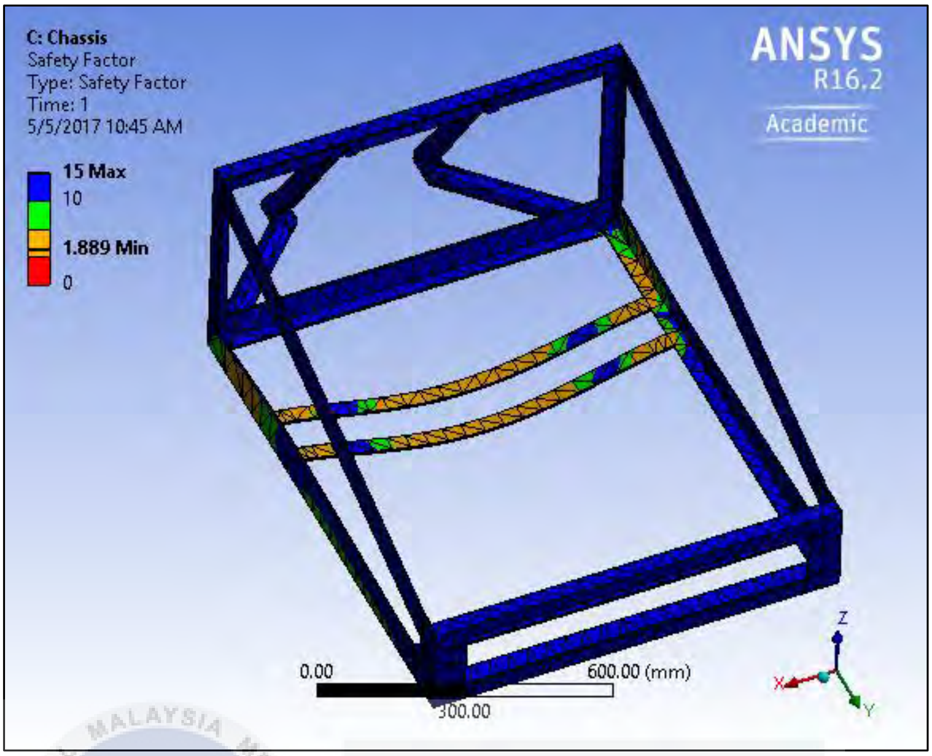


Figure 4.19: Safety factor of structural steel chassis for cornering analysis.

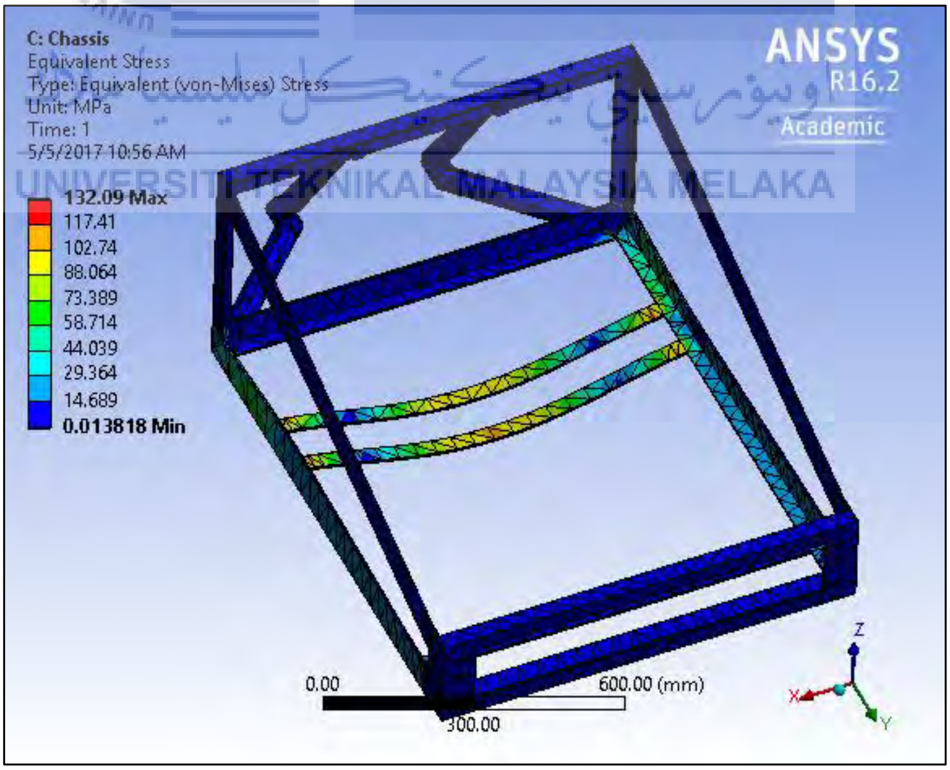


Figure 4.20: Von-Mises stress of stainless steel chassis for cornering analysis.

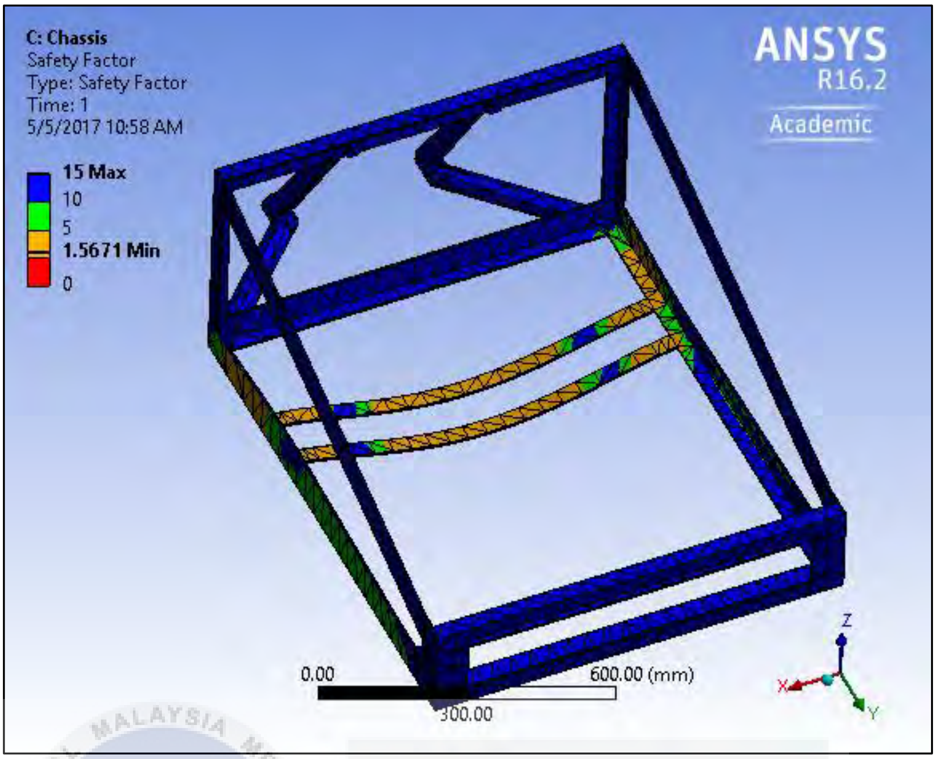


Figure 4.21: Safety factor of stainless steel chassis for cornering analysis.

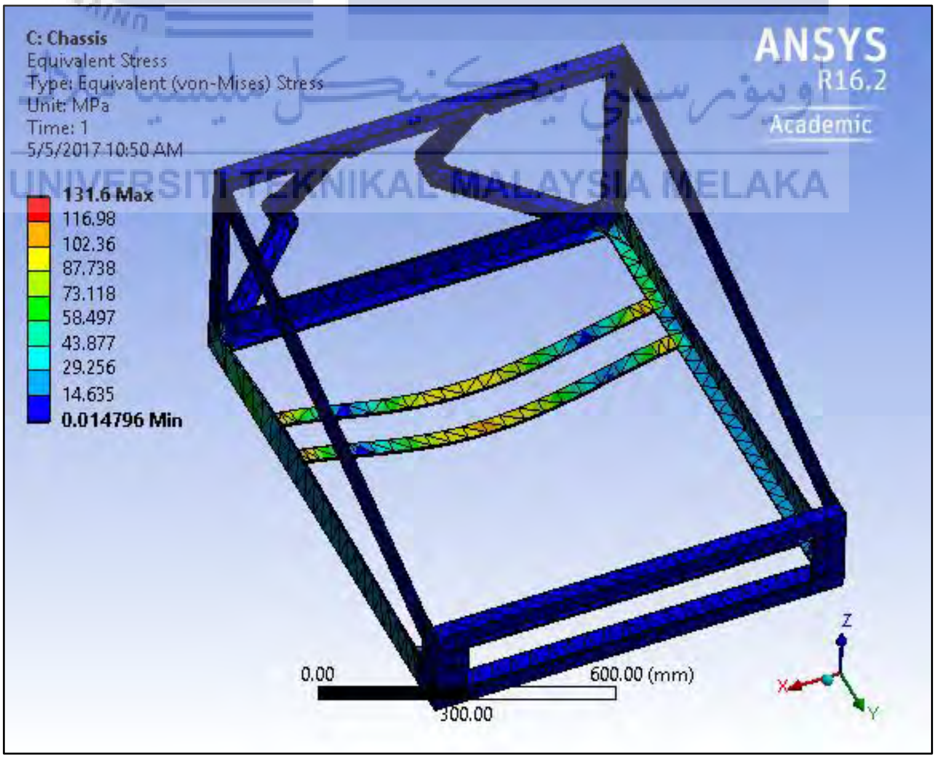


Figure 4.22: Von-Mises stress of aluminium alloy chassis for cornering analysis.

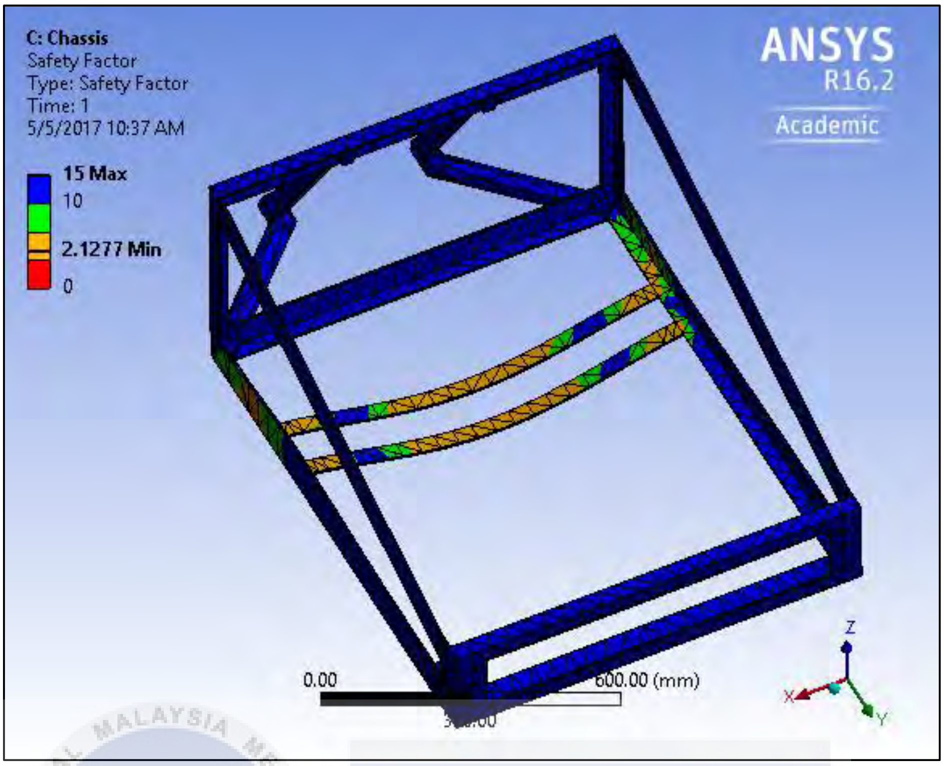


Figure 4.23: Safety factor of aluminium chassis for cornering analysis.

4.3.2 SAFETY FACTOR FOR ACCELERATION ANALYSIS

Figure 4.24 and **Figure 4.25** show the Von-Mises stress and safety factor for structural steel chassis, respectively. Menawhile, **Figure 4.26** and **Figure 4.27** show the same parameters but with stainless steel chassis. Lastly, **Figure 4.28** and **Figure 4.29** show the Von-Mises stress and safety factor for aluminium alloy chassis, respectively.

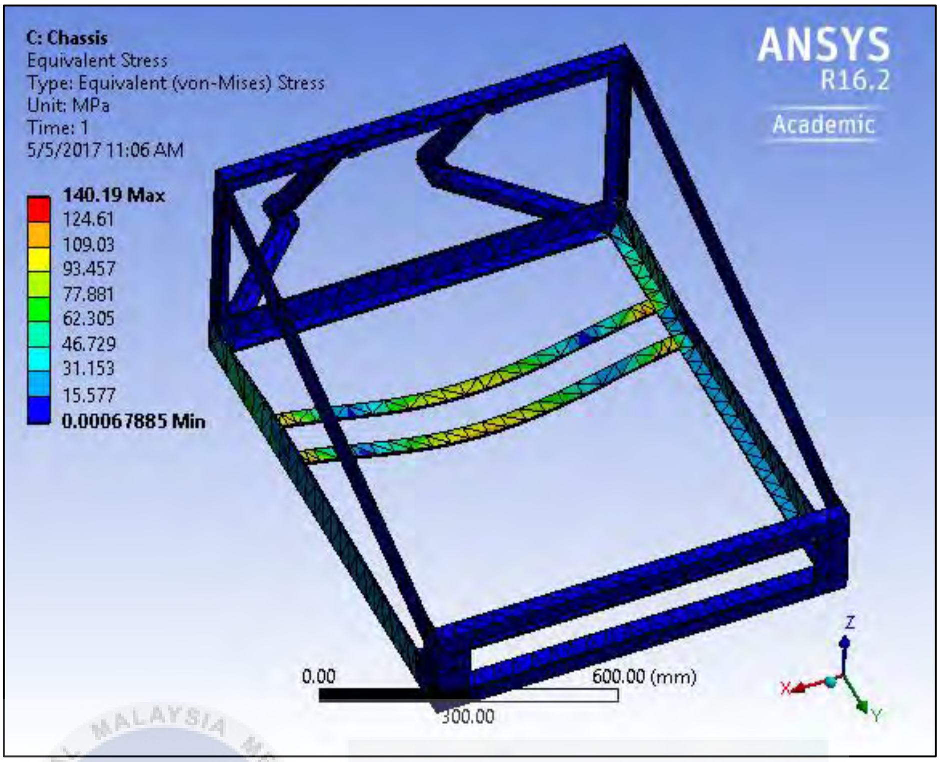


Figure 4.24: Von-Mises stress of structural steel chassis for acceleration analysis.

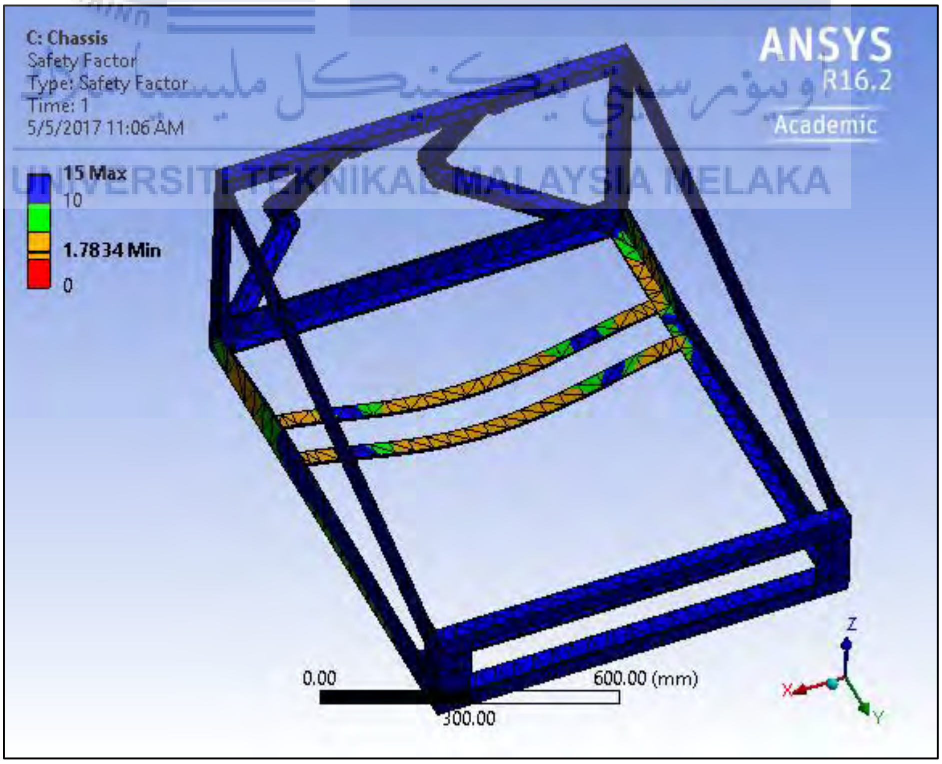


Figure 4.25: Safety factor of structural steel chassis for acceleration analysis.

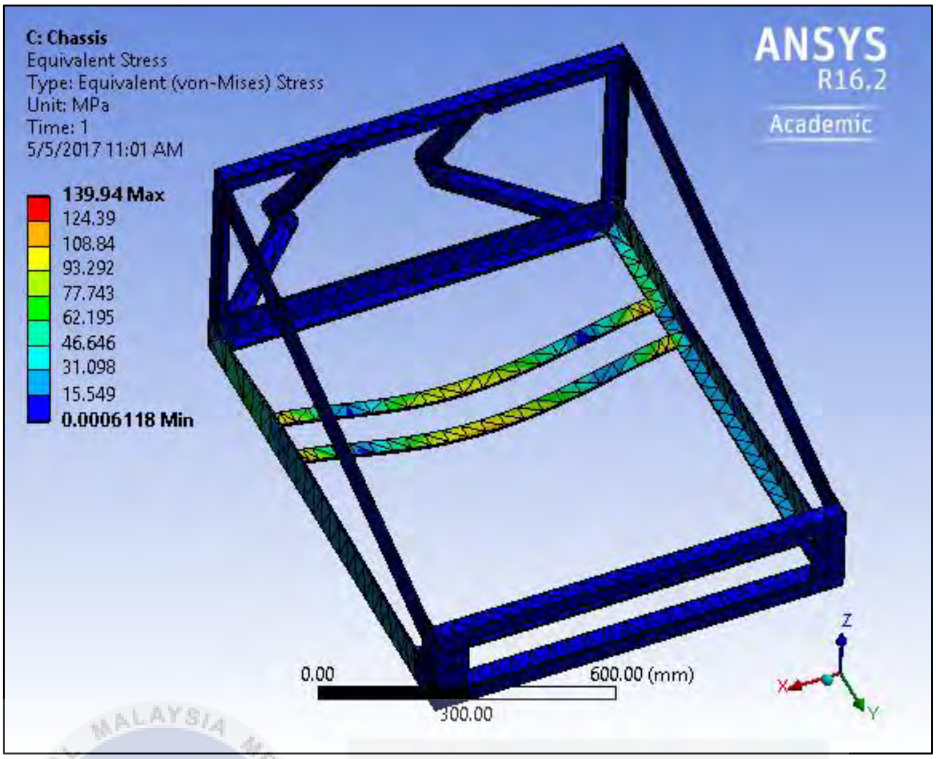


Figure 4.26: Von-Mises stress of stainless steel chassis for acceleration analysis.

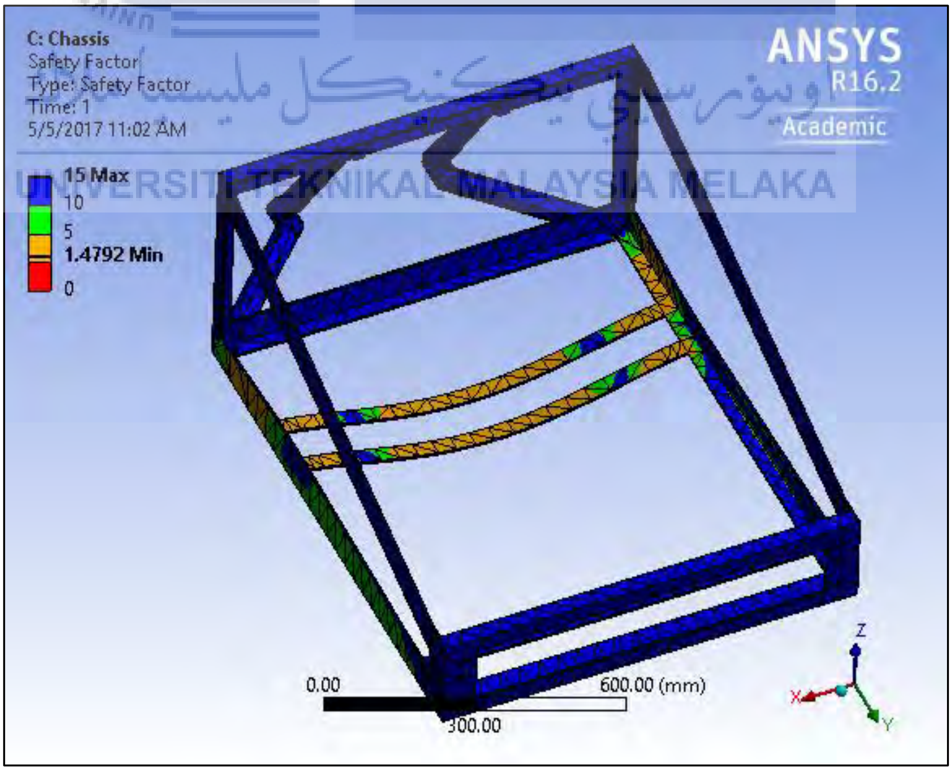


Figure 4.27: Safety factor of stainless steel chassis for acceleration analysis.

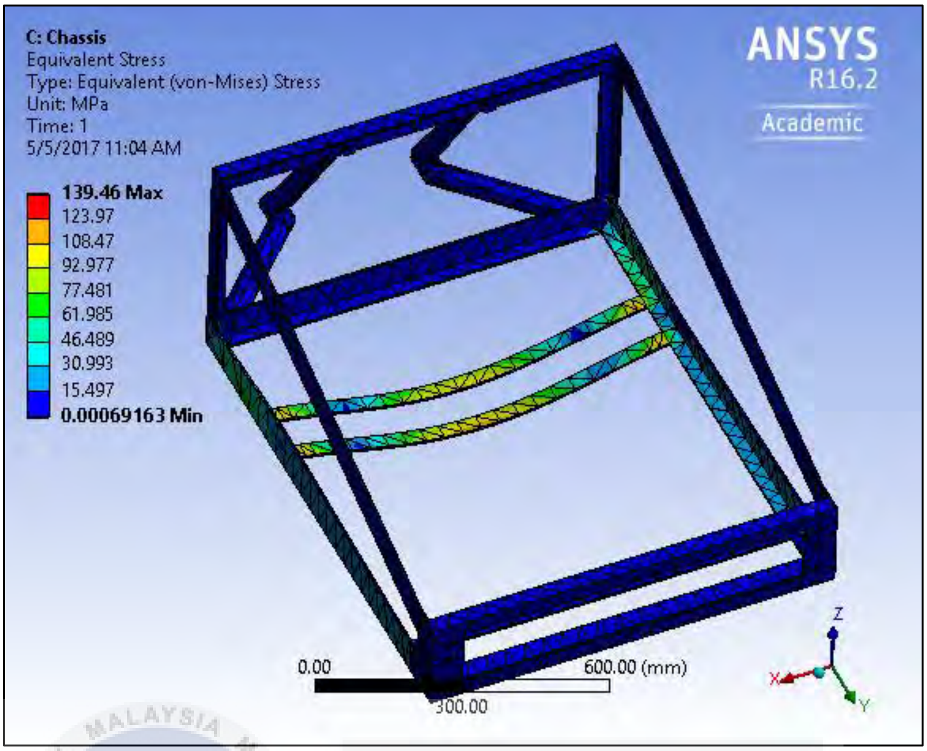


Figure 4.28: Von-Mises stress of aluminium alloy chassis for acceleration analysis.

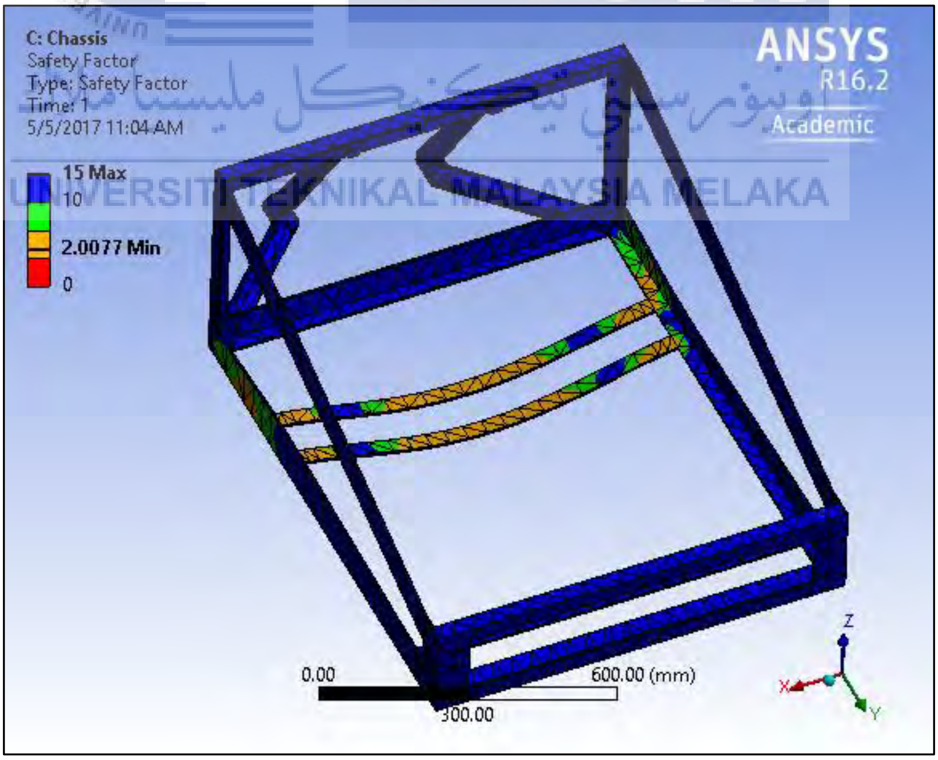


Figure 4.29: Safety factor of aluminum alloy chassis for acceleration analysis.

4.3.2 SAFETY FACTOR FOR TORSIONAL ANALYSIS

Figure 4.30 shows the Von-mises stress for structural steel chassis and **Figure 4.31** shows the safety factor for structural steel chassis. Meanwhile, **Figure 4.32** and **Figure 4.33** show the Von-mises stress and safety factor for stainless steel chassis, respectively. Lastly, **Figure 4.34** and **Figure 4.35** show the Von-mises stress and safety factor for aluminium alloy chassis, respectively. The overall Von-Mises stress and safety factor results are shown in **Table 4.9**.

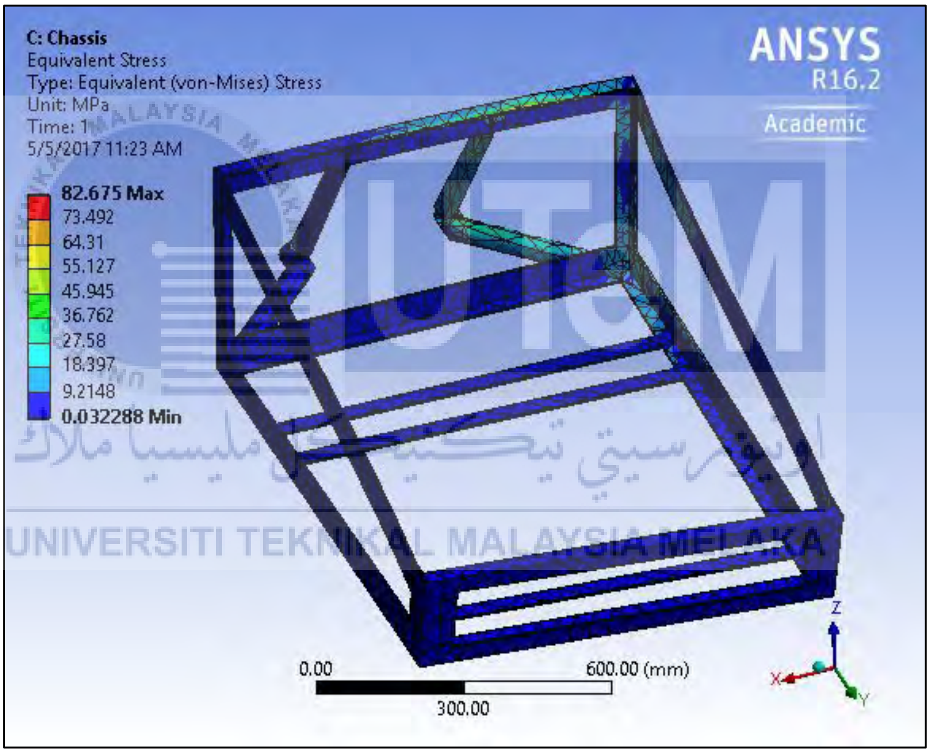


Figure 4.30: Von-mises stress of structural steel chassis for torsional analysis.

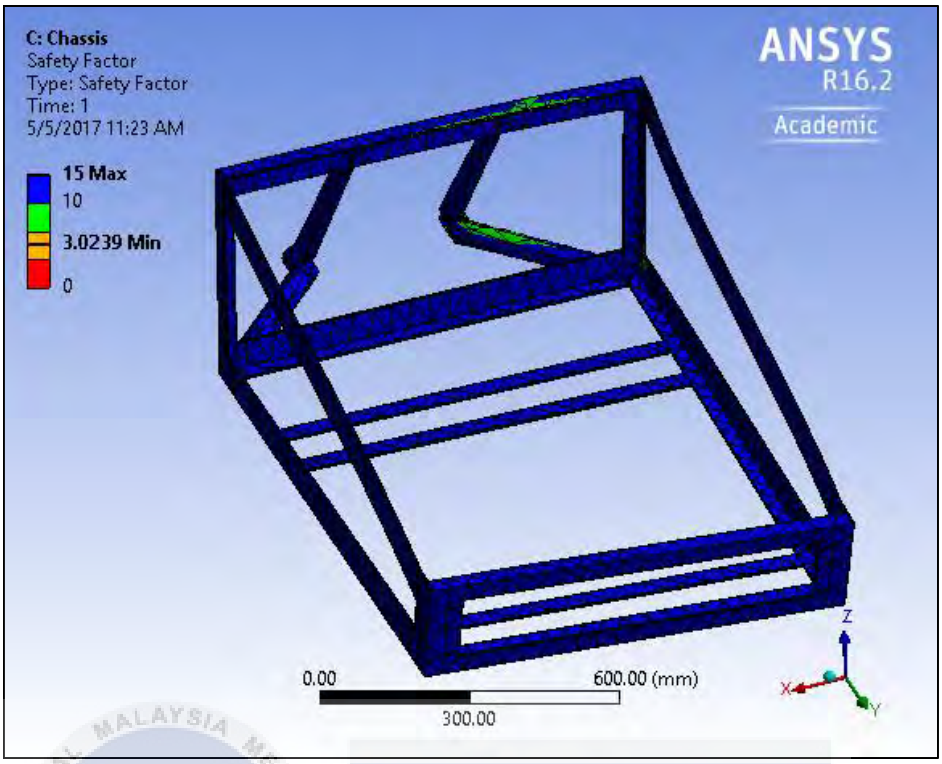


Figure 4.31: Safety factor of structural steel chassis for torsional analysis.

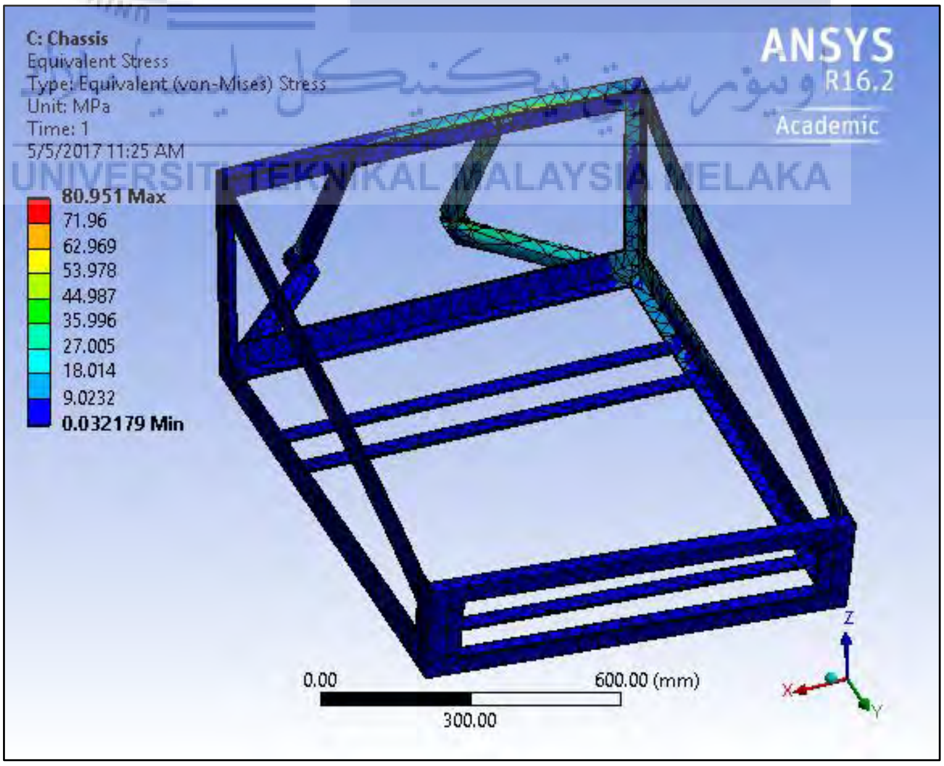


Figure 4.32: Von-mises stress of stainless steel chassis for torsional analysis.

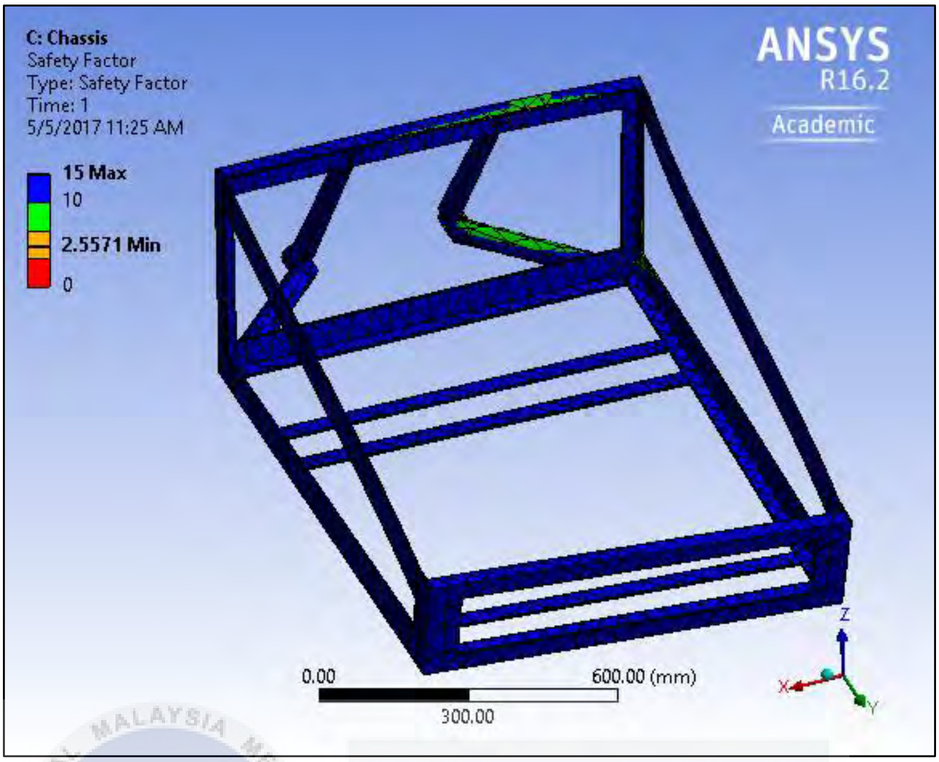


Figure 4.33: Safety factor of stainless steel chassis for torsional analysis.

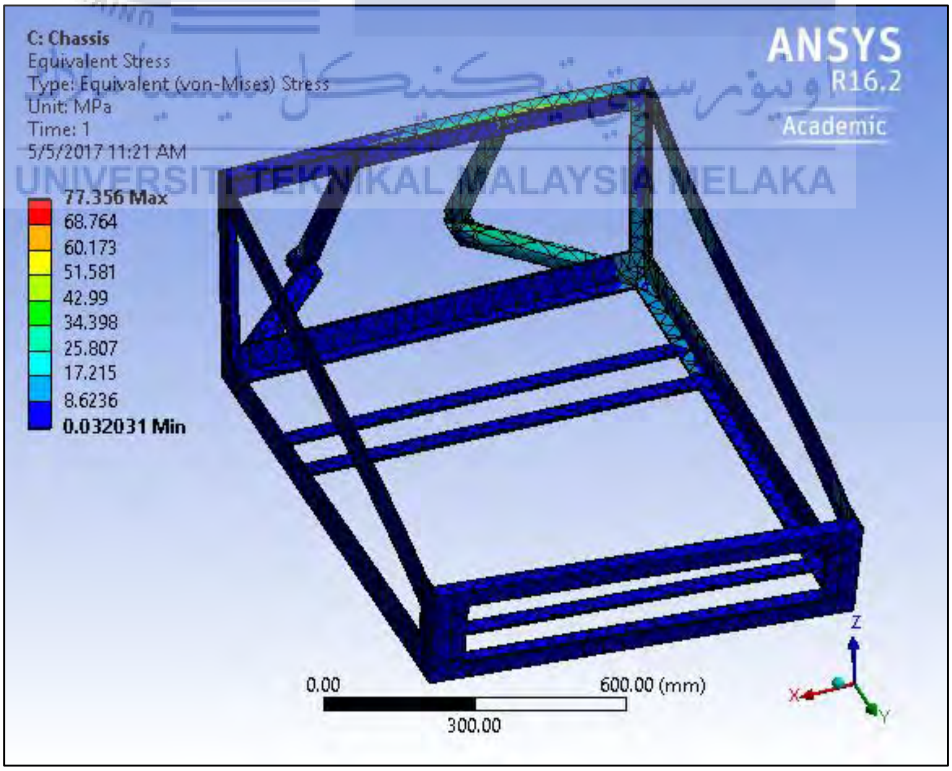


Figure 4.34: Von-mises stress of aluminum alloy chassis for torsional analysis.

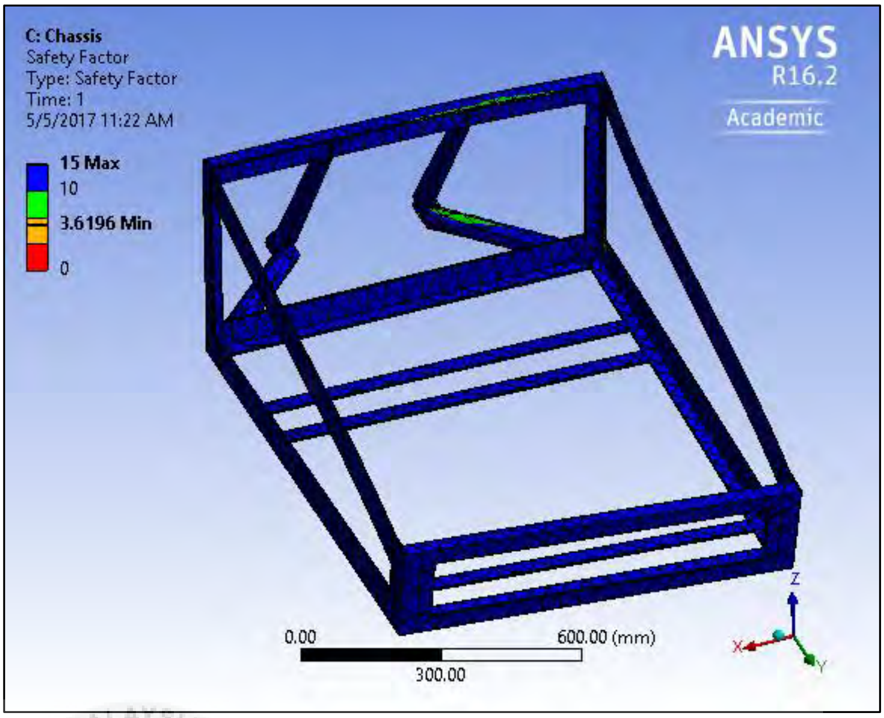


Figure 4.35: Safety factor of aluminum alloy chassis for torsional analysis.

Table 4.9: Overall Von-mises stress and safety factor.

Items	Materials					
	Structural Steel		Stainless Steel		Aluminum Alloy	
	Von-Mises Stress (MPa)	Safety Factor	Von-Mises Stress (MPa)	Safety Factor	Von-Mises Stress (MPa)	Safety Factor
Cornering analysis	132.34	1.89	132.09	1.57	131.60	2.13
Acceleration analysis	140.19	1.78	139.94	1.48	139.46	2.01
Torsional analysis	82.68	3.02	80.95	2.56	77.36	3.62

4.4 WEIGHT DECISION MATRIX

Weight decision matrix analysis is a useful technique to use for a decision making process. It is particularly powerful where one has a number of good alternatives to choose from, and many different factors to take into account. This makes it a great technique to use in almost any important decision where there is no clear and obvious preferred option. Being able to use a Decision Matrix Analysis means that one can take decisions confidently and rationally, at a time when other people might be struggling to make a decision.

4.4.1 SELECTION BY DESIGN

There are four designs that need to be considered and the best design are chosen based on weight decision matrix analysis. The selection by design are determined by comparison of mass as shown in **Table 4.10**. The highest score is chosen based on the analysis. There are two equations of the score which are used to find the best score index. Those equations are expressed as below:

$$\text{Score} = [\ 1 - (\text{Data} / \text{Total Data})\ ] \tag{4.3}$$

$$\text{Score} = [\ (\text{Data} / \text{Total Data})\ ] \tag{4.4}$$

Equation 4.3 is used to calculate the score of total deformation for cornering, acceleration, torsional analysis and mass of the chassis using the results in **Table 4.1**, **Table 4.2**, **Table 4.3** and **Table 4.7,** respectively. Meanwhile, **Equation 4.4** is used to find the score of bending stiffness for cornering and acceleration analysis including the torsional stiffness as well as the safety factor; using the data in **Table**

4.4, **Table 4.5**, **Table 4.6** and **Table 4.9,** respectively. Sample calculation for the first design of structural steel from **Table 4.7** is as follows:

Score = [1 – (Data / Total Data)]

= [1 – (48.596 / 154.968)

= 0.69

Table 4.10: Decision matrix for overall mass of the chassis designs.

Design	Scores			Total Scores
	Structural Steel	Stainless Steel	Aluminium Alloy	
1	0.69	0.69	0.67	2.05
2	0.74	0.74	0.74	2.22
3	0.78	0.78	0.78	2.34
4	0.80	0.80	0.80	2.40

4.4.2 SELECTION BY MATERIAL

Selection by material are done after the stage of selection by design. Since the best design has been chosen, then the selection by material is done among the Design 4. This will determine whether structural steel, stainless steel or aluminium alloy is the best material for the chassis. The decision matrix analysis for the material selection is summarized in **Table 4.11**. Sample calculation for torsional stiffness with structural steel material from **Table 4.6**:

Score = [(Data / Total Data)]

= [(10.27 / 23.93)]

= 0.43

Table 4.11: Decision matrix for the material selection.

No.	Items	Scores		
		Structural Steel	Stainless Steel	Aluminium Alloy
1	Mass	0.57	0.58	0.85
2	Torsional Stiffness	0.43	0.42	0.15
3	Bending Stiffness for Cornering Analysis	0.43	0.42	0.15
4	Bending Stiffness for Acceleration Analysis	0.43	0.42	0.15
5	Total Deformation for Torsional Analysis	0.79	0.79	0.42
6	Total Deformation for Cornering Analysis	0.79	0.79	0.42
7	Total Deformation for Acceleration Analysis	0.79	0.79	0.42
8	Safety Factor for Cornering Analysis	0.34	0.28	0.38
9	Safety Factor for Acceleration Analysis	0.34	0.28	0.38
10	Safety Factor for Torsional Analysis	0.33	0.28	0.39
Total Scores		5.24	5.05	3.71

4.5 DISCUSSION

Deformation describes the transformations from some initial point to some final geometry. It may be caused by external loads, body forces, or changes in temperature, moisture content, or chemical reactions. Therefore, it is not good for some structure to deform with a large value of deformation and it may considered as a low quality structure with a weaker strength. Hence, the lower the total deformation of the structure, the stronger the toughness of the structure.

From **Table 4.1**, Design 1 has the lowest total deformation for cornering analysis which ranged from 1.5 mm to 4.7 mm. Meanwhile, Design 4 has the highest total deformation compared to other designs; which ranged from 3.4 mm to 9.7 mm for all materials. The lowest total deformation for cornering and acceleration analysis belongs to Design 1 with structural steel material in acceleration analysis with total deformation of 1.56 mm.

Meanwhile, the highest total deformation for both cornering and acceleration analysis is Design 4 with aluminium alloy material which deformed with 9.62 mm. In other research, the roll bar of their HPV chassis produced 0.607" or 15.42 mm of overall deformation (Gerlich et al., 2013), which is higher than the highest total deformation for this project. This shows that the total deformation for the chassis design of this project is within acceptable range. Structural steel and stainless steel chassis have consistence value of total deformation for cornering and acceleration analysis in all four designs. However, aluminium alloy chassis shows a huge gap between structural steel and stainless steel chassis as shown in **Figure 4.4** and **Figure 4.8**. It is because aluminium alloy is more malleable, flexible and elastic than steel. Aluminum can go places and create shapes that steel cannot, often forming deeper or more intricate spinnings. Especially for parts with deep and straight walls, it is the material of choice. Steel is a very tough and resilient metal but cannot generally be pushed to the same extreme dimensional limits as aluminium without cracking or ripping during the spinning process. Hence, aluminium alloy is not as good as structural steel and stainless steel material for this analysis.

Stiffness and strength are not exactly the same thing especially when it comes to metal used in automotive design. Strength is a measure of the stress that can be applied to a material before it permanently deforms or breaks. Meanwhile, stiffness relates to how a component bends under certain load while still returning to its original shape once the load is removed. Therefore, a chassis structure with higher stiffness is a better desgin. It demonstrates the ability of the chassis to bend in a certain loads. The higher the stiffness of the chassis, the harder the chassis to elastically deform.

For example, a high-stiffness material like diamond will elastically deform only a small amount when load is applied. The highest bending stiffness for cornering and acceleration analysis lies on Design 1 with structural steel material which indicates 628.85 kN/m as shown in **Table 4.5**. The results of bending stiffness for structural steel and stainless steel chassis in both cornering and acceleration analysis are approximately the same. Meanwhile, aluminium alloy chassis shows inequality bending stiffness for cornering annd acceleration analysis for all four designs compared to the other materials. Furthermore, Design 4 of aluminium alloy chassis has the lowest bending stiffness compared to the other materials with just 102.02 kN/m for cornernring and acceleration analysis. This is illustrated in **Figure 4.13** and **Figure 4.14**.

Design 4 of the chassis with aluminium alloy material has the lowest bending stiffness compared to other designs because it has the smallest size of structural beam as shown in **Table 3.1**. Besides that, the modulus of elasticity for aluminium is only about 1/3 compared to steel. So, the deflection of an aluminium structure will be three times greater than a similar steel structure. This is proven in **Table 4.1**, **Table 4.2** and **Table 4.3**. Thus, that is why the aluminium alloy chassis has lower bending stiffness compared to structural steel and stainless steel in all analysis when the force is devided by the deflection or total deformation. In short, aluminium alloy material is not strong enough for the chassis design of this project as it has the lowest bending stiffness according to the bending stiffness analysis.

Torsional stiffness is one of the most important properties and criteria for chassis design. A stiff chassis has larger cornering torque and easy suspension handling. Therefore, a high chassis stiffness is a wise choice and preferable due to several factors. For example, lack of chassis torsional stiffness affects the lateral load transfer distribution. Besides, it allows displacements of the suspension attachment points that modify suspension kinematics and laslty, it can trigger unwanted dynamic effects like vibrations or resonance phenomena. In fact, most common car manufacturers and vehicle segments set the torsional stiffness from 17 kNm/deg to 40 kN/m (Danielsson & Cocana, 2015).

Table 4.6 shows that Design 1 with structural steel chassis has the highest torsional stiffness with 36.69 Nm/deg. One of the reasons is, it has the largest size of structural beam as shown in **Table 3.1**. This is proven when the torsional stiffness of the same material decreased when the size of structural beam decreased from Design 1 to Design 4. It turns out that Design 4 with aluminium alloy material has only 3.65 Nm/deg which proclaims as the lowest torsional stiffness. The illustration in **Figure 4.16** supports the analysis.

Therefore, the study finds that aluminium alloy chassis is weaker in torsional stiffness compared to structural steel and stainless steel chassis in all four designs. It is because steel is harder than aluminium. Most alloys of aluminum dent or scratch easier compared to steel. Steel is strong and less likely to warp, deform or bend under application of force. Steel is an alloy of iron and other elements which is primarily carbon. Carbon is the most common alloying material in steel which acts as a hardening agent, preventing any dislocations within the iron atom crystal lattice from separating and sliding past each other. Hence, making steel more durable.

With mass growth of global population, lighweight vehicles have become primary criteria in automotive industries. Logically, the higher the mass, the higher the energy needed to move the vehicles. For instance, cars, trains or trucks have to use more power to speed up and keep them moving when they have a heavier mass. Similarly, in HPV, more mass means more power would be needed to move it. Therefore, it is important to design a lightweight HPV for a convenient application in real life such as recreation or racing. Thus, in order to get a lightweight HPV, the design of the chassis plays an important role to achieve the desirable weight.

From ANSYS Workbench data in **Table 4.7**, it is proven that all designs of the chassis structural size from Design 1 to Design 4 and variation of materials have different mass. Design 4 shows that it has the lightest weight among all designs. In other study, a selection of a steel material for frame structure produced a total of 40 lbs which equivalent to 18.14 kg or less (Knaus et al., 2010), which is heavier than the Design 4 of aluminium alloy material. Another study mentioned that the weight of their frame is 20 kg without considering other components which result to a total weight of 50 kg (Abhilash & Sri, 2014).

In addition, Design 4 with aluminium alloy material has the lightest weight among those three materials with only 10.89 kg. The illustration in **Figure 4.17** verifies that all designs with aluminium alloy chassis have the lowest graph pattern compared to structural steel and stainless steel. This is because the size of the structural beam is reduced accordingly from Design 1 to Design 4. Therefore, this proved that the smaller the frame size, the lighter the chassis will be. Meanwhile, structural steel and stainless steel have 30.85 kg and 30.46 kg of mass, respectively for Design 4.

To sum up, it is also proven that aluminium alloy chassis is a lightweight material compared to both structural steel and stainless steel chassis. This is because aluminium is less dense than steel. Plus, it is soft, durable, lightweight, non-magnetic and ductile in nature. Since it is highly reactive in pure form, it is found in combined form for over 270 different minerals. Besides, aluminium is typically not as strong as steel, but it is also almost one third of the weight. Hence, it is often preferred for its lightweight composition. Overall, in the weight category, aluminium takes the prize as it is very lightweight yet sturdy material.

Von-Mises stress is used by engineers and designers to check whether their design can withstand the applied loads or else. When the value of Von-Mises stress in particular material is higher than the yield stress of the material, the design is considered failed. Furthermore, Von-Mises stress need to be calculated in order to get the safety factor of the chassis design. Safety factor is used to determine whether the design structure is safe or not. An ideal chassis is the one that provide low weight, better stiffness and ideal safety factor. One of the research stated that the frame of the chassis was safe in several tests and they obtained the lowest safety factor of 1.5 (Colone et al., 2008).

Therefore, a chassis design with safety factor of more than 1.5 is within acceptable range. From ANSYS Workbench, data in **Table 4.9** demonstrates that Design 4 for structural steel, stainless steel and aluminium alloy material in cornering, acceleration and torsional analysis are all in satisfactory range, except for stainless steel chassis in acceleration analysis which has the safety factor of 1.48. However, the Von-mises stress for the stainless steel chassis in acceleration analysis is 139.94 MPa yet still lower than the yield stress of the material which is 207 MPa. So, theoretically the design is safe but has low quality and unsuitable design. Most likely any engineers will redesign it because they might consider it failed.

Other than that, the Von-Mises stress for all analysis are less than the yield stress for each material which testified that the design can withstand loads. The structural steel chassis in acceleration analysis has the highest Von-mises stress which is 140.19 MPa. However, it is still lower than 250 MPa which represents the yield strength of the material as shown in **Table 4.8**; followed by other material in all analysis with similar findings. Aluminium alloy chassis has the highest safety factor among all the materials for all analysis. This is because it has the highest yield strength with 280 MPa as shown in **Table 4.8**. So, the ratio of yield strength to Von-mises stress is bigger. In conclusion, Design 4 in all analysis are considered safe to use theoretically. There should be no problem as long as the safety factor is more than 1.0. The ratio of yield stress to Von-mises stress is not exceeding each other. Nonetheless, the higher the safety factor, the better the design of the structure. This analysis clarified that chassis design with aluminium alloy material is the best design as it has the highest safety factor compared to structural steel and stainless steel material for all analysis.

Last but not least, the discussion will end with elaboration of weight decision matrix analysis. A weighted decision matrix is a tool used to compare alternatives with respect to multiple criteria of different levels of importance. Engineers are decision makers, and decision making is what differentiates engineers from scientists. The decisions made by engineers have high consequences which might affect the safety of society. Thus, some of the engineers might use the weight decision matrix analysis to make the best decision.

The same goes to the chassis design for this project, different criteria are being compared in order to choose the best design for the chassis. According to the objectives of this project, two parameters are selected which are selection by design and selection by material. The weight decision matrix will produce score index and the highest score is the best selection. As for selection by design, there are four design in total, and one has to make decision which design is the best. The selection by design are determined by comparison of mass as shown in **Table 4.7**. Then, the overall mass of the chassis design is calculated to change into score index using weight decision matrix analysis as shown in **Table 4.10**. The highest score among those four designs in **Table 4.10** is Design 4 which scores 2.40 for all materials. Thus, Design 4 is chosen as the best design of the chassis. This is because Design 4 has the lowest mass for each material compared to the other three designs as shown in **Table 4.7**.

Next is the selection by materials after Design 4 has been selected. The task is to decide whether structural steel, stainless steel or aluminium alloy is the best material for the chassis. Based on **Table 4.11**, the highest score between the materials is structural steel which scores 5.24. Therefore, theoretically, the best material for the chassis design is structural steel. It is based on the weight decision matrix analysis even though it shows the heaviest mass among the materials for each design as shown in **Table 4.7**. It has disadvantage in mass but it wins all other engineering criteria. Plus, the safety factor is also within an acceptable range even though it is less than the safety factor of aluminium alloy. Hence, Design 4 with structural steel material is the best design for this project, theoretically. However, Design 4 with aluminium alloy material can still be used or manufactured considering it has the lowest mass with 10.89 kg and the safety factor is in the safe range. Nevertheless, it is not the best design according to the calculated theoretical design.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 CONCLUSION

The goal of Human Powered Vehicle (HPV) for this project is to design a chassis based on three major design considerations, namely lightweight, ideal stiffness and acceptable safety factor. Generally, a chassis acts as a support system for the HPV including all the sub-systems. When the HPV travel along the road, the chassis is subjected to a stress, bending moment and vibration induced by road roughness. Therefore, the chassis has to withstand the stress developed, deformation, shock, twist vibration and other stress.

The most crucial part is the selection material for chassis as it will affect the HPV in terms of its weight, strength and rigidness. Moreover, the material, size of frame structure, shape of frame structure, and design of the chassis will affect the mass of the chassis, bending and torsional stiffness, total deformation, Von-Mises stress and lastly the safety factor. As for the first objective, the lightweight chassis can be found in Design 4 with aluminium alloy material with just 10.89 kg, which fulfilled the lightweight requirement as discussed earlier. Even though the stiffness is not as good as structural steel and stainless steel, the safety factor is higher compared to both materials. On the other hand, stiffness is related to the total deformation or total deflection of the structure. The total deformation obtained in ANSYS Workbench are mostly low and less than the benchmark which make it an ideal design, thus produce an ideal stiffness. Therefore, the first objective is successfully achieved.

Next is the second objective of the project. The best selection of the chassis design through weight decision matrix analysis is conducted by selecting two parameters which are selection by design and selection by materials. For selection by design, there are four designs in total. The findings suggest that the best design is Design 4 because it has the highest score index. Selection by design is related to the mass of the chassis. Hence the highest score for Design 4 indicates that it has the lightest weight among all designs. With regards to the selection by material, there are three materials to choose from: structural steel, stainless steel and aluminium alloy. This is done shortly after Design 4 was selected. Using weight decision matrix analysis, the structural steel material is selected as the best chassis based on the scores index. Although it is heavier and has lower safety factor compared to aluminium alloy chassis, structural steel chassis has greater advantages with respect to other engineering criteria, theoretically. However, the aluminium alloy chassis still can be used for racing or recreation since it has the lightest weight and it is also safe to use regarding the high value of safety factor. In sum, the second objective for this project has been accomplished.

5.2 FUTURE WORK

In the future, it is recommended that the existing chassis for this project is replaced with carbon fibre material instead of steel. This is due to several reasons. Firstly, carbon fibre is composed of carbon atoms which bond together to form a long chain. It is basically very thin strands of carbon which is even thinner than human hair. The strands can be twisted together, like yarn and the yarn can be woven together, like cloth. These cloths and yarns can be moulded and bonded together into any shape desired according to the design and dimension of the product. This bond is formed by using heat and pressure, combining the fibre with a plastic or a polymer. Carbon fibre is about five times stronger than steel, two times stiffer, yet weights about two-thirds less than steel.

In addition, carbon fibre has slowly made its way into multiple industries, replacing metal in certain applications. In fact, carbon fibre is also offered as chopped strands and powder. This lay up's characteristic is then determined by the added materials such as glass fibres, Kevlar or aluminium. There are many factors affecting the physical properties of carbon fibre but the most important factor is the degree of carbonizing which the carbon contents are usually more than 92 percent by weight and the orientation of the layered carbon planes called the ribbons.

Furthermore, the future chassis based on current project should have different design. The existing design contains three tyres. Adding one more tyre will complete four tyres in total for the design. This might increase the balancing of the chassis in cornering and acceleration. Lastly, one of the efforts in the future for this project is to fabricate the chosen design of the chassis and compared the results with computer simulations. This will make the project more efficient and accurate because it has theoretical and experimental data to be compared from simulation and practical experiment. Thus, one can decide whether the chassis is a good design or else in reality.

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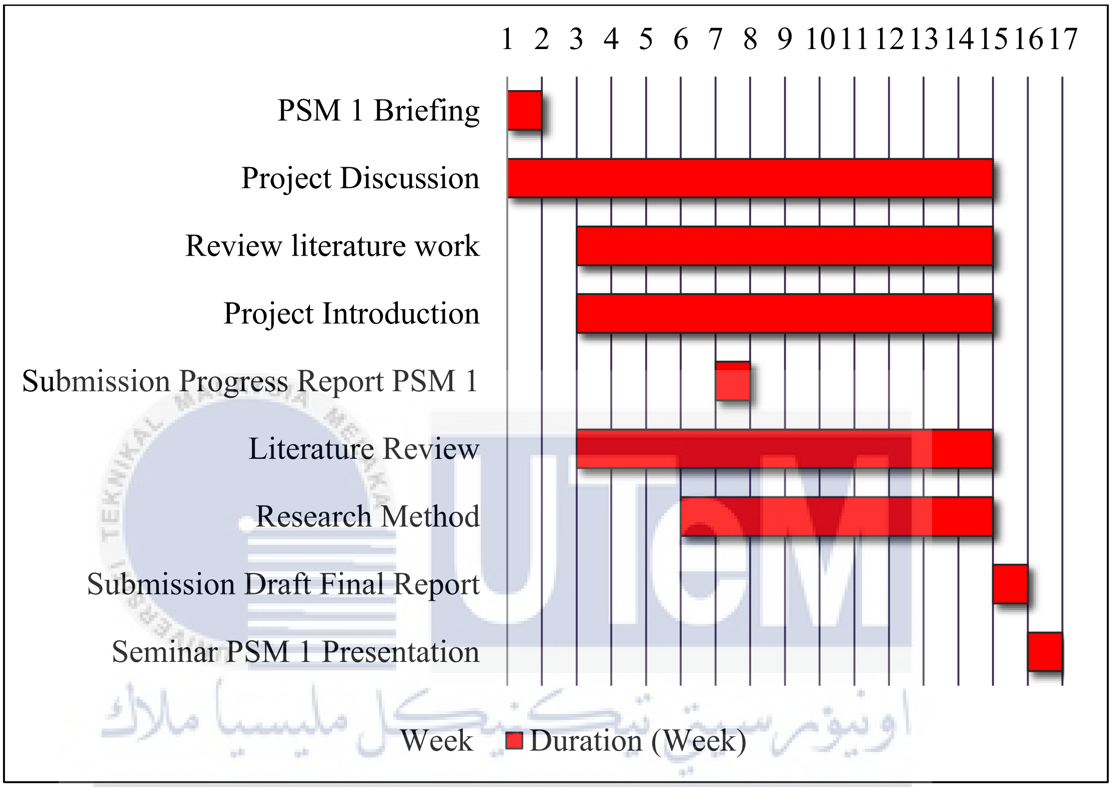
APPENDICES

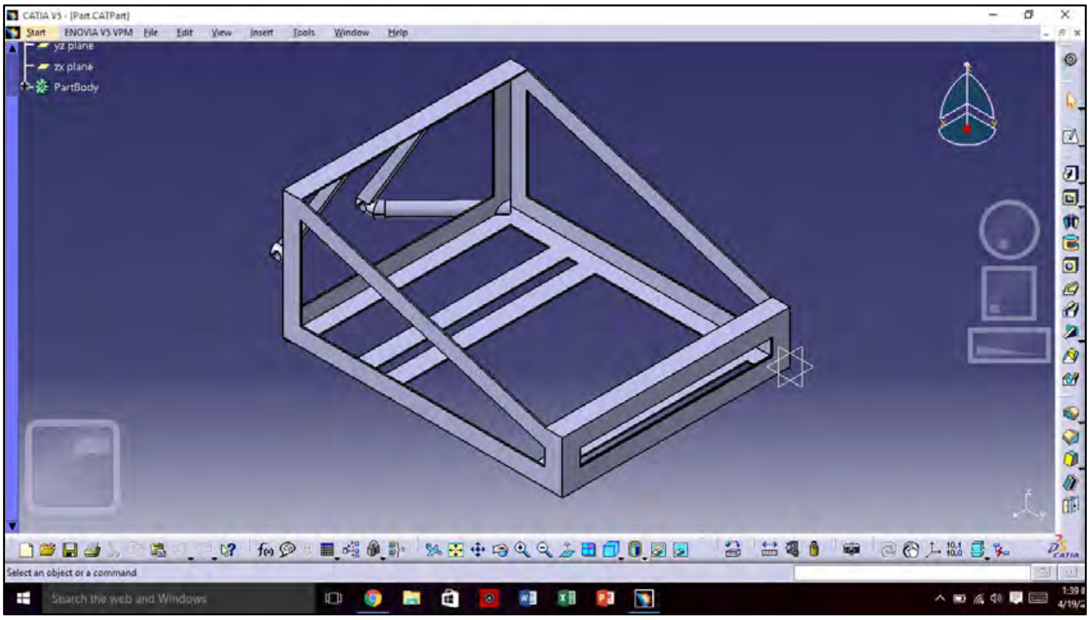
Appendix A: Gantt Chart for PSM 1.



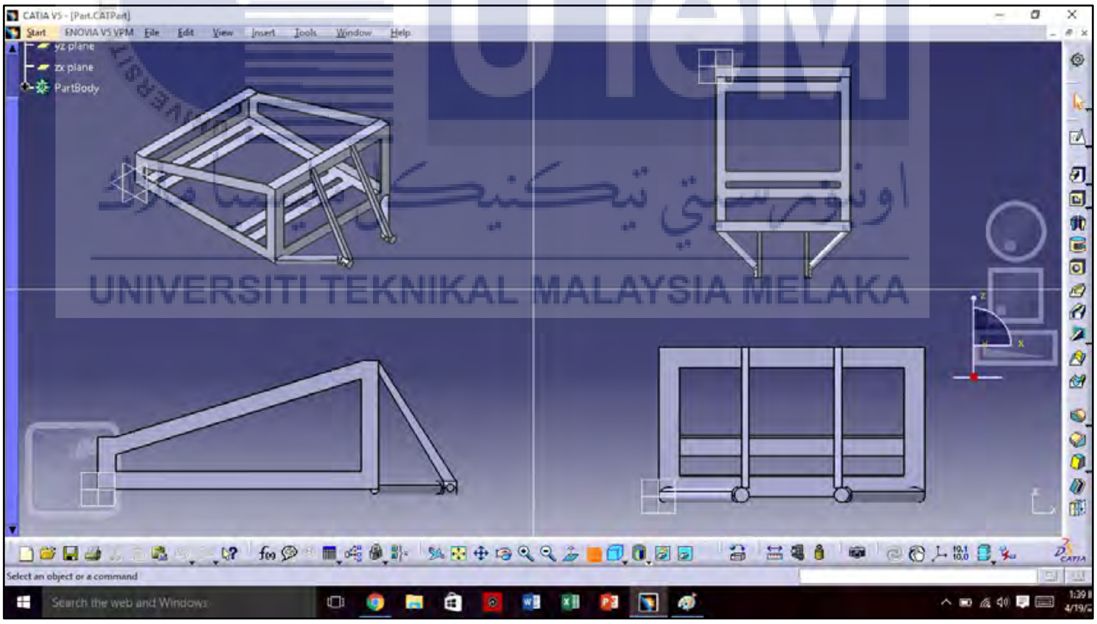
Appendix B: Material with Grade in the Market.

Material	Grade
Structural Steel	HA 250
Stainless Steel	AISI 304 L
Aluminium Alloy	2024-T3

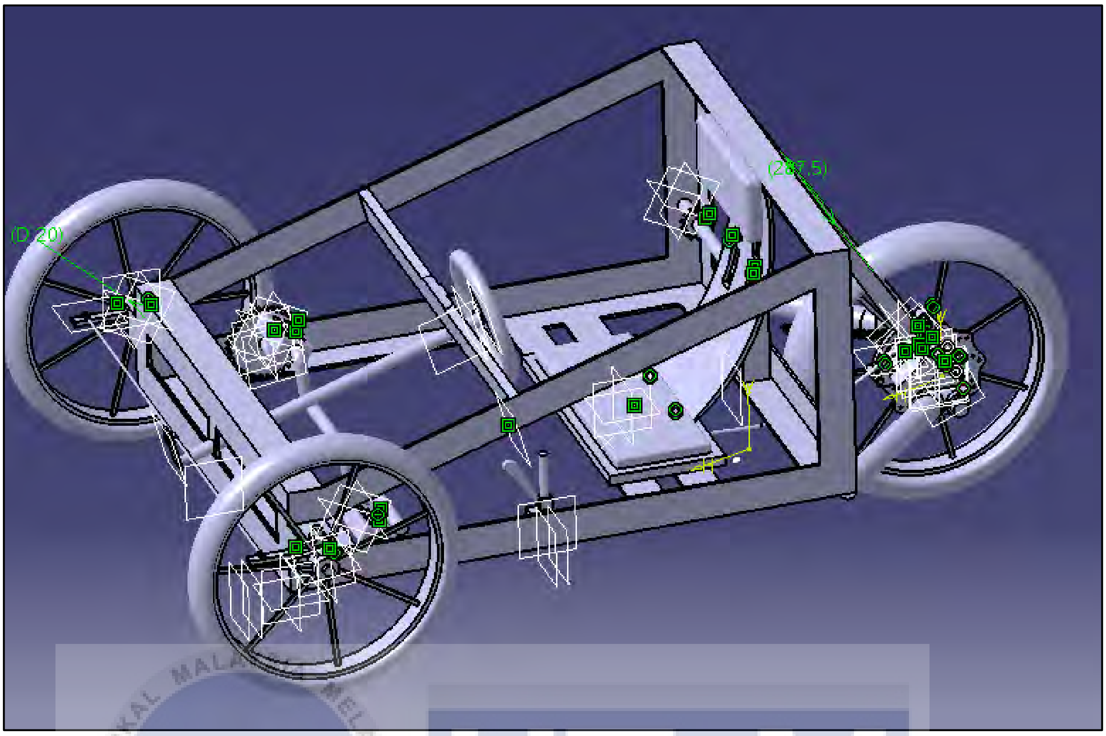
Appendix C: Isometric View in Catia.



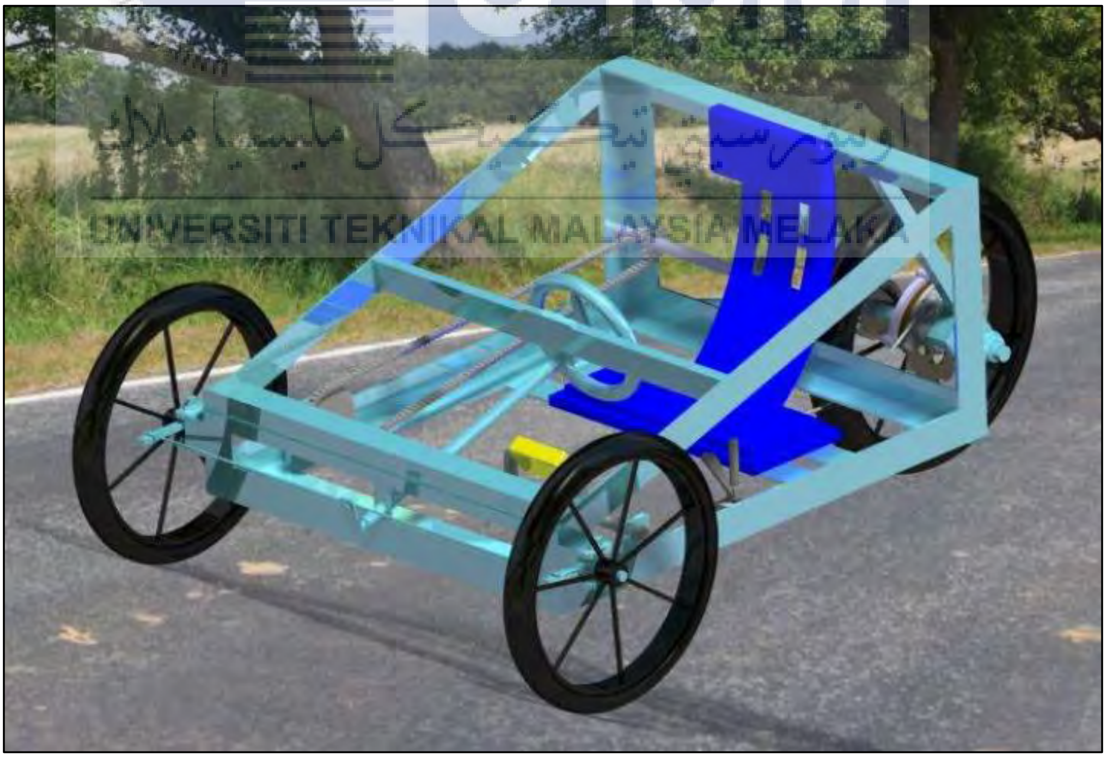
Appendix D: Orthographic View in Catia.



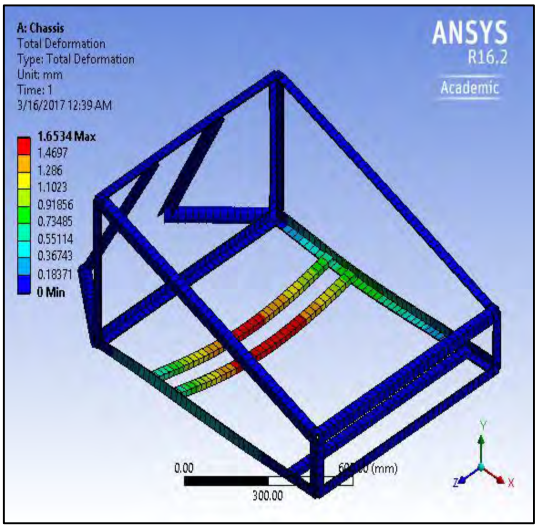
Appendix E: Final Product of HPV.



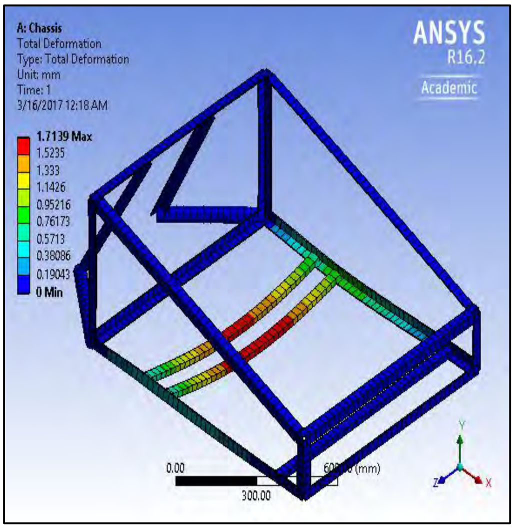
Appendix F: Rendering Image of Final Product.



Appendix G: Design 1 in Cornering Analysis.

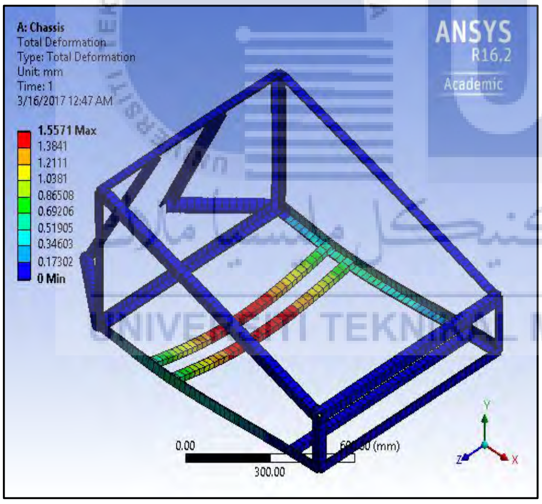


Structural Steel



Stainless Steel

Appendix H: Design 1 in Acceleration Analysis.



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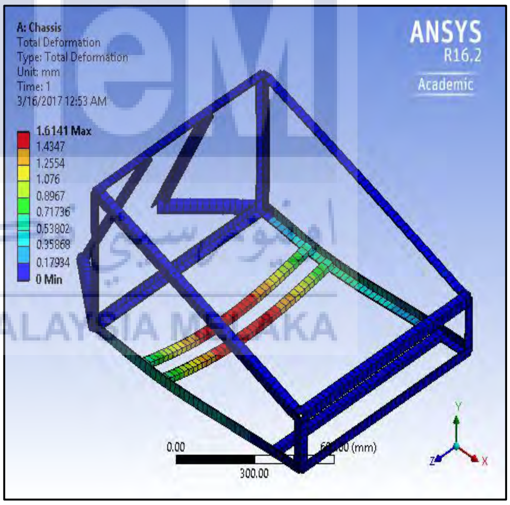
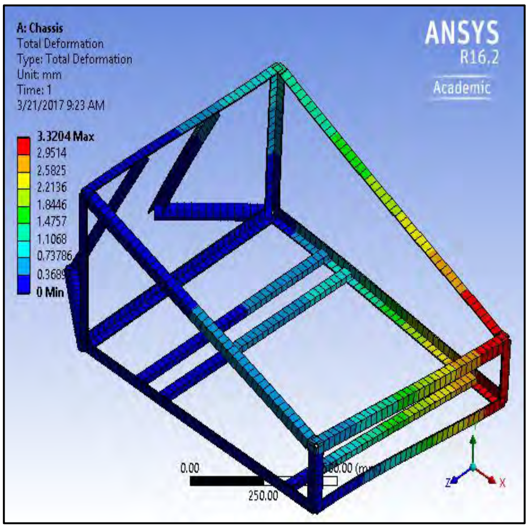


Stainless Steel

Appendix I: Design 1 in Torsional Analysis.



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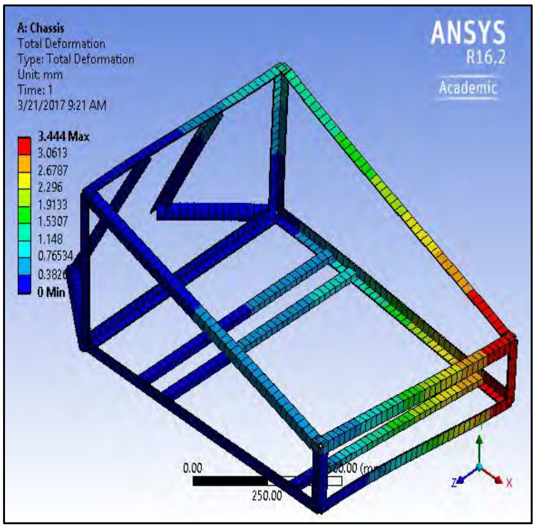
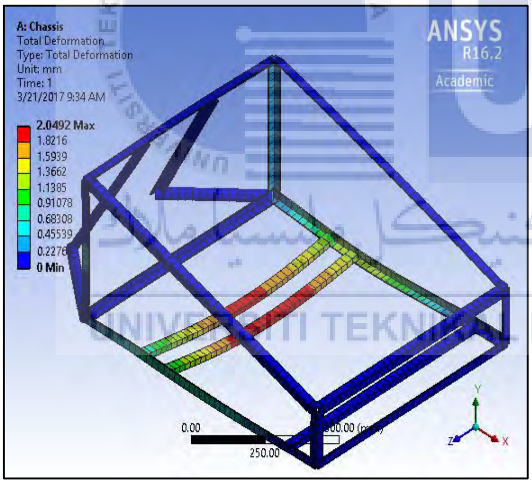


Stainless Steel

Appendix J: Design 2 in Cornering Analysis.



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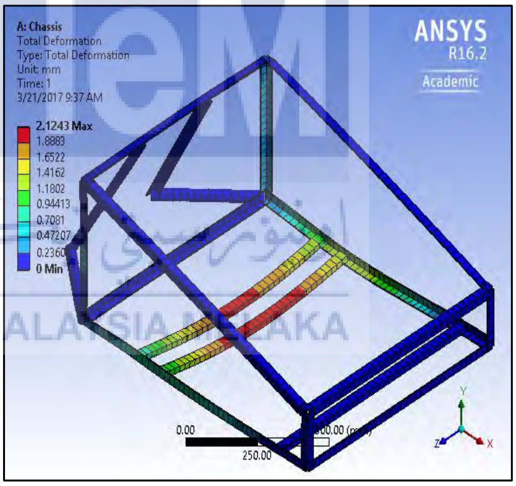
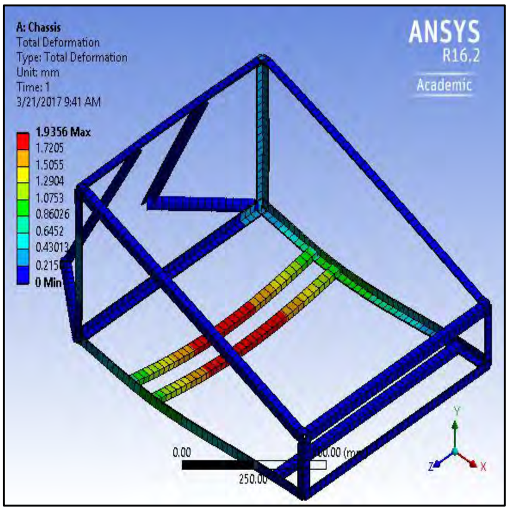
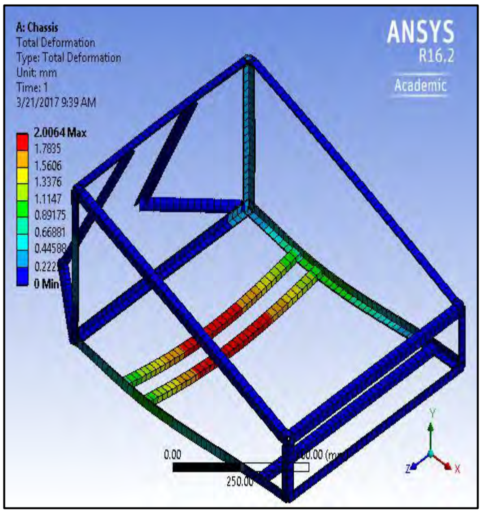


Stainless Steel

Appendix K: Design 2 in Acceleration Analysis.

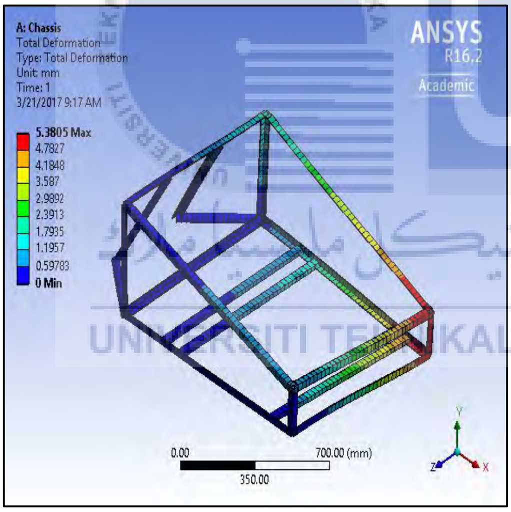


Structural Steel

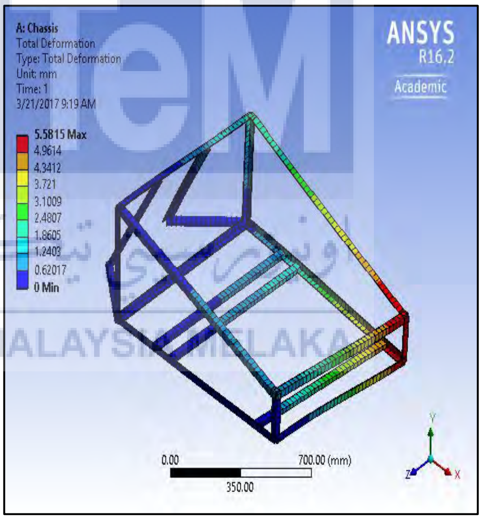


Stainless Steel

Appendix L: Design 2 in Torsional Analysis.

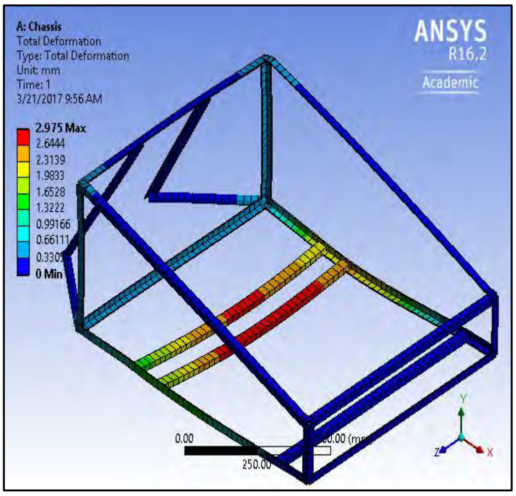


Structural Steel



Stainless Steel

Appendix M: Design 3 in Cornering Analysis.



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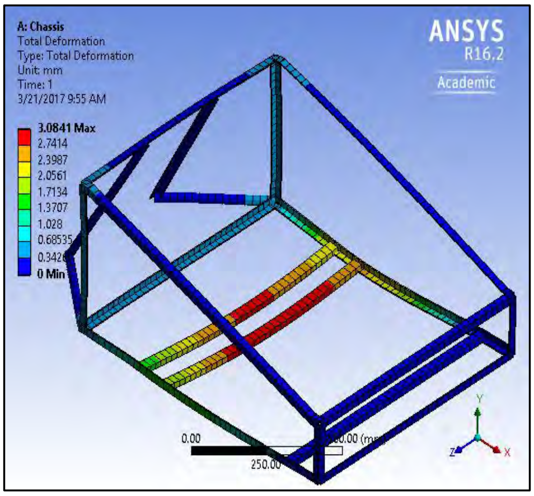
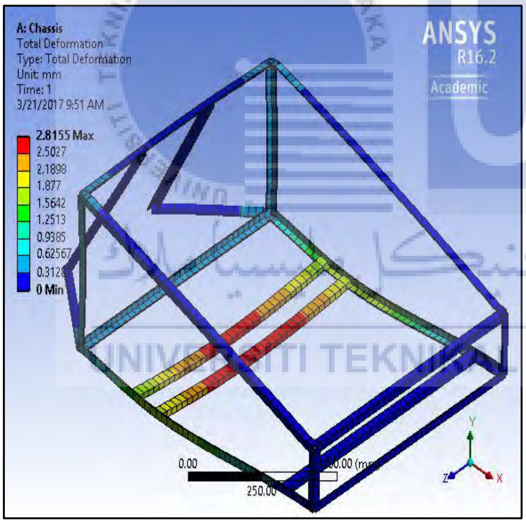


Stainless Steel

Appendix N: Design 3 in Acceleration Analysis.



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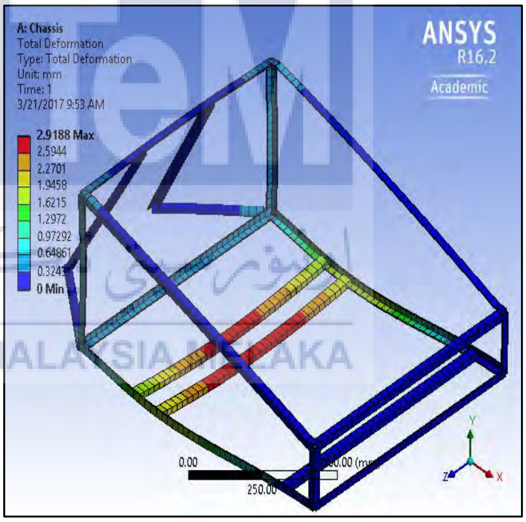
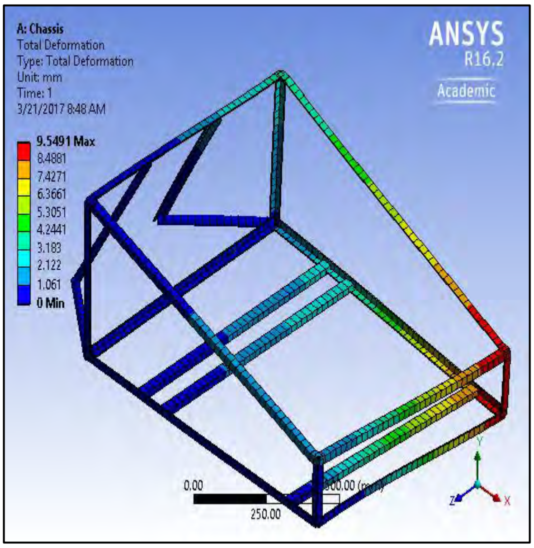


Stainless Steel

Appendix O: Design 3 in Torsional Analysis.



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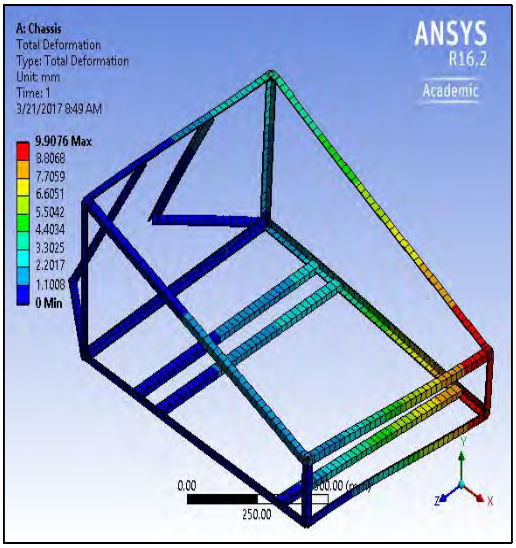

Stainless Steel