IMPACT TEST STUDY FOR THE FRONTAL AND SIDE OF SPACEFRAME FOR FORMULA RACING CAR

NG LIM HUAT

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

IMPACT TEST STUDY FOR THE FRONTAL AND SIDE OF SPACEFRAME FOR FORMULA RACING CAR

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A report submitted
In fulfillment of the requirements for the degree of
Bachelor of Mechanical Engineering (Hons)

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DECLARATION

I declare that this project report entitled "Impact test study for the frontal and side of Spaceframe for Formula Racing Car" is the result of my own work except as cited in the references.

Signature : ………………………………

Name : ……………………………....

Date : ………………………………

APPROVAL

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

Signature : ………………………………

Name : ……………………………....

Date : ………………………………

DEDICATION

To my beloved mother, Kong Kim Poh

and my father, Ng Peng Khoon

ABSTRACT

Formula Society of Automotive Engineers (FSAE) competition is a worldwide racing competition that allow the university students to develop and fabricate their own formula racing car with the practical skills and knowledge learnt throughout the academic years. Before the event started, every racing team must be confident as their racing car is well developed and well prepared. Sometimes the accident still possible to happen due to some uncontrollable factors such as weather, road condition and driver status. To prevent severe injuries to driver, the racing car must strong enough to provide a good protection. The main component that should be first to design when building a racing car is the chassis (space frame) as it plays the role as the outer shell for protection and the backbone to carry all component. Hence, the objective of this project is to design and analyze the space frame chassis for the frontal and side impact test. The design criteria for the space frame chassis is predicated to FSAE rule 2019 where the other factor like ergonomics, load analysis and safety factor are considered as well. Software used in this project for 3-Dimensional (3D) modeling and crash test simulation is Computer-Aided Three-Dimensional Interactive Application Version 5 (CATIA V5). Seven concepts had been proposed in this project by combining different component of chassis such as front bulkhead, main roll hoop, front roll hoop, side impact structure and bracing. The three best concepts were selected based on the criteria like chassis weight, material cost, manufacturability, safety and triangulation as stated in evaluation of the concept selection via weighted matrix decision method. The selected concept designs will be proceeded into the 3D modelling and Finite Element Analysis (FEA) using CATIA V5 to find out the best among three designs on protecting the driver from frontal and side impact. The value of von mises stress (N/m^2), deformation (mm) and factor of safety will be discussed and used to identify the best design.

ABSTRAK

Pertandingan Persatuan Jurutera Automotif Formula (FSAE) adalah pertandingan perlumbaan di seluruh dunia yang membolehkan pelajar universiti untuk membangun dan membentuk kereta lumba formula mereka sendiri dengan kemahiran dan pengetahuan praktikal yang dipelajari sepanjang tahun akademik. Sebelum acara bermula, setiap pasukan perlumbaan mestilah yakin bahawa kereta lumba mereka sudah bersedia. Kadang-kadang kemalangan itu masih mungkin berlaku disebabkan beberapa faktor yang tidak dapat dikawalkan seperti cuaca, keadaan jalan raya dan status pemandu. Untuk mengelakkan kecederaan yang teruk kepada pemandu, kereta lumba mesti kuat untuk memberikan perlindungan yang terbaik. Komponen utama yang perlu dibuat pertama apabila membina sebuah kereta perlumbaan adalah casis (kerangka) kerana ia memainkan peranan sebagai perlindungan luar untuk keselamatan pemandu dan juga tulang belakang untuk menanggung semua komponen. Oleh itu, matlamat projek ini adalah untuk merekabentuk dan menganalisis casis rangka ruang untuk ujian hentaman hadapan dan sampingan. Kriteria rekabentuk untuk casis berdasarkan pada aturan FSAE 2019 di mana faktor lain seperti ergonomik, analisis beban dan faktor keselamatan juga dianggapkan. Perisian yang digunakan dalam projek ini untuk pemodelan 3-Dimensi (3D) dan simulasi ujian kemalangan adalah Aplikasi Interaktif Tiga Dimensi Interaktif Versi 5 (CATIA V5). Tujuh konsep telah dicadangkan dalam projek ini dengan menggabungkan komponen yang berbeza dari casis seperti tiang depan, gelung roll utama, gelang roll depan, struktur kesan sampingan dan pengaman. Tiga konsep terbaik dipilih berdasarkan kriteria seperti berat casis, kos bahan, "manufacturability", keselamatan dan triangulasi seperti yang dinyatakan dalam penilaian pemilihan konsep melalui kaedah "weighted decision matrix". Rekabentuk konsep yang dipilih akan diteruskan ke tahap pemodelan 3D dan Finite Element Analysis (FEA) menggunakan CATIA V5 untuk mengetahui rekabentuk yang terbaik antara tiga rekabentuk tersebut dalam melindungi pemandu dari hentaman depan dan sampingan. Nilai von mises stress (N / m2), ubah bentuk (mm) dan faktor keselamatan akan dibincangkan dan digunakan untuk mengenal pasti rekabentuk terbaik.

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Last but not least, thanks to my family for their support and my friends that helped me overcome the problems facing in this project. Thank you and hopefully this report will be useful as a guidance for other students in the future as a reference in their study.

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LIST OF ABBREVIATION

2D	**-Two-dimensional**
3D	**-Three-dimensional**
AISI	**-American Iron and Steel Institute**
AL	**-Aluminium**
ASTM	**-American Society for Testing and Materials**
ATD	**-Anthropomorphic Test Dummy**
CATIA V5	**-Computer-Aided Three-Dimensional Interactive Application Version 5**
F1	**-Formula One**
FEA	**-Finite Element Analysis**
FOS	**-Factor of Safety**
FSAE	**-Formula Society of Automotive Engineers**
IS	**-Indian Standards**
JSAE	**-Student Formula Japan**
MS	**-Mild Steel**
OD	**-Outside Diameter**
RPM	**-Revoulution per minute**
RPS	**-Rotation per second**
SI	**-Simulation**
TIG	**-Tungsten Inert Gas**
UTeM	**-Universiti Teknikal MalaysiaMelaka**

LIST OF SYMBOLS

a	**-**	**Acceleration**
F	**-**	**Force**
m	**-**	**Mass**
r	**-**	**Radius of wheel**
t	**-**	**Time**
t	**-**	**Time of impact**
u	**-**	**Initial Velocity**
v	**-**	**Final Velocity**
x	**-**	**Chassis weight**

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of the study

The Formula SAE competitions is an annual event that attracts many teams from universities all over the world. It is a good platform for the undergraduate and graduate students to conceive, fabricate, develop and compete with their designed formula style vehicles. Formula SAE is a competition that strongly related to engineering education as the required performance demonstration of vehicles is the core of events. Each teams given the chance to fabricate their vehicle with creativity and engineering skills as they followed the technical requirement and FSAE rule. A high performance and durable vehicle is the key to successfully complete all the events at the Formula SAE competitions because each design will be judged and evaluated against other competing designs in a series of Static and Dynamic events. The progress of the teams to build their formula car can be assumed that they are actually work for an engineering company that focus on designing, fabricating, testing and demonstrating of vehicle. It will be a great and only chance for the student's career (Rules, 2019).

There is always a rule and regulation that every team must obeyed. The functional requirement or the criteria of the equipment must be fulfilled to ensure the safety of the driver. Tough the requirement is achieved but sometime the accident can still be happened due to some factors such as track condition, driver experience and healthy status and weather. Based on the result of Formula Student East 2017, it shows that some team had failed the dynamic event due to the accident or malfunction of the formula car (Stuttgart *et al.*, 2017). From internet resources, the accidents especially frontal collision had happened at the past five year events. Besides that, the side impact velocities in rally racing are sometime more dangerous than in most crash (Njuguna, 2011). Although the driver was unharmed and no any death case is recorded yet but it is frustrated as the whole team have spent their time and money on the project, just for it to be damaged on the day.

Hence, to reduce the damage from the accident, it is important to improve the structural crashworthiness of the racing car. The crashworthiness refers to the ability of vehicle on the energy absorption if a collision occurs (Wang *et al.*, 2016). The impact test of the vehicle has been important in designing and testing for the manufacturing of vehicle. Crash test dummies are one of the engineering measuring devices that used to predict the severity of potential real-world injuries to the driver and passenger during an impact. With nowadays technologies, some drawing software are improved and able to do impact test in car simulation such as CATIA and SolidWorks that can perform Finite Element Analysis (FEA) (Outline, 2016). This helped to save the budget in testing of vehicle by simulating the crash scenarios using such software. The data analyzed is also reliable as the structural frame of the vehicle and its material used is same as the one to manufacture.

1.2 Problem Statement

Formula SAE is a favor event among the university all over the world. This event has created a great chance for the students to form a team and built their racing car based on original design. They are coming to the competition with confident as the car is well established, well prepared, and safe through the event. But there are some factors that is unpredictable like weather, road condition and driver status. These factors may lead to an accident that happen during the race and injured the car driver, other racer and the audience. With such a high speed acts on the racing car, some common crashes may happen. For example, frontal impact can occur when the racing car is losing control and directly collide with an obstacle or another vehicle. Side impact may occur when the car is sliding, it may hit randomly with an obstacle or another vehicle. Hence, the space frame chassis of the racing car plays an important role to maximize the protection. The common types of crashes such as frontal impact and side impact must be simulated for the space frame design to make analysis and obtain the data and result. By comparing the simulated result with the result that tested with current design, we are able to improve and design a space frame for racing car based on the impact test studied and tends to provide better and safer protection to the driver.

1.3 Objectives

- To design a space frame that provide better protection when the impact happens.
- To analyze the impact test result that can be used to compare with the existed impact test result tested using the designed space frame.

1.4 Scopes

- Design a space frame for formula racing car according to product design specification using the design software, CATIA V5R19.
- Use the CATIA V5R19 to do Finite element analysis (FEA) for car simulation

1.5 Gantt Chart

Task	Academic Week of Semester															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Introduction																
Selection of PSM Title																
Identify the Scope and Objective of the Project																
Review of Problem Statement																
Literature Review																
Explore the Information, Journals and Reference Book																
Implement Literature Review																
Conceptual Design																
Product Design Specification																
Morphological Chart																
Concept Generation																
Concept Selection																
Submit of Report																
Seminar																

Figure 1.1: Gantt chart PSM I

Task	Academic Week of Semester															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Detail Design																
Software Drawing																
Finalize the Design																
Data Analysis																
Performing FEA Simulation with Different Speed																
Result and Discussion																
Dynamic Crash Result																
Deformation																
Conclusion																
Recommendation																
Submit of Report																
Seminar																

Figure 1.2: Gantt chart PSM II

1.6 Methodology view

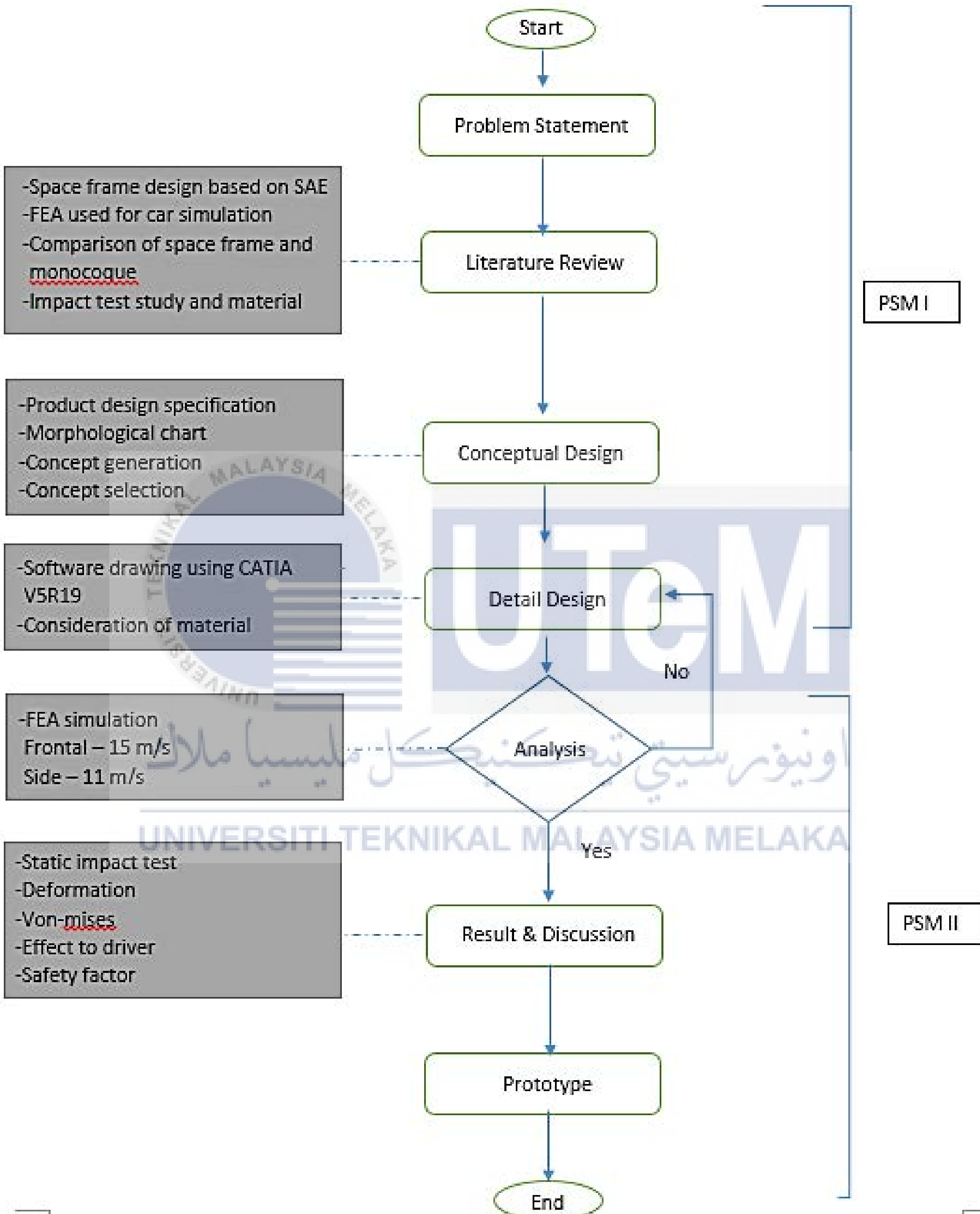


Figure 1.3: General methodology flow chart

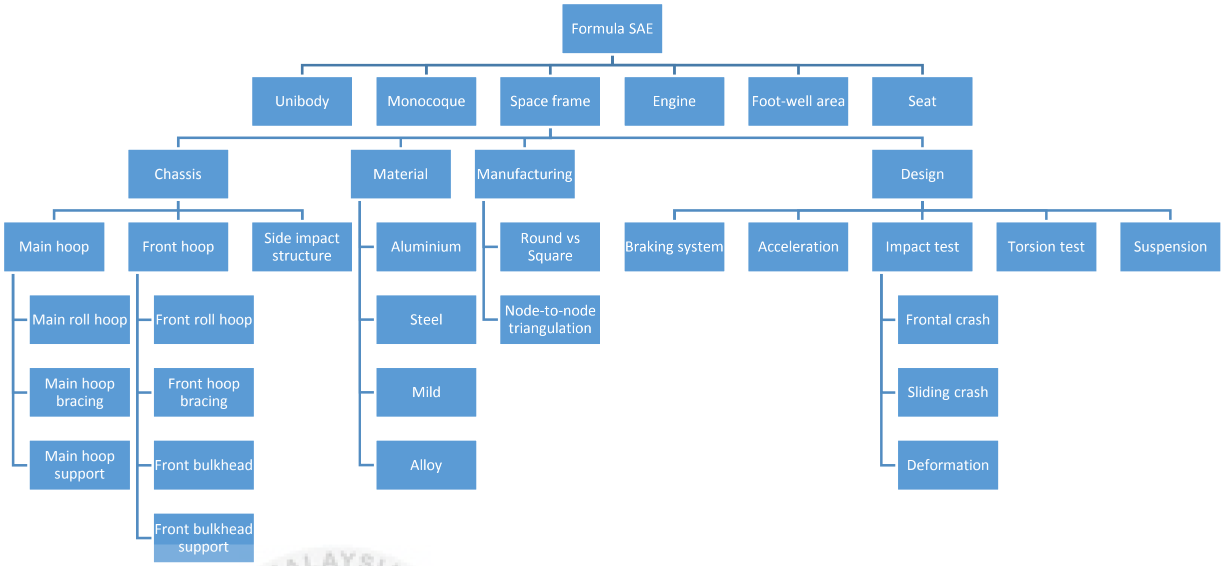


Figure 1.4: Formula SAE components

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this section, the data and results from the past research, experiment and reports in the form of journal will be used as a reference. All the content used and referred from the journals is related to the research on chassis, formula racing car design, structural design and analysis in Finite Element Analysis (FEA). Since the chassis is normally used for a competition, there must be standard for the dimensions and components to be followed based on the FSAE rules and regulation that updated every year (Regulations *et al.*, 2018), (Rules, 2019).Only the racing car that meets with the requirements is allowed to compete in the event.

2.2 Chassis

Chassis is the structural assembly of a system while also can be defined as the framework of a vehicle where the other components like engine and suspension mounted onto it. It can be a single fabricated structure, multiple fabricated structures or a combination of composite and welded structures. There are three different types of chassis frames are commonly used in automobile manufacturing nowadays, ladder chassis, back bone chassis and monocoque chassis (Y and S, 2013). Generally, there are two types of chassis used for the Formula SAE competition which are monocoque and space frame member (Rules, 2019). A well-designed chassis is capable to carry the total load that acted on the racing car and able to withstand the forces and stress caused due to the braking and acceleration of the car without failure (Patil and Joshi, 2015).

2.2.1 Ladder chassis

This kind of chassis is made with two longitudinal rail interconnected with lateral braces to form the connection between cross section. By designing and optimizing the twist fixture and jig of the chassis, the ladder chassis will have a small deflection on the frame and make it suited as the truck chassis and pickup chassis which requires a good handling characteristic (Ojo *et al.*, 2018).

2.2.2 Back bone chassis

A tubular beam and located at the center of the chassis is built as the backbone which joins the front and rear axle. The other mechanical parts like suspension system and powertrain system is mounted onto the back bone as well. The tubular backbone is functioned as the resistance to the torsion twist acted on the chassis to reduce the possibility of wear out (Patil and Joshi, 2015).

2.2.3 Monocoque

The monocoque can be defined as the outer structural skin without the support of internal frame. To fulfill the requirements of the FSAE rules, the usage of composite material is allowable as the documentation and evidence are shown. The documentation must be detailed about the material type, cloth weights, resin type, fiber orientation, number of layers, core material and layup technique. The calculation for the buckling, bending and tension should be prepared as well as the result of the monocoque laminate testing for the primary structure of the chassis(Rules, 2019). Monocoque chassis can be also built with metal to enhance the crash protection but resulted as the increasing of weight as well. A metal monocoque is rarely to be used in FSAE competition because the sheet metal used to build the monocoque surface is far weaker than the metallic tubing used for space frame chassis while the lightweight characteristic of a composite monocoque is wasted (Praveen, 2016).

2.2.4 Space frame member

A space-frame chassis is constructed from an arrangement of simple straight members which make up a larger frame as shown in Figure 2.1. The members generally constructed in a triangular pattern which are always in pure compression or tension in help the frame to support bending loads (Waterman, 2011).

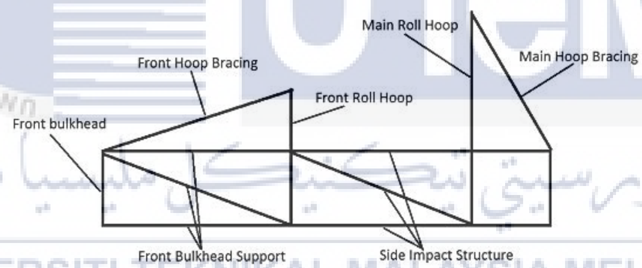


Figure 2.1: the frame members connection required by the FSAE rules.

Source: (Waterman, 2011)

The FSAE rules define a minimum size for all the chassis members which is also called as primary structures. To avoid the increase of un-necessary weight, the chassis design should make best use of the required members so that as few possible additional members are needed. Optimization of the size of the chassis members are important as the suitable addition of members can enhance the safety and durability of the chassis without violating the rules (Waterman, 2011). The front roll hoop, the main roll hoop, the front bulk head and the rear bulk head were fixed since the first stages of design. The position of the main roll hoop was fixed considering the engine mounting points and the drive shaft positions that were fixed earlier, a space was utilized for the engine and the power train components as shown in Figure 2.2. The main roll hoop is functioned as a protection to the upper body of the driver while the front roll hoop protected the driver's arm when the car rolls over. Side impact structure is the beams that connected between two roll hoop and helped to protect the driver from any side collision (Marzuki and Azmi, 2015).

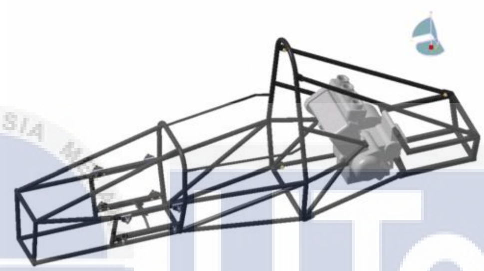


Figure 2.2: Chassis assemblies with engine

Source: (Chang *et al.*, 2010)

A space between the main roll hoop and the front roll hoop is provided for the driver which is also known as cockpit area. A template of the cockpit opening and foot-well area are needed for inspection to ensure the driver fit to the space, Figure 2.3. It is better to maximize the cockpit area to provide a safe and comfort zone for driver. The foot-well area is also another important space where the accelerator and brake pedal located. (Waterman, 2011).

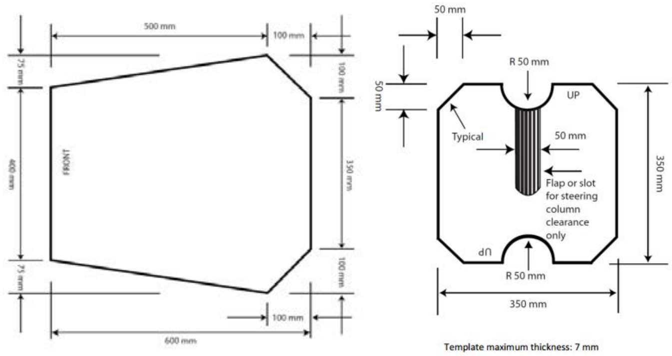


Figure 2.3: Cockpit area template

Source: (Rules, 2019)

Front bulkhead is the frame with a cross section that was fixed at the front end of the chassis. The area of the cross section is designed based on the length of the manikin's leg room. A front roll hoop was fixed at an angle to have suspension nodes on the members. Links from the front bulk head to the front roll hoop were made such as to include the other two pairs of suspension hard points. Main roll hoop was roughly designed at same optimum angle with constraint and must make sure the front roll hoop is not intercept with the driver's vision (Prajwal Kumar M., Vivek Muralidharan, 2018).

The seat for the driver must be followed the rule of 95th percentile male can drive the car with clearance to the two roll hoops. 95th percentile male is one of the crash test dummy that widely used in the inspection of impact test, Figure 2.4. 95th percentiles are also equal to two standard deviations on either side of the mean. The 95th percentile ATD represents the first 95% of the whole male population (or two standard deviations) while neglecting the last 5% who are the tallest people (Outline, 2016).

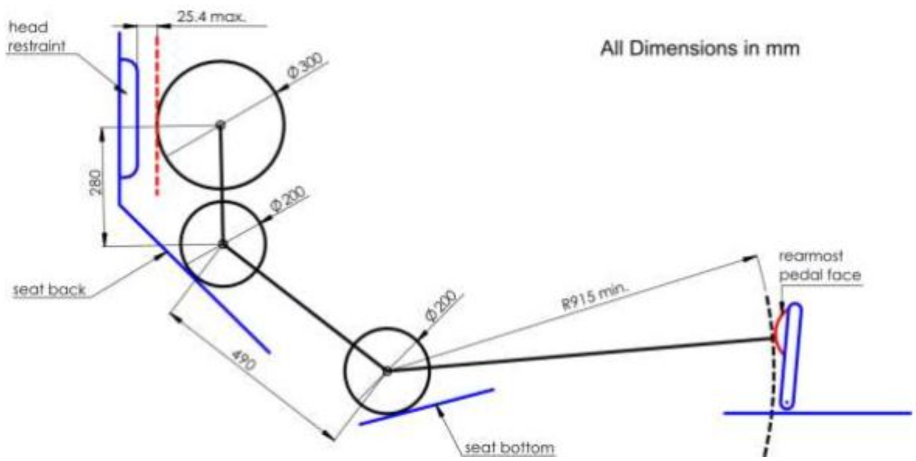


Figure 2.4: 95th male percentile template

Source: (Rules, 2019)

Since the 95th percentile male is the largest template representing the driver, if the template is fit with the seat, then the driver must be fit and able to be protect by the chassis (Waterman, 2011).

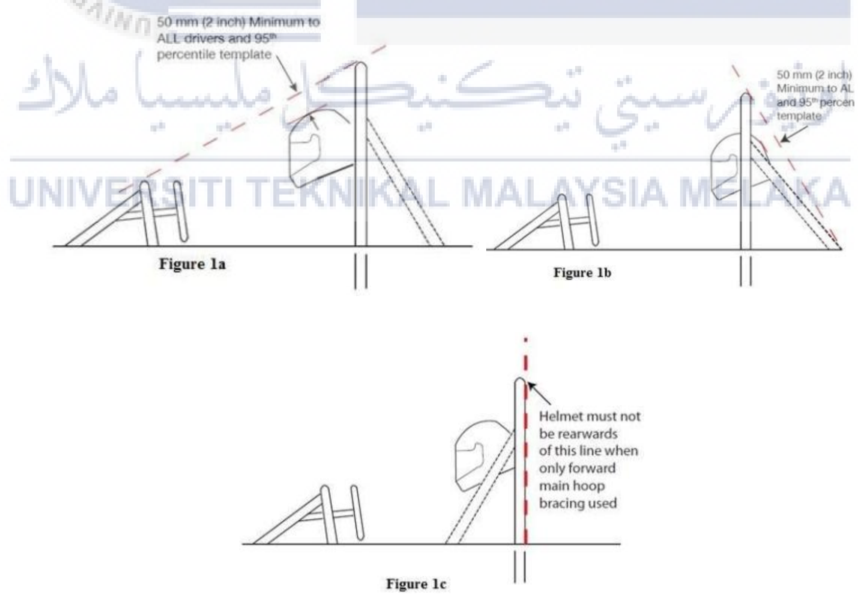


Figure 2.5: Helmet clearance

Source: (Rules, 2019)

There are aslo some rules for the helmet clearance where the minimum distance of the driver helmet is 2 inches from the top end of the main roll hoop to protect the driver from roll-over accident as shown in Figure 2.5 (Rules, 2019).

2.2.5 Comparison

Monocoque chassis has better performance due to its properties of maintaining rigidity in bending and torsion, providing efficient load absorption and a great reduce on weight (Denny *et al.*, 2018) compare to space frame chassis. Sometimes, a space frame chassis was chosen over a monocoque chassis despite being heavier (Prajwal Kumar M., Vivek Muralidharan, 2018). This is because the requirement of manufacturing skills, cost, manufacturing time to make a space frame chassis is considered lower than a monocoque chassis (Hagan, Rappolt and Waldrop, 2014). The only tools required to construct a space frame is a saw, measuring device and welder. The space frame still has advantages over a monocoque as it can easily be repaired even after the inspection of the impact test (Mughal, Mughal and Mughal, 2013).

2.2.6 Space frame tubing regulation

According to the FSAE rules, the primary structure of the car must be constructed of either round or square, mild or alloy steel tubing (minimum 0.1% carbon) that not exceed the minimum dimensions specified in the following Figure 2.6.

Application	Outside Diameter and Wall Thickness Options
Main Hoop, Front Hoop, Shoulder Harness Mounting Bar	Round 1.0 inch x 0.095 inch, Round 25.0 mm x 2.50 mm
Side Impact Structure, Front Bulkhead, Roll Hoop Bracing, Driver Restraint Harness Attachment (other than Shoulder Harness Mounting Bar), (EV) Accumulator Protection Structure	Round 1.0 inch x 0.065 inch, Round 25.0 mm x 1.75 mm, Square 1.0 inch x 1.0 inch x 0.047 inch, Square 25.0 mm x 25.0 mm x 1.20 mm
Front Bulkhead Support, Main Hoop Bracing Supports, Shoulder Harness Mounting Bar Bracing, (EV) Tractive System Component Protection	Round 1.0 inch x 0.047 inch, Round 25.0 mm x 1.5 mm
Bent Upper Side Impact Member	Round 1.375 inch x 0.047 inch Round 35.0 mm x 1.2 mm

Figure 2.6: Steel tubing dimensions

Source: (Regulations *et al.*, 2018)

There are some materials have been chosen to manufacture the space frame chassis in the past event such as chromoly 4130 steel, cold rolled steel, 1018 SAE grade steel, mild steel and composite material like aluminium, titanium and magnesium. Aside from cost there are other advantages to using mild steel over more expensive alloy steel, it is easy to machine and weld, also it does not become brittle in the heat affected zone when welding.

2.2.6.1 Square or Round

As the rules stated, some member of the chassis can be built with either square or round steel tubing. Some simple calculations have been done before by comparing both pipes' cross sections to identify their advantages and disadvantages (Waterman, 2011). In this test, the dimension of tubes prepared are closest to the minimum requirement based on the FSAE rule. Although this test is made according to the FSAE rule, 2011 where the dimension of tubing is different with the latest rule, it does not affect the result as the aim of this test is to find out which type of tubing is more essential in manufacturing the chassis.

	Round	Square	%Difference
Cross Sectional Area [m]	119.6318	132.7175	10.93829
Mass per Unit length [kg/m]	0.933128	1.035197	10.93829
Second Moment of Area [mm^4]	8508.815	12688.02*	49.11618
Buckling Load for 1m Length** [N]	16795.73	25045.15	49.11618

Figure 2.7: Comparison of round tubing and square tubing

Source: (Waterman, 2011)

The cross sectional area, mass per unit length, second moment of area and the buckling load for 1m length have been calculated and shown in the Figure 2.7. From the result of the difference percentage, it has claimed that a square tubing is more essential compared to round tubing as it has nearly doubled the yield strength while only increase in one-tenth of the weight.

Beside the material properties, square tubing also advanced in manufacturing section. A square tubing that used for the horizontal sections such as front bulkhead or side impact structure, the joints between members in the chassis can easily be cut and welded with other flat surface (Waterman, 2011).

2.2.6.3 Triangulation

The simplest triangulation involves adding a diagonal member to an arrangement of four members to break the section into two sections. The resulting triangles are able to carry all forces in pure tension or compression without introducing bending stresses into the joints. A simulation using SolidWorks has been made by comparing the un-triangulated square frame and the triangulated frame. In the figure below, the data mass of frame, peak stress, and maximum displacement is collected and compared.

	Weight [kg]	Displacement [mm]	Von-Mises Stress [MPa]
Square Frame	1.99	2.65	188
Diagonal Member	2.62	0.0727	18.94

Figure 2.8: Square frame compare with triangulation

Source: (Waterman, 2011)

From the result in Figure 2.8, the addition of a diagonal member into a square frame has increased the weight of frame. This might be the only weakness of the triangulation but it can extremely decreases the maximum displacement peak stress which guaranteed the safety provided by the frame (Waterman, 2011). A thin wall tubing is well against tension and compression but weak against bending stress (Das, 2016). A triangulated frame will not deformed easily and able to withstand a high amount of stress.

2.2.7 Ergonomics

Ergonomic is related to the design, aesthetics, efficiency, safety, user friendly and performance of a product. As for the good ergonomic in designing a racing car, some key factor has to be defined during the early phase of design. A low center of gravity of vehicle is required for a racing car to prevent sliding and rollover when cornering in the event (Manoharan, 2016). For this, a minimum ground clearance is determined for the racing car.

Serviceability is related to the time consuming on removing and installing of the components. During the manufacturing phase, optimization, repair and maintenance is sometimes needed, the mechanical part such as battery, engine or motor has to be removed from the chassis for inspection (Munir, Adnan and Malingam, 2017). If the frame member designed is complex, the team is wasting unnecessary effort and time (Kemna, 2011). Hence, the design of the chassis must be compact but also considering the ease of manufacturability especially the rear of the chassis as the inspection, servicing and replacement of power train system is focused on the section (Mihailidis *et al.*, 2009).

As mentioned before, some dimensions of the part of chassis has to be determined earlier. For example, wheelbase and track width is very important as these parameters will affect the handling characteristics, weight transfer and turning radius (Guimaraes *et al.*, 2016). According to the FSAE rules, the wheelbase, distance between front and rear axle must be at least 1525 mm and the narrower track must not be less than 75 percent of the wider track. This limitation of the parameter has guaranteed the minimum cockpit area for the driver without causing any uncomfortable. A racing car with short wheelbase and wide tracks are less stable towards the straight roads but very efficient in cornering (Mihailidis *et al.*, 2009).

In designing a Formula racing car, many features and dimensions of the parts is considered to achieve the standard of safety and maintain the human's life and environment (Abdullah *et al.*, 2017). The cockpit area template used for the racing car gives the driver an area with at least 600mm x 550 mm. Besides the 95th percentile male, there is another template which is called 5th percentile female with a shorter and smaller body dimension. Although the two templates are complex as the dimensions are totally different, only 95th percentile male is used as the template for the FSAE competition. If the designed cockpit area is referred to a larger template, the smaller driver should have no problems and completely fit to the cockpit area (Buffington, 2014).

To ensure the aerodynamics is not disturbing the racing car, the front and rear dimensions is defined as no aerodynamic device exceed more than 700mm forward the front of the front tires, 250mm rearward of the rear of the rear tires and not higher than 1.2 meters above the ground. For side impact structure, the upper member must connect main hoop and front hoop with a height ranged between 300mm and 350mm while the lower member must connect the bottom of main hoop and front hoop. The space availability between bulkhead and roll hoop must be large enough for installation of suspension and power train unit (Rules, 2019).

The dimension of the front bulkhead is able to determine since the early design phase. An impact attenuator, Figure 2.9 is a device that attached on the front of the front bulkhead as a protection to the chassis. The impact attenuator is designed to absorb a great amount of energy during the frontal impact intends to reduce the injuries to the driver (Mechanics, Naiju and Krishnamoorthy, 2012). The minimum dimension given for the attenuator is 100mm x 200mm which can be determined as the minimum dimensions of the front bulkhead as well. The impact attenuator should not be screwed with the screws positioned in the longitudinal direction because the large impact may cause it enters the cockpit and injures the driver (Mihailidis *et al.*, 2009).

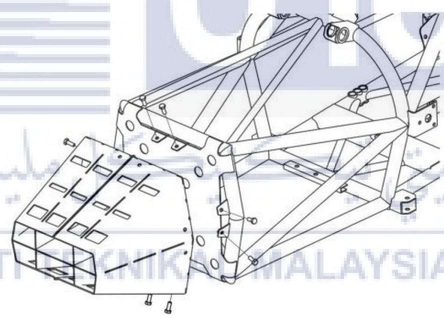


Figure 2.9: Impact attenuator screwed in front of chassis

Source: (Mihailidis *et al.*, 2009)

2.3 Suspension system

Suspension system is one of the major consideration when designing the chassis to achieve ergonomic. Suspension is suggested to be mounted on the frame with triangulation as it needs to absorb a high amount of force. Normally, the front wheel suspension is attached to the section before the front hoop while the rear wheel suspension is attached to the rear of the chassis to achieve balancing and a required wheelbase (Das, 2016). Suspension is the device that deals with the frequency generated from the vibration of the chassis when driving on the track. To avoid resonance, the suspension is designed until it is out of the range of the natural frequency of the chassis. The torsional stiffness is able to be calculated based on the displacement of the chassis. A high stiffness of chassis tends to decrease the possibility of bending or twisting of the chassis (Abrams, 2008). The balancing of the suspension is also important as it keeps the tires always contact the path at all time for stability and provide the friction (Biswal *et al.*, 2017).

2.4 Accident

In the journal of Guzek, a statistical data that collected from police and traffic department in Poland stated that the driver is the major causes to accidents. Despite of the malfunctions of the vehicle, the improper operation of driver is the probably reason of a happened accident. This case is possible happens during the FSAE events due to the status of driver, weather and the reaction time when found an obstacles (Guzek and Lozia, 2012). To reduce the injuries causing from the accidents, the chassis is normally simulated for the engineering analysis such as torsional test, impact test, cornering test, acceleration test, brake test and bending test.

2.5 Finite element analysis (FEA)

Finite element analysis is a computerized method that allows the user to make simulation on the product designed. With the material properties of the product decided and the given phenomenon, the product will react to a real forces, fluid flow, vibration and other physical effects. FEA analysis is popular to use for simulation of the racing car to test the impact, torsion, bending and displacement of the frame. From the testing, the data is obtained for the use of optimization once the product does not meet the requirement. But results obtained may be slightly different from the actual performance. A prototype always provide more accurate result but it consumes a lot of time (Wang *et al.*, 2017).

2.5.1 Constraints

The wheels of a vehicle are always in contact with the ground when loading. This type of boundary condition will divert the impact energy into kinetic energy and become the forces to push the vehicle. In FEA test, four wheels are normally selected to become the fixed support to study its performance under a scenario of the absorption of impact energy. All the weight including the components will be calculated and acted on the chassis before starting the test (Hazimi *et al.*, 2018).

2.6 Current space frame

As a favor event all over the world, there are many space frame chassis has been designed in the past. Most of the team's chassis is successfully developed and able to compete the events without failure. The steps started from designing until the manufacturing phase is recorded and presented in the form of journals and reports. The chassis designed by different teams is considered different criterion such as low cost, safety first, ergonomic, performance and materials. The chassis has been simulated using FEA for the engineering analysis such as torsional stiffness and impact testing. These data is normally used by the other teams as benchmark to improve their own chassis for the competition.

As an engineering student, many UTeM students also compete in such events to create their racing car based on the knowledge learnt before. In the journal (Abdullah *et al.*, 2013), two different concepts of chassis is designed and analyzed using CATIA CAD. The safety factor of both chassis is obtained as shown in Figure 2.10 based on the analysis in acceleration, bending, braking, torsion and impact.

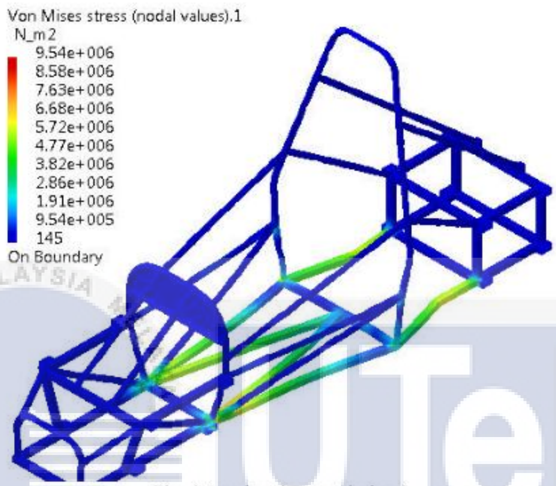


Fig. 4 Acceleration test design 2

TABLE III
FACTOR OF SAFETY

Analysis	Design 1	Design 2
Acceleration	6.61	5.49
Bending	5.98	7.16
Braking	6.38	6.21
Torsion	2.51	2.25
Impact	4.07	4.34

Figure 2.10: Factor of safety of chassis on different analysis

Source: (Abdullah *et al.*, 2013)

2.7 Material Selection

2.7.1 Monocoque chassis materials

The material property is an important criterion while designing and manufacturing a FSAE chassis. For the monocoque chassis, the carbon fiber composite will be the perfect material to construct it. In the design for motor vehicle, carbon fiber is always the best choice of material to make the chassis due to its advantage of light weight and strength (Diaz, Gonzalez and Diaz, 2015). They are ease in forming complex form without reducing its resistance in strength (Denny *et al.*, 2018). This property has make it an effective material for manufacturing the outer structural skin to be aerodynamic. Besides that, some team has tried to use aluminium as the main material in the monocoque form instead of carbon fiber composite to reduce the material cost. But this benefit is gained by the increase on the chassis weight which can be considered as a not so efficient replacement(Diaz, Gonzalez and Diaz, 2015). Due to the lightweight characteristic, composite material is widely used in building the racing car. But there is a weakness of this material as when there is an impact on such material, it will cause an internal damage which is hardly detectable. The internal damage is possible to weaken the strength of the part involved and causing failure (Weiße, 2009).

2.7.2 Space frame chassis materials

For the material used to build the space frame chassis, there is a values that needed to be fulfilled. For a non-welded material properties, the young's modulus (E) is equal to 200 GPa, Yield strength (Sy) is equal 305 MPa and the value of ultimate strength (Su) is 365 MPa. Any material that fulfilled the required properties is able to use as the chassis material.

Table 2.1: Analysis with different steel alloy

Source: (Manoharan, 2016)

MATERIAL	**CHROMOLY 4130**	**ASTM A252**	**AISI 1018**	**IS 3074**	**ASTM A106B**
Carbon content(%)	0.32	0.18	0.18	0.20	0.30
Yield strength (MPa)	395	350	365	372	383
Tensile strength (Mpa)	560	455	450	473	466
Elongation (%)	25	20	20	5	20
Cost in rupees /m	550	650	600	800	500
Availability	Easy	Medium	Easy	Difficult	Easy

2.7.3 Steels and steel alloy

Steel is an alloy of iron and carbon and other elements. With the different contents of carbon mixed with iron, the steel is categorized into different family of steel based on different standard. In the journal (Manoharan, 2016), the team has choose the material to build the chassis using decision matrix method. There are five types of steel with different content of carbon percentage listed in Table 2.1, chromoly4130, ASTM A252, AISI 1018, IS 3074 and ASTM A106B. After the decision, chromoly4130 is chose as the material as it has the highest carbon content, yield strength, tensile strength elongation with a reasonable price as shown in the Table 2.2.

Table 2.2: Decision matrix

Source: (Manoharan, 2016)

MATERIAL	**Chromoly 4130**	**Astm a252**	**Aisi 1018**	**Is 3074**	**Astm a106b**
PARAMETER					
Carbon content (%)	5	1	1	3	4
Yield strength(MPa)	5	1	2	3	4
Tensile strength (MPa)	5	2	1	4	3
Elongation (%)	5	2	2	1	2
Cost in rupees /meter	2	4	3	5	1
Availability	1	3	5	1	5
TOTAL	23	3	4	17	19

These five materials have achieved the minimum requirement of the material properties based on the FSAE rules, but Chromoly4130 is stronger and more flexible among these materials.

In the journal (Abdullah *et al.*, 2013), material that used for chassis is ASTM A500 Grade B, hot roll steel square tubing. The chassis specifications and the safety factor that been analyzed is shown in Table 2.3 and Table 2.4.

Table 2.3: Chassis Specifications

Source: (Abdullah *et al.*, 2013)

Parameter	Value	Unit
Material	ASTM A500	
Kerb weight	165.33	kg
Mass	21.86	kg
Density	7850	kg/m3
Volume	0.003	m3
Young’s Modulus	200	GPa
Yield Strength	250 x 10^6	Nm2
Load	6000	N

Table 2.4: Factor of safety

Source: (Abdullah *et al.*, 2013)

Analysis	Design 1	Design 2
Acceleration	6.61	5.49
Bending	5.98	7.16
Braking	6.38	6.21
Torsion	2.51	2.25
Impact	4.07	4.34

The material selection is acceptable as the chassis analysis produced a high safety of factor which is greater than 2. In the journal (Mahesh *et al.*, 2014) and (Singh, 2010), AISI 4130 and IS 3074 are chose as the material of chassis where the result of factor of safety is acceptable as it achieve the target.

2.7.4 Composite materials

Carbon fiber is one of the material that can be used to make space frame chassis. Based on the journal (More *et al.*, 2017), a comparison of AISI 1080 and carbon fiber is studied in this journal by analyzing the deformation on the frame.

Table 2.5: AISI 1080 and Carbon fiber

Source: (More *et al.*, 2017)

Tests	AISI 1018 Steel Deformation (mm)	Carbon fiber pipe 4 Deformation (mm)
Front	3.2562	1.5544
Rear	0.40692	0.19905
Side	0.27077	0.39334
Torsional	0.63953	0.34185

The results is shown at the Table 2.5, where the carbon fiber has a smaller deformation compared to steel except for the side test. However, both materials also showed their advantages on making the frame as the deformation are smaller than 1mm except for the front test where a great amount is experienced there.

2.7.5 Aluminium and alloy

Aluminium is a soft and ductile material which also provides a great resistance to corrosion. Like the iron, aluminium can be mixed with other materials to form alloy to enhance its properties. Aluminium also possessed a high amount of energy absorption make it a great use in the frontal impact studies..(Thota, 2010).

In the journal (Praveen, 2016), a comparison between Mild steel, Al6061 and Al7075 is studied. The material properties such as density, young's modulus and yield strength is listed in Table 2.6.

Table 2.6: Material properties

Source: (Praveen, 2016)

Material	Density (g/m^3)	Young's Modulus (GPA)	Yeild Strength (MPA)
Mild steel	7.83	210	280-310
Al6061	2.70	69	64-350
Al7075	2.78	71	95-345

Table 2.7: Result validation

Source: (Praveen, 2016)

SI No	Analysis type	Condition	MS Frame	Al6061 Frame	Al7075 Frame
1	Frontal impact test	Displacement (mm)	2.640	3.13	3.45
2		Stress	12.509	14.95	16.45
3	Side impact test	Displacement (mm)	1.640	1.982	2.222
4		Stress	10.603	11.555	12.229
5	Rear impact test	Displacement (mm)	3.465	4.778	5.123
6		Stress	11.29	13.45	15.78
7	Roll over test	Displacement (mm)	13.5	14.8	15.23
8		Stress	18.23	22.13	26.32
9	Torsional test	Displacement (mm)	13.23	15.36	17.25
10		Stress	20.22	26.32	28.74

The displacement on the chassis and the stress based on different types of analysis are simulated with the three different materials and shown in the Table 2.7. From the result, it can be concluded that steel material has better resistance against the stress acted on the chassis and reduce the displacement. Although the aluminium is considered lighter than the mild steel, it can maximize the speed performance of the chassis but also put the driver in a danger situation once the accident happened. The hardenability and strength of the material is the first to consider when designing a safe chassis (Guimaraes *et al.*, 2016).

2.8 Impact test

After the completion of the chassis, it usually will going through the testing like impact test or torsion testing. In the journal (Sood, 2015), a scenario is simulated where a vehicle is in static condition and rear side of the vehicle is in contact with a rigid wall while another vehicle having the same mass hits that vehicle at a speed of 145 km/h (40.27 m/s).

Force = Mass x Acceleration,

$$F = ma \tag{2.1}$$

Acceleration = velocity of impact/time of impact,

$$a = \Delta v/\Delta t \tag{2.2}$$

By using the Eq. (2.1) and (2.2), the force acting on the vehicle during the impact is calculated where the force is high about 50kN with the displacement of 3.9mm to the front member of chassis.

The simulation is repeated with another scenario. The vehicle is now in static condition and right side of the vehicle is in contact with a rigid wall. Another vehicle with the same mass hits our vehicle at the side with a speed of 100 km/h (27.7 m/s). After the calculation, the force acting on the vehicle during the impact is about 35kN with the displacement of 7.5mm to the side impact structure of chassis. The design of chassis is concluded as a safe frame as it satisfied the SAE rule.

The crash speed is always an important topic to be discussed during the impact test simulation because this simulation is aimed to estimated and calculated the stress and deformation during the impact. If the speed decided is too high or too low for a FSAE racing car, the data calculated is not reliable and the miscalculation of the force may endanger the driver.

In the journal (Hagan, Rappolt and Waldrop, 2014), the team has investigated for the crash test from the Formula One Technical Regulation to develop the possible impact scenarios for the chassis. The crash speed recorded for the frontal and side impact is about 15m/s and 10m/s respectively. These speeds are surprisingly slow as the F1 racing car have average speed of 100 to 150 mph during the race. This unexpected result is explained with three reasons. First, the driver action and awareness will cause the car typically slow before the impact. When there is an impact, it mostly occur with a non-rigid structure and is likely to occur at some amount of angle instead of head-on impact. The front crash speed of 15m/s is the estimated maximum speed that may occur during a head-on impact. Since a side impact likely involve the car sliding or spinning, its speed is normally slower than frontal impact.

In the journal (Praveen, 2016), a frontal and side impact assumption are made with a set of given car weight, car velocity, crash impulse time and force distribution ratio. By using the following formula:

Final velocity (v) = initial velocity (u) + acceleration (a) * time (t)

Total force(f) = mass(m)*acceleration(a)

The acceleration and total force acting on the body is obtained and can be used for simulation on observing the total deformation in the body and the stress acting on the body.

An extreme accident scenario simulation is studied in the journal (Mechanics, Naiju and Krishnamoorthy, 2012) where the impact attenuator is included during the frontal impact test.

As a protective device is attached at the front, a full speed impact of 20,000 N is used in the analysis. Except for this journal, the impact test simulations studied from the other journal are comprising the chassis only without the impact attenuator. Normally, the speed of formula racing car is limited due to the multiple corner along the track, the car velocity is assumed in a normal speed.

2.9 Manufacturing

For the manufacturing of space frame chassis, only some process is required such as cutting, bending and welding. This is one of the reason that space frame chassis is superior compared to monocoque chassis in saving the processing time.

2.9.1 Jigging

Jig is a welded base that is famous and widely used during the manufacturing of the chassis. Except for the base frame, a welding jig is also built with some upright beams that can hold the roll hoop and prevent it from tilting during the welding process. With this, the major frame members are fixed level and relative to each other so they can be welded with great accuracy tends to increase the welding accuracy(Diaz, Gonzalez and Diaz, 2015). In engineering field, the accuracy is generally related to the money and time. Jigging is one of the method that used to eliminate those waste (Allen, 2009).

Figure 2.11: Jig

Source: (Allen, 2009)

2.9.2 Bending

The main roll hoop and front roll hoop needed to be bent before being welded. The bending diameter is depending on some factors such as the design, the die prepared for bender or the machine for bending process (Prajwal Kumar M., Vivek Muralidharan, 2018). The bending diameter must followed the FSAE rule as well for the safety purpose. The minimum radius of any bend must be at least three times the tube outside diameter (3 x OD) starting measured from the tube centerline. Bends must be smooth and continuous without crimping or wall failure (Rules, 2019).

2.9.3 Welding

Tubular chassis are quite difficult to assemble due to its circular surface. However, they are prone to asymmetry due to the rigging, the length tolerance due to the trimming of each tube, as well as the thermal expansion due to the welding process. Steel tubular structures are relatively easy to weld and usually require oxygen-acetylene welder, while aluminum tubes require expert welders and the use of tungsten inert gas (TIG) (Outline, 2016). TIG welding is suggested to be used because of the quality of welds produced. Due to the highly focused electrode, shielding gas, and the large degree of control, the strong and consistent welds can be produced (Allen, 2009).

CHAPTER 3

METHODOLOGY

3.1 Introduction

This section is where the phase of conceptual design started. In this chapter, the product design specification is determined based on the data and theory that gathered in the literature review. Material selection can be done by comparing the past experiment results and data that have been conducted in the past. Morphological chart and weighted decision matrix is popular in concept selection during the designing phase. The chosen concepts will be drawn for detail drawing with dimension using CATIA V5R19.

3.2 Product design specification

Some dimensions and connection of the frame member has to be determined earlier before starting the detail drawing to prevent the violation of the FSAE rules. The thickness of the tubing used for construction must be followed the rules as the specified part of the chassis body must be manufactured with the specified dimensions. The specified dimension is listed below:

Wheelbase must be at least 1525 mm, the narrower track must not be less than 75 percent of the wider track, cockpit area an area at least 600mm x 550 mm, the upper member must connect main hoop and front hoop with a height ranged between 300mm and 350mm, the lower member must in connection with main hoop and front hoop and bulkhead with at least 100mm x 200mm for the space of impact attenuator. The dimension of the chassis considered is also referred to the vehicle dimension that participated the events of JSAE in 2011(Program, 2011).

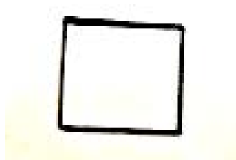
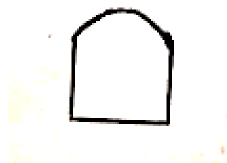
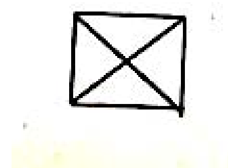
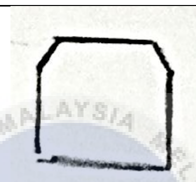
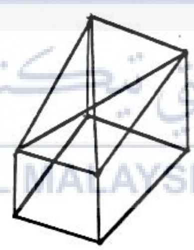
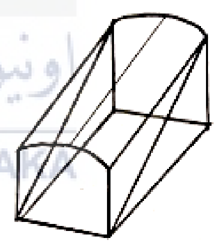
3.3 Material selection

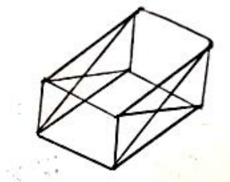
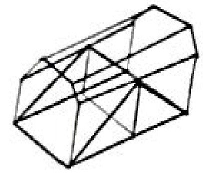
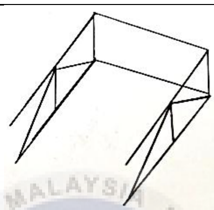
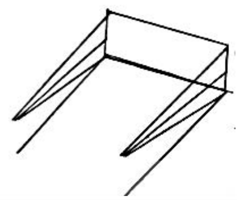
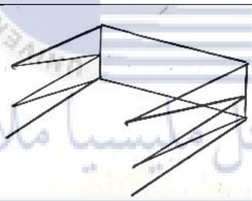
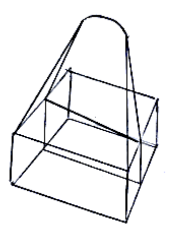
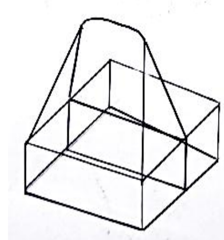
Based on the data analysis that collected from journals, it has stated that composite material suchas carbon fiber has better endurance compared to aluminium and steel alloy but resulted in high manufacturing cost and time consuming. Aluminium is lighter than steel but only gives a weak protection for the chassis. There are a lot of steel alloy has been used for chassis manufacturing, chromoly4130 is considered the best choice among the other alloy. As for mechanical properties, chromoly4130 is one of the alloy that satisfied the required properties in Young' Modulus, Yield strength and tensile strength. The elongation of the chromoly4130 also make it a high stiffness material. The high content of carbon in the steel alloy has better weld ability which can shorten the manufacturing time (Manoharan, 2016).

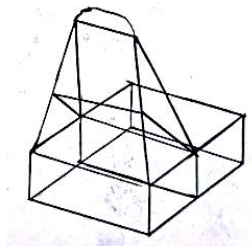
3.4 Morphological Chart

The part to build the space frame chassis is listed in the morphological chart below while the different design of concept is listed as the option. The different option of the parts will be choose to generate seven concepts of space frame chassis with different design of parts as shown in Table3.1.

Table 3.1: Morphological Chart

PART	CONCEPT 1	CONCEPT 2	CONCEPT 3
Front Bulkhead	 Quadrilateral	 Dome shape	 Square with crossbar
	CONCEPT 4		
	 Hexagon		
	CONCEPT 1	CONCEPT 2	CONCEPT 3
Front Hoop and Bracing	 Hexagon with star-shaped support	 Rectangular with top cross support	 Dome with one top support and side support

	CONCEPT 4	CONCEPT 5	
	 Rectangular with side cross support	 Hexagon with three side supports	
PART	CONCEPT 1	CONCEPT 2	CONCEPT 3
Side Impact Structure	 Three frames	 Two frames	 Z-shaped
	CONCEPT 4		
	 Double Z-shaped		
	CONCEPT 1	CONCEPT 2	CONCEPT 3
Main Hoop and Bracing	 Round with two supports	 Flat-head	 Sharp-head

	CONCEPT 4		
	 Round with six supports		

3.5 Concept Generation

3.5.1 Concept 1

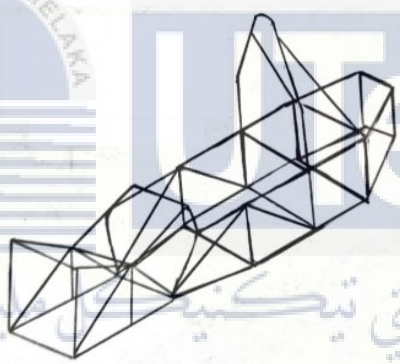


Figure 3.1: Chassis Concept 1

Concept 1 has a rectangular-shaped of front bulkhead which connect to a hexagon front roll hoop with the five frames star shaped support. The front roll hoop is connect to the main roll hoop with the three frames side impact structure. This concept uses round head design of main roll hoop with two main roll hoop bracings that connect to the rearbox.

3.5.2 Concept 2

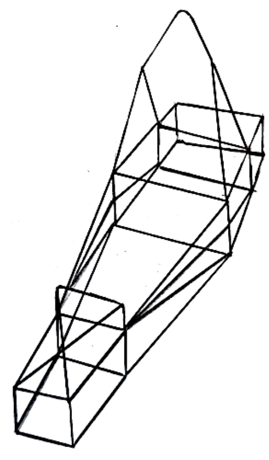


Figure 3.2: Chassis Concept 2

Concept 2 uses a square-shaped of front bulkhead that connect to a rectangular front roll hoop with top cross support. The front roll hoop is connect to the main roll hoop with the two frames side impact structure. This concept has the sharp head design of main roll hoop with two main roll hoop bracings. Four frames is connect between the lower and upper side impact member and the main hoop.

3.5.3 Concept 3

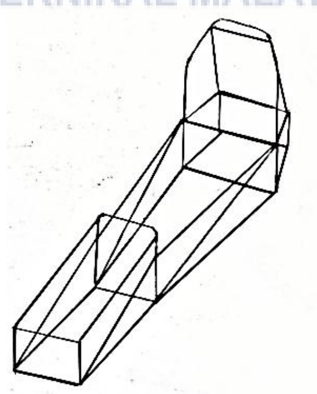


Figure 3.3: Chassis Concept 3

Concept 3 uses a rectangular-shaped of front bulkhead that connect to a rectangular front roll hoop.there is a beam connect theupperside impact member to the front bulkhead. The front roll hoop is connect to the main roll hoop with the side impact structure of z-shaped frame. This concept has using the flat head design of main roll hoop with two main roll hoop bracings to the end of the chassis.

3.5.4 Concept 4

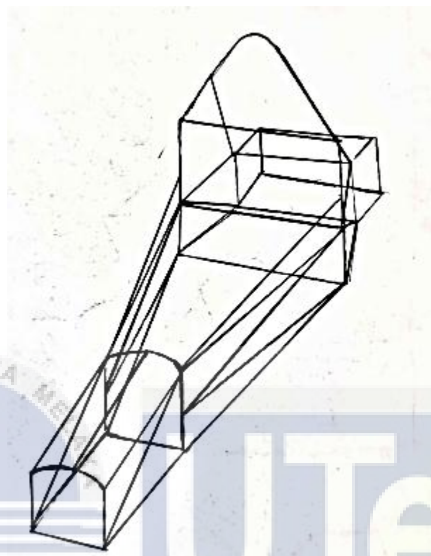


Figure 3.4: Chassis Concept 4

Concept 4 uses a dome-shaped of front bulkhead that connect to a dome-shaped front roll hoop with two bulkhead support. A frame is added to support the upper member of front bulkhead and front roll hoop. The front roll hoop is connect to the main roll hoop with the side impact structure of double z-shaped frame. This concept uses the round head design of main roll hoop with two main roll hoop bracings. A frame is added in between the main roll hoop as a support.

3.5.5 Concept 5

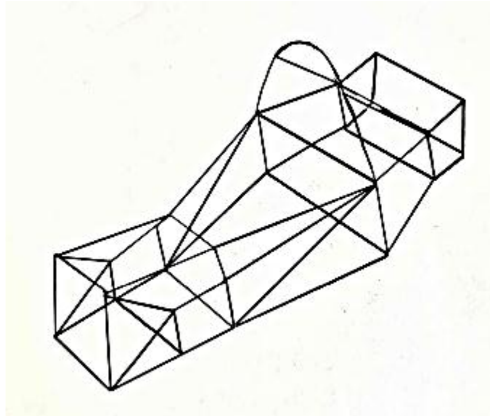


Figure 3.5: Chassis Concept 5

Concept 5 uses a rectangular-shaped of front bulkhead that connect to a hexagon-shaped front roll hoop with the four frames star-shaped support. A single frame is add between the front bulkhead and front roll hoop as the support. The front roll hoop is connect to the main roll hoop with the two frames side impact structure. This concept uses the round head design of main roll hoop with two main roll hoop bracings connect to the rear box.

3.5.6 Concept 6

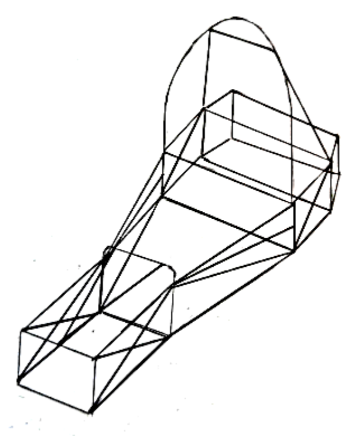


Figure 3.6: Chassis Concept 6

Concept 6 uses a vertical rectangular-shaped of front bulkhead that connect to a rectangular front roll hoop with the side cross frame support. The front roll hoop is connect to the main roll hoop with the two frames side impact structure. This concept uses the flat head design of main roll hoop with two main roll hoop braces.

3.5.7 Concept 7

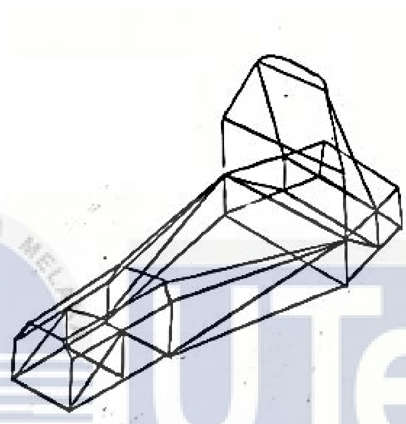


Figure 3.7: Chassis Concept 7

Concept 7 uses a hexagon-shaped of front bulkhead that connect to a hexagon-shaped front roll hoop. The two frames is connect with the top cross support and three side supports. A squared frame is add as a support between front bulkhead and front roll hoop. The front roll hoop is connect to the main roll hoop with the two frames side impact structure. This concept uses the flat head design of main roll hoop with two main roll hoop braces. Two frames is adding to support the main hoop braces and connecting to the lower side impact member.

3.6 Concept Selection

In this section, weighted decision matrix, Table 3.2 is used to choose the three best design of the space frame chassis from the seven concepts that generated. The criterion that required for a chassis is listed as well. Chassis weight is always the most important specification for the space frame as the lighter chassis makes better performance on acceleration (Reid, 2009). Material cost is related to the number of frame and brace added onto the design. A higher number of frame also increased the manufacturing cost and material cost (Alejandro, 2014). Manufaturability means for the ease of manufacture the chassis. If the chassis has more separated part, it can be welded separately and then joined together to shorten the processing time (Brendan, 2011). Safety is related to the design of outer frame of chassis. Additional of rear box or widen the side impact zone can help to reduce the damage to the driver if accident happened (Alejandro, 2014). Triangulation of the frame is important because the resulting triangle can reduce the displacement and stress acting on the frame(Brendan, 2011). Each of the criterion is given the weight according to their importancy. The rating of 1 to 5 is given to each concept based on the criterion. The rating is ascending as the status is from poor to good.

Table 3.2: Weighted Decision Matrix

Criterion	Concept		1		2		3		4
	Weight	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Chassis Weight	0.25	3	0.75	4	1.00	5	1.25	2	0.50
Material Cost	0.15	3	0.45	4	0.60	5	0.75	2	0.30
Manufacturability	0.15	3	0.45	3	0.45	5	0.75	2	0.30
Safety	0.20	3	0.60	3	0.60	1	0.20	5	1.00
Triangulation	0.25	3	0.75	2	0.75	1	0.25	5	1.25
Total	1.00		3.0		3.15		3.2		3.35

Criterion	Concept		5		6		7
	Weight	Rating	Score	Rating	Score	Rating	Score
Chassis Weight	0.25	3	0.75	3	0.75	2	0.50
Material Cost	0.15	3	0.45	3	0.45	2	0.30
Manufacturability	0.15	3	0.45	3	0.45	2	0.30
Safety	0.20	5	1.00	5	1.00	5	1.00
Triangulation	0.25	4	1.00	3	0.75	4	1.00
Total	1.00		3.65		3.4		3.1

Based on the result of the Table 3.2 , the concept 5 has the highest score of 3.65 among the concepts. This concept uses an average of number of frame which make it has the acceptable chassis weight, material cost and manufacturability. The additional rear box and widen of side impact zone also make it a safer design. The frames that support the front bulkhead and the side impact member have create much triangulation for the chassis also guarantee its durability. Concept 6 has the second highest of score is which is 3.4. This concept has achieve the same criteria statusas the concept 6 but with less triangulation. Concept 4 has scored about 3.35 which make it the third highest score. The use of the number of frame is high which make it has the highest rating on both safety and triangulation but also increase the chassis weight and cost as well. Based on the result, concept 4, 5 and 6 are chose for the future analysis study as these three concepts shared the top three of score.

3.7 Detailed design drawings

As the concepts is selected for further study and analysis, the detail drawing of these concepts is drawn using CATIA V5R19. All the frame member connection and dimensions must fulfill the minimum requirement stated in FSAE rules (Rules, 2019). By using Part Design mode in CATIA V5, the chassis 3D drawing is able to complete with the use of sketching features like sketch, line and plane. The feature, rib is used to create the hollow tubing with different thickness that used to build the whole chassis body. All the 2D drawings with the measured dimensions of three concepts is generated using the Drafting mode.

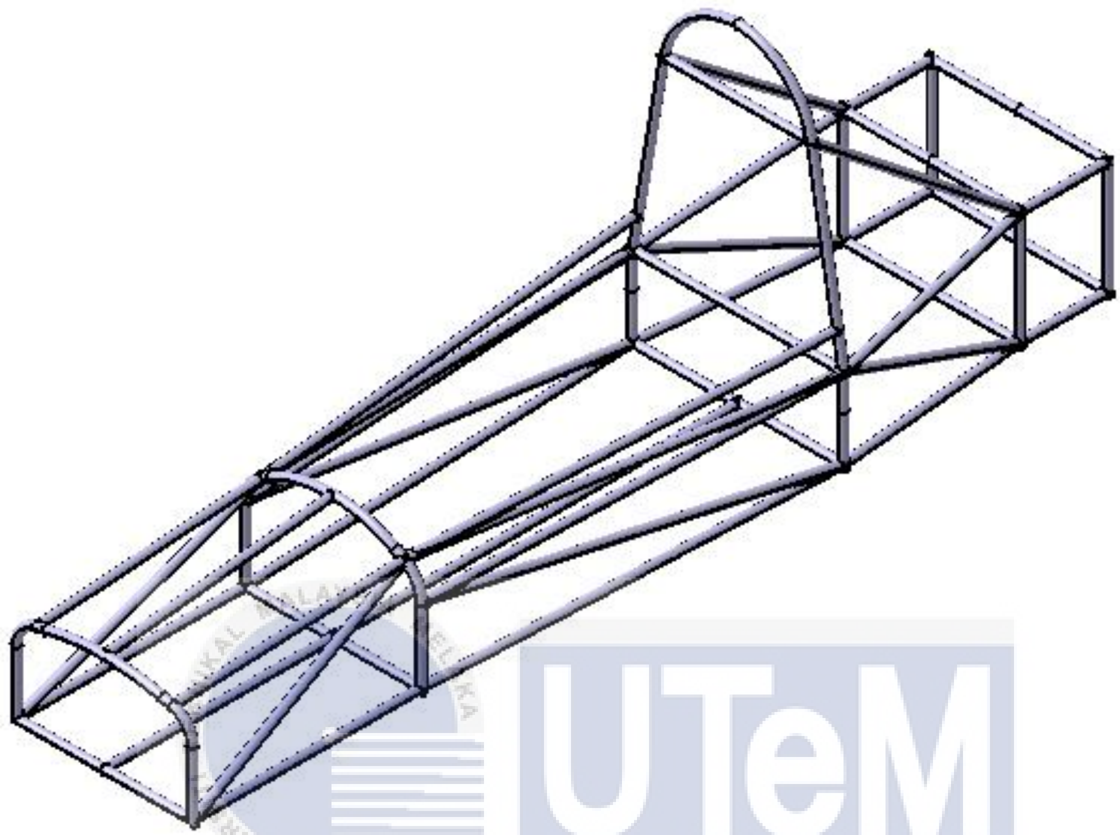


Figure 3.8: Concept 4 isometric view

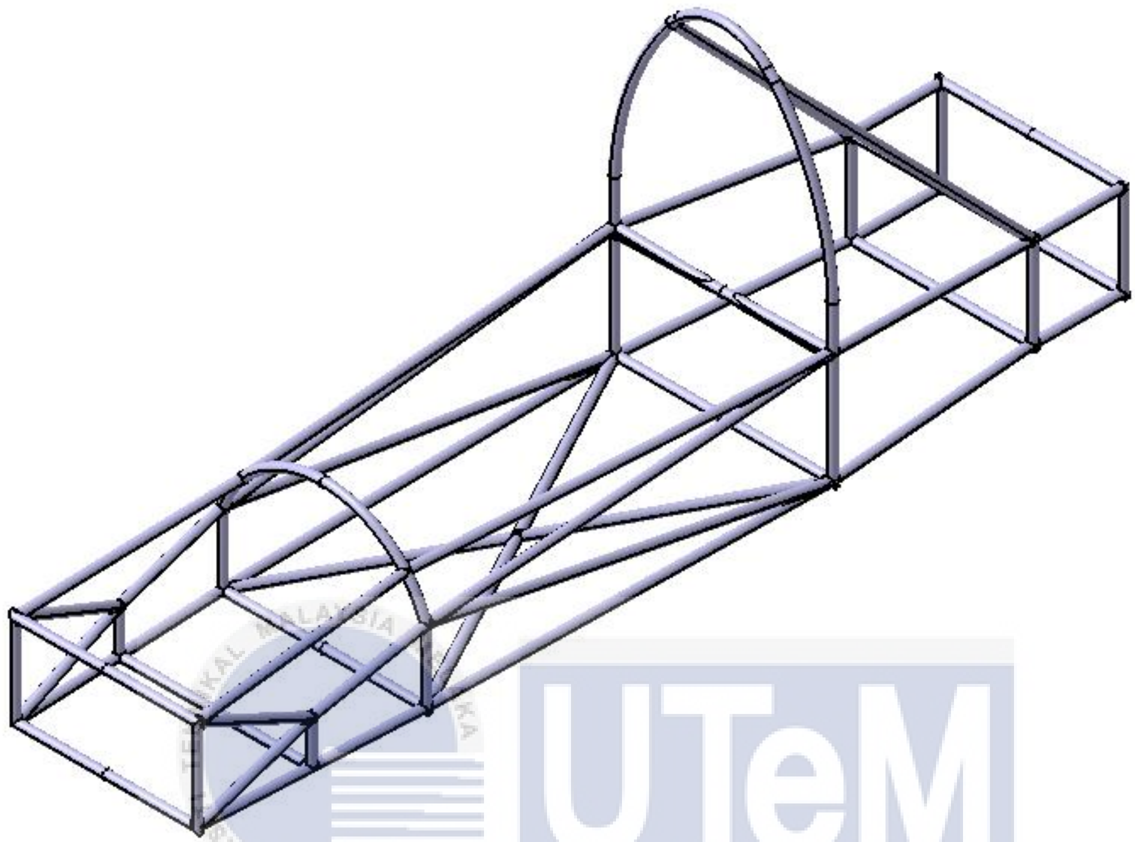


Figure 3.9: Concept 5 isometric view

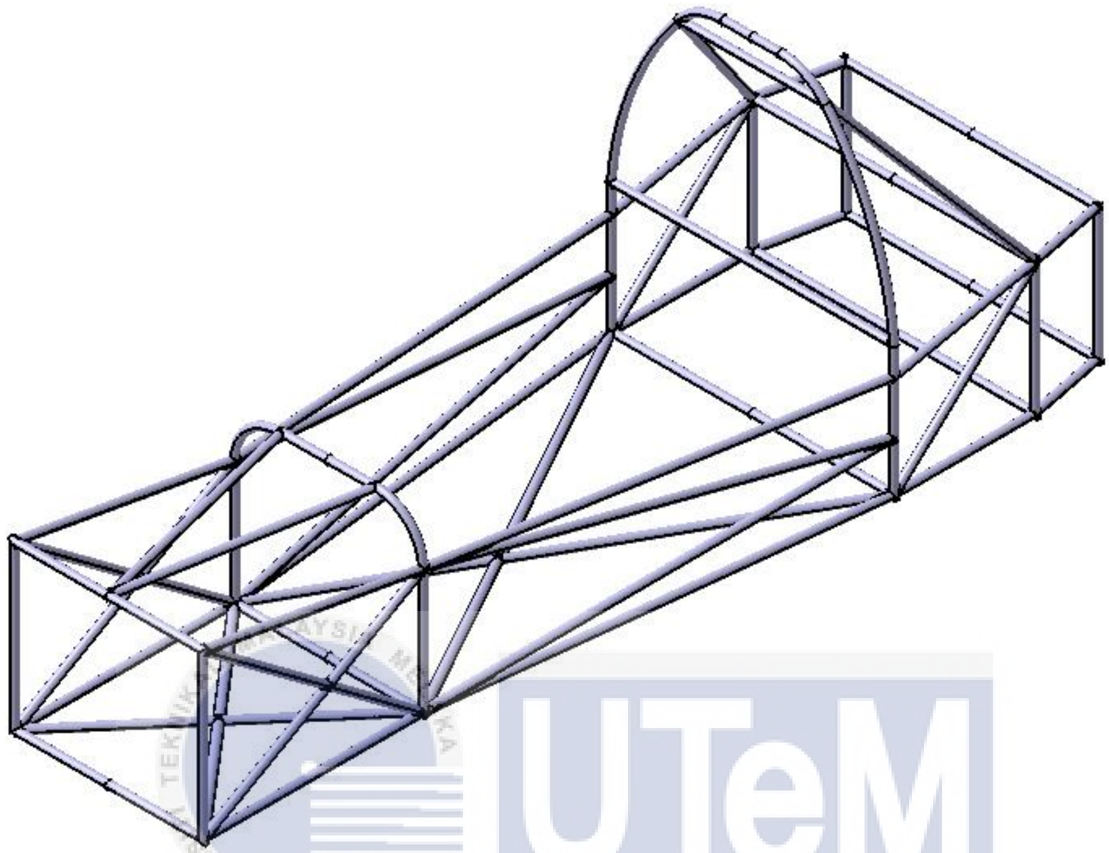


Figure 3.10: Concept 6 isometric view

CHAPTER 4

RESULT AND DISCUSSION

4.1 Verification and Validation

A journal, (Sood, 2015) is chose to validate the design and FEA analysis as the simulation of crash test has been analyzed using SolidWorks-2013 inside that journal. The space frame chassis shown in the journal is redrawn using CATIA V5R19 by referring to the orthographic view. The FEA analysis is simulated to determine the stress applied on beam (Von mises stress), displacement of beam and the safety factor.

A set of data for the frontal collision scenario is determined as below:

Vehicle speed, v = 145km/h = 40.77 m/s,

Total mass, m = 250 kg,

Impact time, t = 0.2 s

Velocity after impact = 0 m/s,

Acceleration is calculated using Eq. (2.2), a = v/t = (40.77-0)/0.2 = 201.385 m/s^2

According to Eq. (2.1), Force = mass x acceleration = ma = 250(201.385) = 50,346.25 N

Force, F is round down to 50,000 N and used for the analysis.

Another set of data is determined for the scenario of side impact test:

Vehicle speed, v = 100km/h = 27.77 m/s,

Total mass, m = 250 kg,

Impact time, t = 0.2 s

Velocity after impact = 0 m/s,

Acceleration is calculated using Eq. (2.2), $a = v/t = (27.77-0)/0.2 = 138.85\ m/s^2$

According to Eq. (2.1), Force = mass x acceleration = ma = 250(138.85) = 34,712 N

Force, F is round down to 35,000 N and used for the analysis.

To validate the method and the accuracy of the FEA analysis, the chassis designed from the journal is redrawn again using CATIA V5 and having frontal impact and side impact test via CATIA V5 Generative Structural Analysis. The setting material has also the exact properties as the journal shown.

4.2 Material properties shown in journal

Table 4.1: Material properties of AISI 4130

Material	Steel AISI 4130
Young's modulus	205 GN/m^2
Poisson's ratio	0.285
Density	7850 kg/m^3
Coefficient of thermal expansion	$1.17x10^{-5}$/ Kdeg
Yield strength	460 MN/m^2

4.3 Boundary Condition

The boundary condition is an aspect of the FEA on the study of the constraint and load that applied to the design. (Hazimi *et al.*, 2018) states that the wheels of the vehicle is often selected as the constraint in FEA crash test because the fixed support will absorb the impact energy when the collision happens. Thus, it helps to study the performance and reliability of the design of vehicle whether the vehicle can sustain the large impact generated from the crashes.

Since there is only the chassis designed in this study, the location of the wheels are assumed to install at the front and rear suspension part. The beam at the bottom of both suspension part is selected as the constraints to fix. The bad effect such as over-constrained and under-constrained must be avoid (Vince, 1999).

4.4 Frontal Impact test

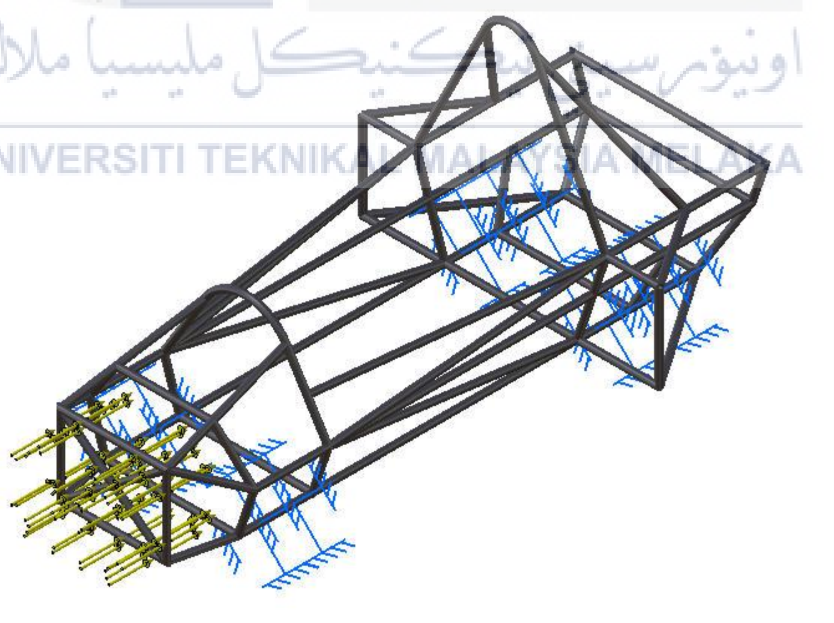


Figure 4.1: Boundary condition in frontal impact test

The front and rear suspension of the chassis is fixed as constraints while the force of 50,000 N is distributed at the front bulkhead with an opposite direction toward the chassis as shown in Figure 4.1.

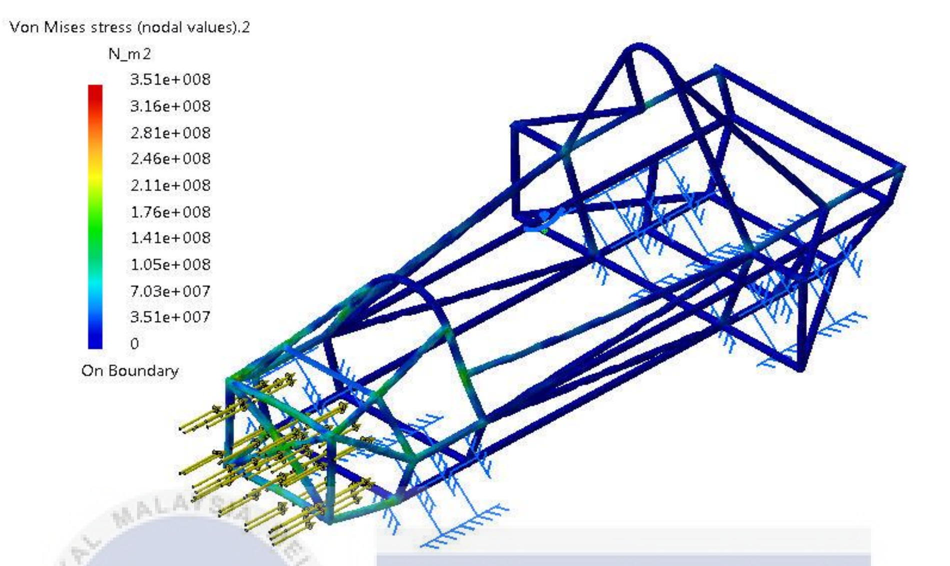


Figure 4.2: Von Mises stress (N/m^2) of frontal impact test

4.5 Side Impact test

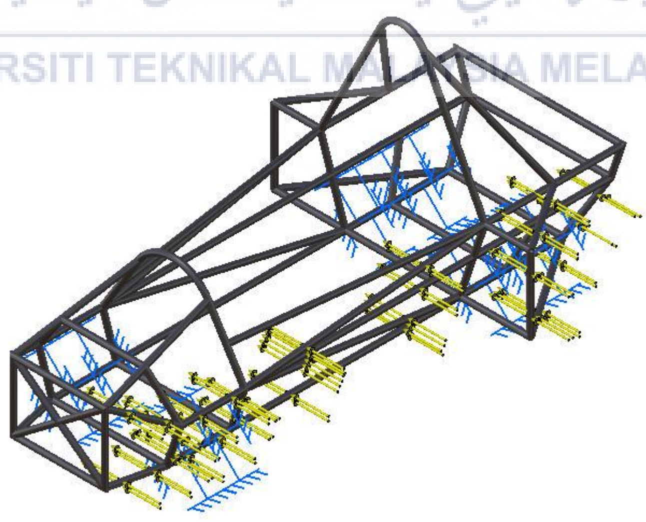


Figure 4.3: Boundary condition in side impact test

The front and rear suspension of the chassis is fixed as constraints while the force of 35,000 N is distributed on the outer beam positioned at left hand side of the chassis as shown in Figure 4.3.

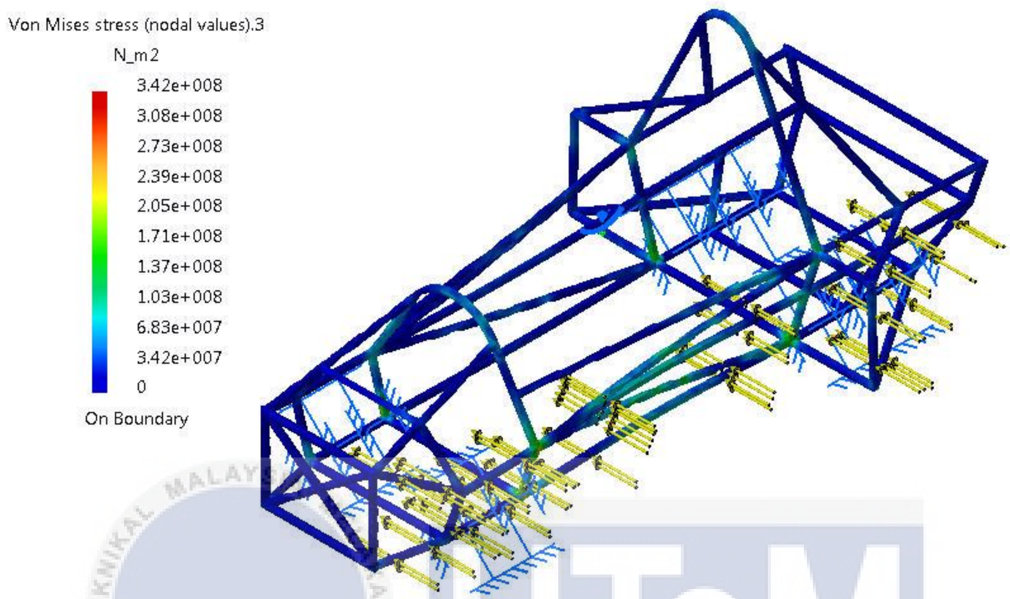


Figure 4.4: Von Mises stress (N/m^2) of side impact test

After the simulation, the results of von mises stress are obtained and used to calculate the factor of safety using the Eq. (4.1):

$$\text{F. O. S} = \text{Yield strength / Applied stress} \qquad \textbf{(4.1)}$$

Both result is used to compare via the percentage of error that calculated using Eq. (4.2).

$$\%\ \text{error} = \frac{Approximate - exact}{exact} \times 100 \qquad \textbf{(4.2)}$$

Table 4.2: Comparison between the result of journal and validation

		Journal	Validation	Percentage of error (%)
Frontal Impact test	Von mises stress (MN/m^2)	340	351	3.33
	Safety factor	1.35	1.31	2.96
Side Impact test	Von mises stress (MN/m^2)	336	342	1.89
	Safety factor	1.37	1.35	1.46

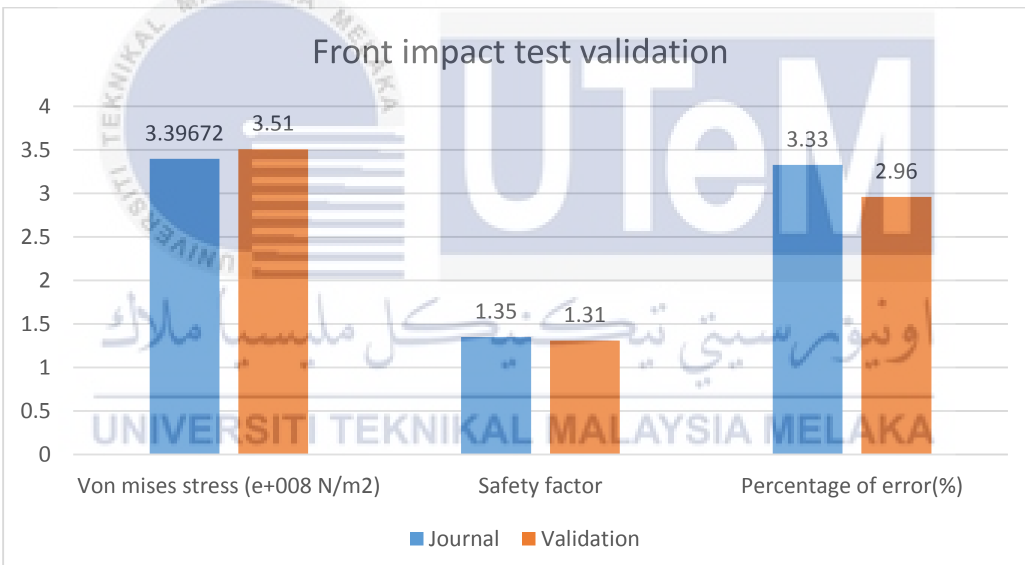


Figure 4.5: Frontal impact test validation

From the chart of Figure 4.5, we can see that the validated frontal impact simulation shows a very close value as simulated in the journal. This proves the boundary condition and the distributed force applied on the chassis for the frontal impact simulation is reliable to get an accurate value even proceed in CATIA V5.

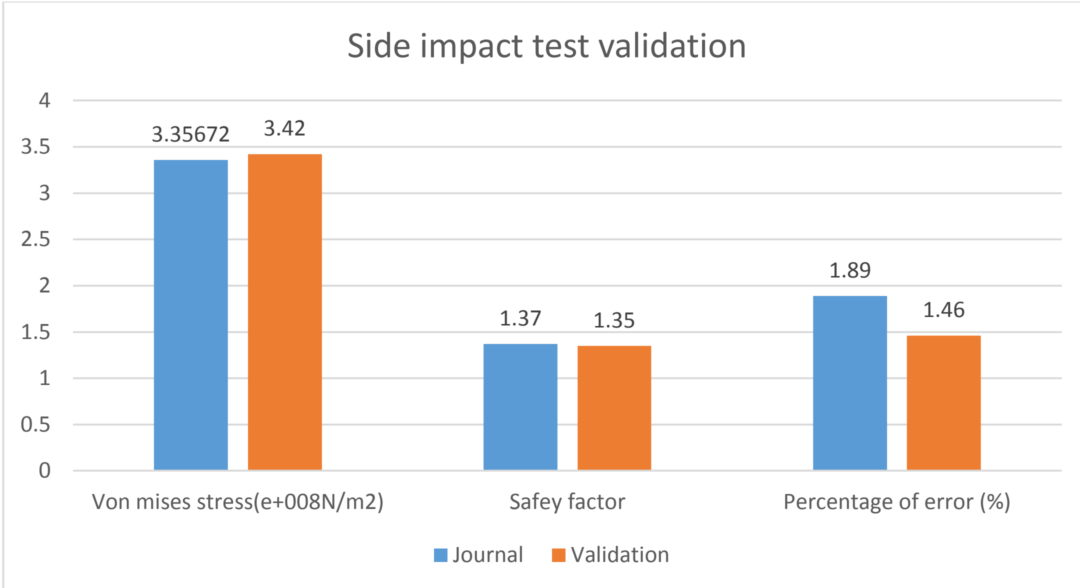


Figure 4.6: Side impact test validation

From the chart of Figure 4.6, we can see that the validated side impact simulation also shows a very close value to journal results either von mises stress or factor of safety. This proves the boundary condition and the distributed force applied on the chassis for the side impact simulation is reliable to get an accurate value even proceed in CATIA V5.

4.6 Finite Element Analysis

Before we started the FEA analysis, a set of data for the collision scenario has to be determined. The data includes the velocity before and after impact, impact time, acceleration and total mass which will be used to calculate the force distributed on the chassis.

According to the latest rules of FSAE 2019, the engine used for the racing car must be a piston engine(s) using four stroke primary heat cycle and have a total combined displacement that smaller or same as 710cc per cycle. For this case, the Engine of the 2017 KTM 690 Duke is chose to calculate the possible maximum speed that the racing car can achieve (Ramesh K M, Vinaykumar M N, Sathyanarayana, 2018).

Table 4.3: 2017 KTM 690 Duke Specification

Engine Configuration	Single, 4-Stroke
Engine Displacement	692.7cc
Engine Cooling System	Liquid
Compression Ratio	12.7:1
Bore x Stroke	105.0mm x 80.0mm
Measured Peak Horsepower	70.56 bhp @ 8,350 rpm
Measured Peak Torque	50.93 lbs-ft @6,600 rpm
Engine Redline	10,000 rpm
Fuel Capacity	3.7 gallons (14.0 liters)
Transmission Type	6-speed, Constant mesh
Primary Drive	Gear (Straight-cut)
Primary Drive Gear Teeth (Ratio)	79/36 (2.194:1)
Final Drive Sprocket Teeth (Ratio)	40/16 (2.500:1)

Primary Drive Gear Teeth (Ratio): 79/36 (2.194:1)

Final Drive Sprocket Teeth (Ratio): 40/16 (2.500:1)

Table 4.4: 2017 KTM 690 Duke Overall gear ratio

Transmission gear	Individual gear (ratio)	Overall gear ratio
Gear 1st	35/14 (2.500:1)	13.713: 1
Gear 2nd	28/16 (1.750:1)	9.599: 1
Gear 3rd	28/21 (1.333:1)	7.312: 1
Gear 4th	23/21 (1.095:1)	6.006: 1
Gear 5th	22/23 (0.957:1)	5.249: 1
Gear 6th	20/23 (0.870:1)	4.772: 1

Overall gear ratio = Primary drive ratio x secondary drive ratio x Individual gear ratio **(4.3)**

Table 4.5: 2017 KTM 690 Duke RPM and RPS

Engine RPM	Overall gear ratio	RPM (each gear)	RPS
Gear 1st	13.713: 1	291.694	4.862
Gear 2nd	9.599: 1	625.065	10.418
Gear 3rd	7.312: 1	1094.091	18.235
Gear 4th	6.006: 1	1665.002	27.750
Gear 5th	5.249: 1	1905.125	31.752
Gear 6th	4.772: 1	2095.557	34.926

RPM = Engine rpm / overall ratio **(4.4)**

RPS = RPM / 60 s **(4.5)**

Table 4.6: 2017 KTM 690 Duke theoretical maximum speed

Engine RPM	RPS	Speed (km/h)	Speed (m/s)
Gear 1st	4.862	18.1570	5.0436
Gear 2nd	10.418	38.9058	10.8072
Gear 3rd	18.235	68.0981	18.9161
Gear 4th	27.750	103.6317	28.7866
Gear 5th	31.752	118.5770	32.9381
Gear 6th	34.926	130.4302	36.2306

$$\text{Radius of wheel, } r = 13 \text{ inch} / 2 = 6.5 \text{ inch} = 0.1651 \text{ m} \quad \textbf{(4.6)}$$

$$\text{Speed (km/h)} = \text{RPS} \times 2\pi r \times 3.6 \quad \textbf{(4.7)}$$

$$\text{Speed (m/s)} = \text{Speed (km/h)} \times 1000 / 3600 \text{ s} \quad \textbf{(4.8)}$$

Using the Eq. (4.3), the overall gear ratio is calculated for each gear. RPM and RPS are then calculated from the Eq. (4.4) and (4.5) respectively. Eq. (4.6) is used to calculate the radius of the wheel with 13 inch. By the calculation using the Eq. (4.7) and (4.8), the maximum speed for the engine KTM 690 Duke with the use of 13 inch wheels is 130.4302 km/h or 36.2306 m/s.

4.7 Load Estimation

According to the rules, FSAE car parts are designed to withstand 3.5 g bump, 1.5 g braking and 1.5 g lateral forces. For the test, the loads of components have to be determined. The magnitudes, types and center of gravity of loads have to be considered individually and combined while designing the frame structure. A load estimation shown in Table 4.7 is considered by referring to the journals, (Singh, 2010) and (Mahesh *et al.*, 2014).

Table 4.7: Load estimation

	Components	Mass (kg)
1	Driver	90
2	Engine	75
3	Drive-train	20
4	Steering	10
5	Battery	4
6	Others(wishbones, fuel tank, attenuator, accumulator)	35
7	Chassis	x
	Total	**234 + x**

The mass of 234 kg is not including the chassis mass due to multiple chassis selection. As if the racing car is running at its maximum speed, 36.2306 m/s right before having an impact with non-deformable barrier with an impulse time of 0.25 s. The velocity after impact is equal to 0 m/s. The acceleration can be calculated using the equation:

$$v = u + at \quad \textbf{(4.9)}$$

$$0 = 36.2306 + a\,(0.25)$$

$$a = -144.9224 \text{ m/s}^2 \text{ (deceleration)}$$

The acceleration value calculated from Eq. (4.9) is then applied to the Eq. (2.1) from Newton's second law, where the net force is equal to the product of mass multiple with the acceleration.

$$F = ma = (234+x)\,(144.9224)$$

In different case of simulation, three different chassis will be used. Since every chassis has own weight, the force acted on the chassis will have different values. After the evaluation made by referring to some journals as stated earlier in the literature review, the material used to build the chassis is Chromoly 4130 while the material properties is shown in table 4.8:

Table 4.8: Materials properties of chassis (Chromoly 4130)

Material	AISI Chromoly 4130
Young's modulus	205 GN/m^2
Poisson's ratio	0.29
Density	7850 kg/m^3
Yield strength	435 MN/m^2

4.8 Time of impact

According to laboratory test procedures (The *et al.*, 2012), the time of impact after the chassis hit on the rigid obstacle is less than 0.3 s because the test data captured with the high speed digital camera during crash test will be truncated at 300 ms. From the journal (Ambati, Srikanth and Veeraraju, 2012), it states that if a rigid obstacle is used in study of crash test, the deceleration rates will be very high. Thus, the impact time used in this project is determined as 0.25 s. The shorter the time of impact, the higher the deceleration of the chassis. The time of impact and calculated velocity will be used in Eq. (2.1) to calculate the deceleration of the chassis.

4.9 Case 1 (Chassis Concept 4)

In this case, the chassis concept 4 weighed about 33.88 kg. By applying the weight to the force formula, Eq. (2.1):

F = ma = (234+x) (144.9224)

= (234 + 33.88) (144.9224)

= 38,821.81 N ≈ 38,822 N

The force of 38822 N will be used as distributed force acts on the chassis in both front and side impact test. The boundary condition in both test will be defined as well.

4.9.1 Frontal impact test of Concept 4

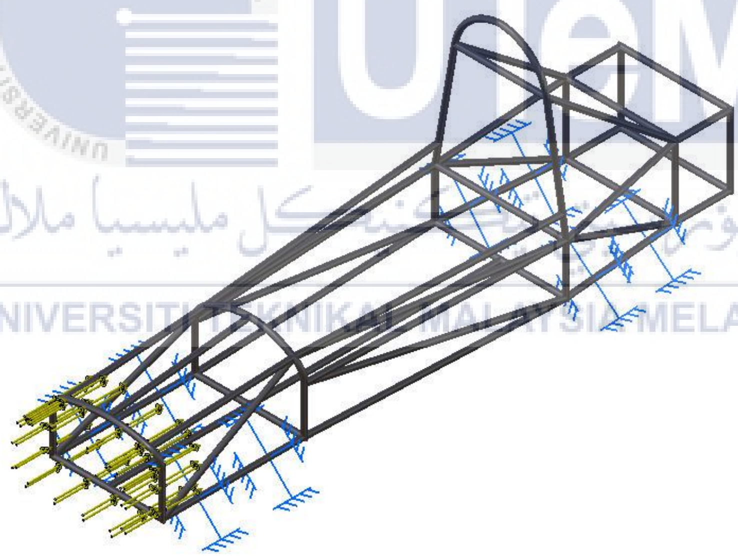


Figure 4.7: Boundary condition in frontal impact test of chassis concept 4

The front and rear suspension of the chassis is fixed as constraints while the force of 38,822 N is distributed at the front bulkhead with an opposite direction toward the chassis as shown in Figure 4.7.

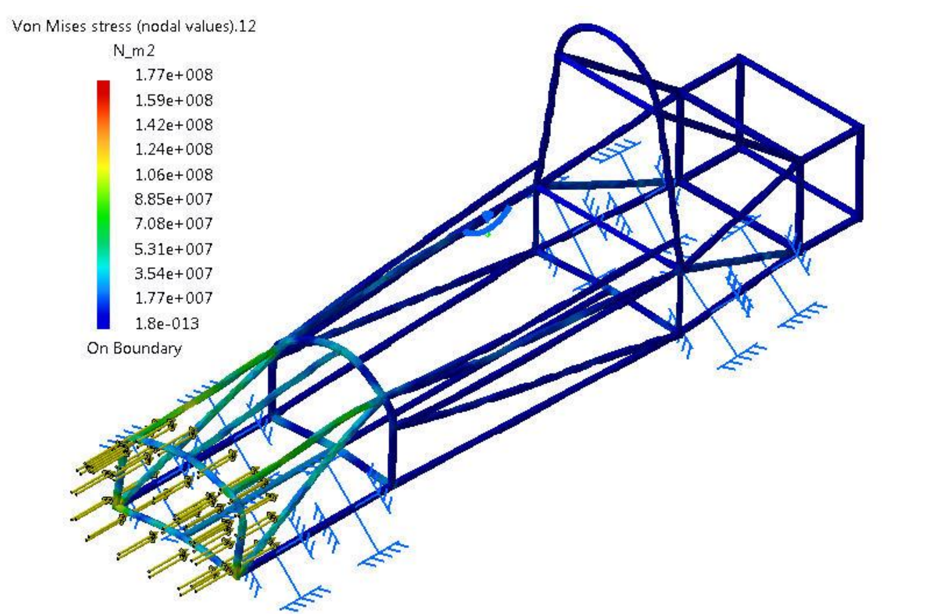


Figure 4.8: Von Mises stress (N/m^2) of frontal impact test of chassis concept 4

4.9.2 Side impact test of Concept 4

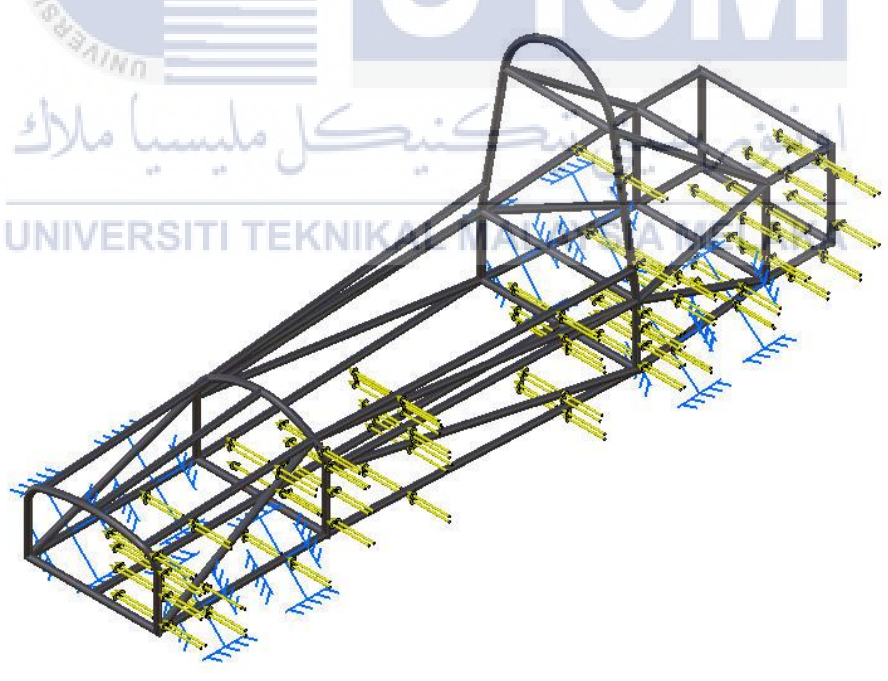


Figure 4.9: Boundary condition in side impact test of chassis concept 4

The front and rear suspension of the chassis is fixed as constraints while the force of 38,822 N is distributed on the outer beam positioned at left hand side of the chassis as shown in Figure 4.9.

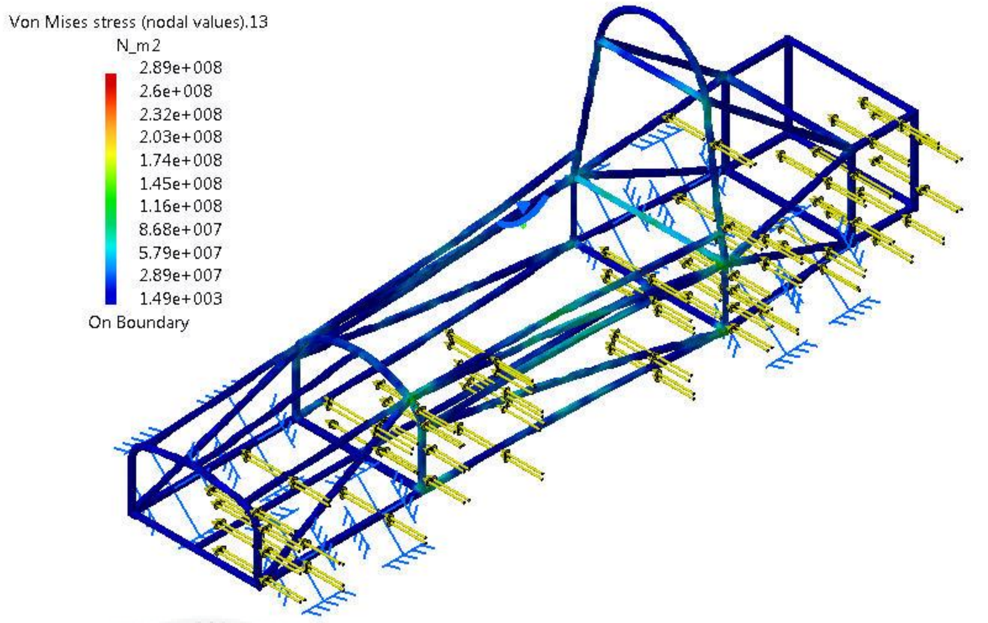


Figure 4.10: Von Mises stress (N/m^2) of side impact test of chassis concept 4

4.10 Case 2 (Chassis Concept 5)

In this case, the chassis concept 5 weighed about 31.26 kg. By applying the weight to the force formula, Eq. (2.1):

$$F = ma = (234+x)(144.9224)$$

$$= (234 + 31.26)(144.9224)$$

$$= 38{,}442.16 \text{ N} \approx 38{,}442 \text{ N}$$

The force of 38442 N will be used as distributed force acts on the chassis in both front and side impact test. The boundary condition in both test will be defined as well.

4.10.1 Frontal impact test of Concept 5

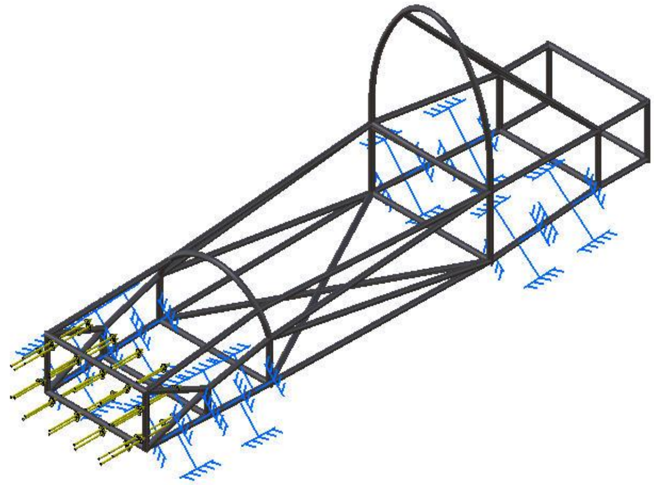


Figure 4.11: Boundary condition in frontal impact test of chassis concept 5

The front and rear suspension of the chassis is fixed as constraints while the force of 38,442 N is distributed at the front bulkhead with an opposite direction toward the chassis as shown in Figure 4.11.

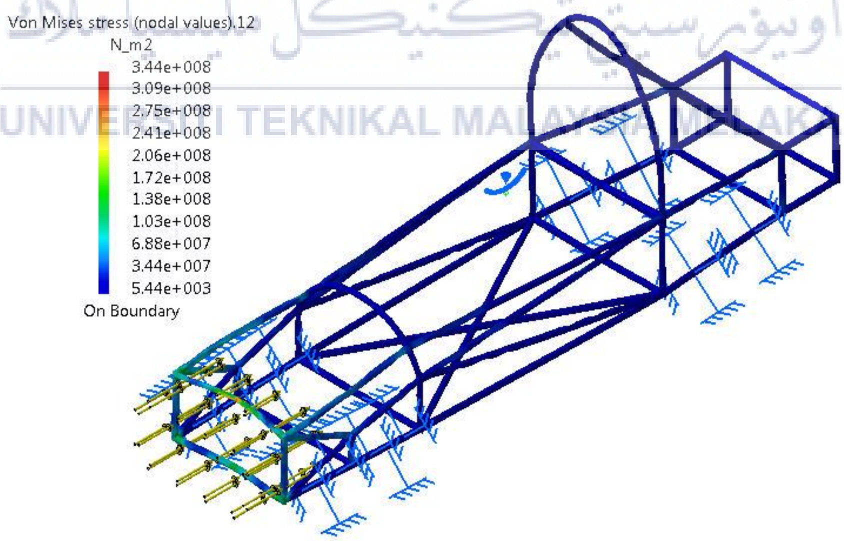


Figure 4.12: Von Mises stress (N/m^2) of frontal impact test of chassis concept 5

4.10.2 Side impact test of Concept 5

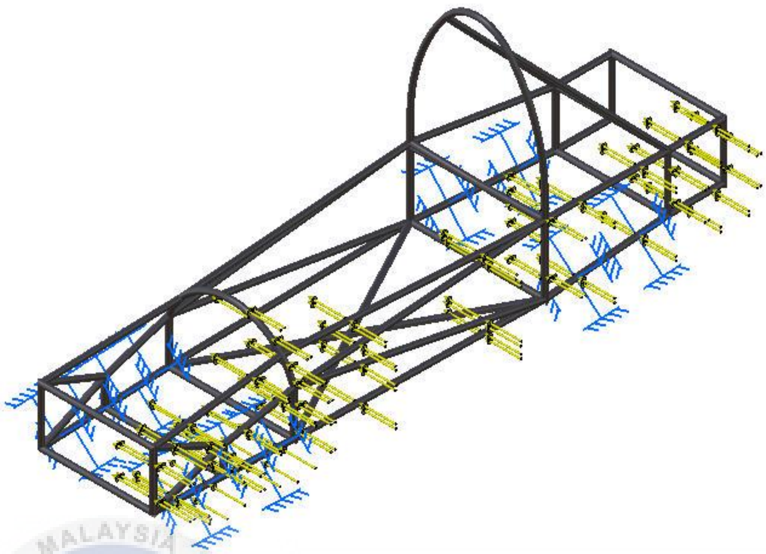


Figure 4.13: Boundary condition in side impact test of chassis concept 5

The front and rear suspension of the chassis is fixed as constraints while the force of 38,442 N is distributed on the outer beam positioned at left hand side of the chassis as shown in Figure 4.13.

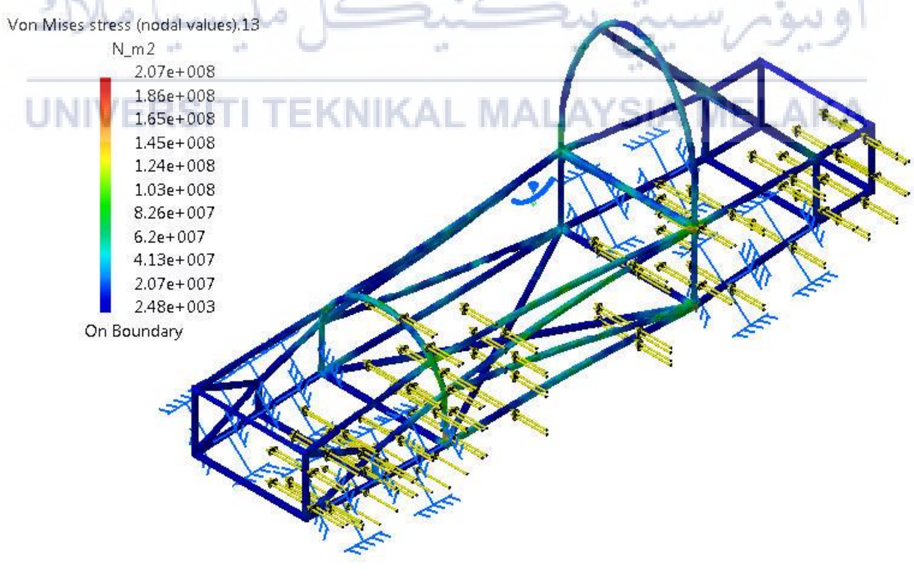


Figure 4.14: Von Mises stress (N/m^2) of side impact test of chassis concept 5

4.11 Case 3 (Chassis Concept 6)

In this case, the chassis concept 6 weighed about 43.27 kg. By applying the weight to the force formula, Eq. (2.1):

$$F = ma = (234+x)\ (144.9224)$$

$$= (234 + 43.27)\ (144.9224)$$

$$= 40{,}182.63\ N \approx 40{,}183\ N$$

The force of 40183 N will be used as distributed force acts on the chassis in both front and side impact test. The boundary condition in both test will be defined as well.

4.11.1 Frontal impact test of Concept 6

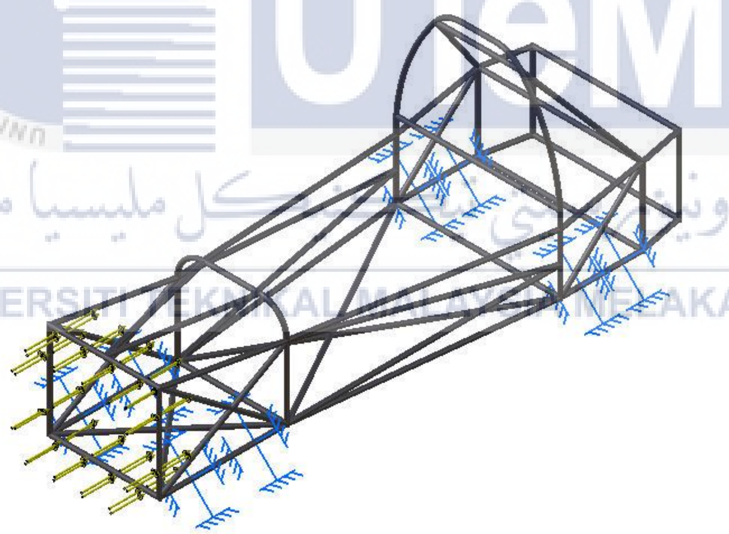


Figure 4.15: Boundary condition in frontal impact test of chassis concept 6

The front and rear suspension of the chassis is fixed as constraints while the force of 40,183 N is distributed at the front bulkhead with an opposite direction toward the chassis as shown in Figure 4.15.

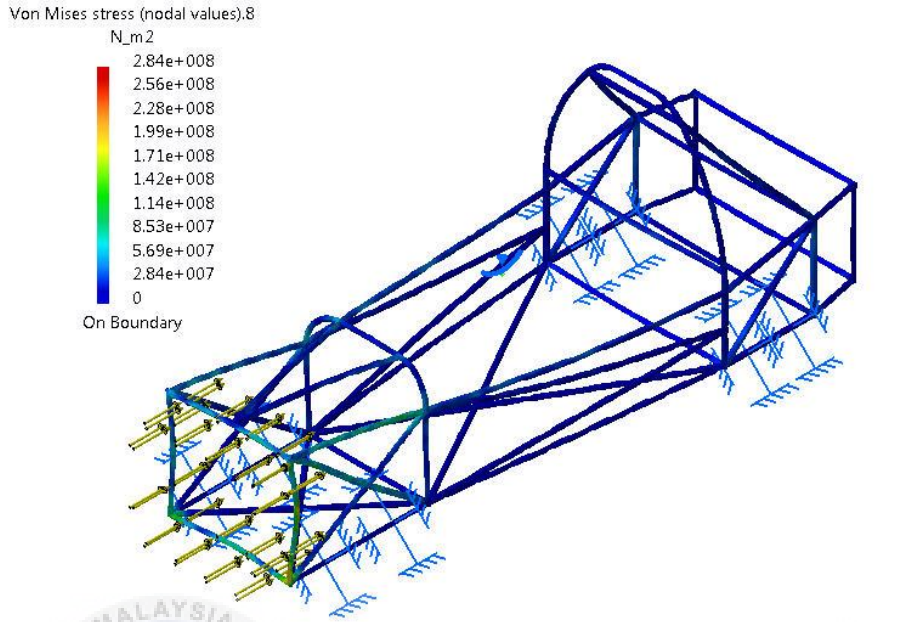


Figure 4.16: Von Mises stress (N/m^2) of frontal impact test of chassis concept 6

4.11.2 Side impact test of Concept 6

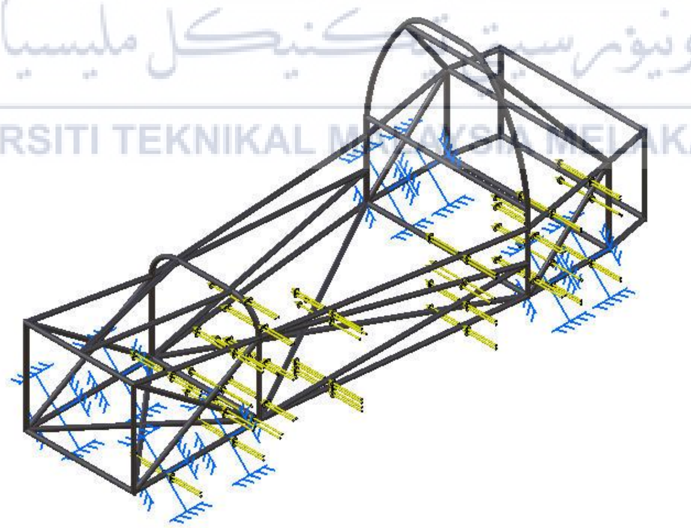


Figure 4.17: Boundary condition in side impact test of chassis concept 6

The front and rear suspension of the chassis is fixed as constraints while the force of 40,183 N is distributed on the outer beam positioned at left hand side of the chassis as shown in Figure 4.17.

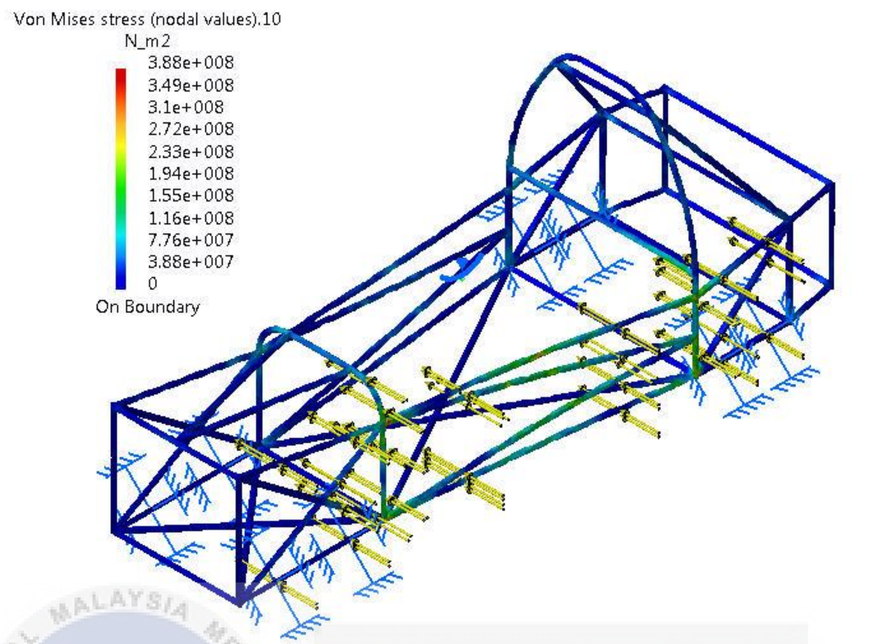


Figure 4.18: Von Mises stress (N/m^2) of side impact test of chassis concept 6

After the simulation, the result of von mises stress and displacement from three cases are obtained while the value of von mises stress is used to calculate the factor of safety using the Eq. (4.1).

Table 4.9: Von mises stress, displacement and safety factor of three concepts

Impact test	Chassis concept	Concept 4	Concept 5	Concept 6
Frontal impact test	Von mises stress (MN/m^2)	177	344	284
	Displacement (mm)	0.54	1.17	1.23
	Factor of safety	2.46	1.26	1.53
Side impact test	Von mises stress (MN/m^2)	289	207	388
	Displacement (mm)	2.60	2.64	8.72
	Factor of safety	1.51	2.10	1.12

4.12 Discussion

From the FEA results as shown in table 4.9, the factor of safety for both impact test with different chassis are vary between 1.12 and 2.46 which satisfy the fundamental of the safety factor as the ratio of the material strength and applied stress is greater than unity, $n > 1$. The safety factor of 1.25 to 1.5 shows a good value as the low weight criteria is considered in the design(A. C. Ugural, 2015). A high safety factor can be defined as over-designed for a product where the product weight and the manufacturing cost is high. Factor of safety is the level of confidence of the product. A high safety factor sometimes is selected for the design so that the designed product can be reliable in uncertain environment or subjected to uncertain stresses without failures.

From the table 4.9, the factor of safety for the chassis concept 4 in the frontal impact test is high about 2.46 while it has a 1.51 of safety factor for the side impact test. As for the chassis concept 5, the safety factor for the front and side impact test is 1.26 and 2.10 respectively while the chassis concept 6 has the factor of safety of 1.53 and 1.12 in the front and side impact test. All deformation values are smaller than 9mm which is small enough to be neglected. This proved that the chassis is strong and will have a deflection only after impact.

When comparing the value between the three cases, chassis concept 4 is considered over-designed to sustain the frontal crash since it has the highest safety factor which is far from the other values. But chassis concept 4 does show a higher level of confidence to protect the driver when the frontal crash happened. Concept 5 chassis gives a result of the lowest safety factor among the frontal impact tests and the highest safety factor among the side impact tests. This means the chassis concept 5 has a design of focusing on the protection of side impact structure instead of the frontal bulkhead. However, chassis concept 6 is just barely passes the side impact test with the value of safety factor that is nearly to 1.1. This is because the concept 6 has the heaviest chassis which also increase the force exerted on the chassis. This result shows that the chassis with concept 6 is not reliable to provide the best protection if the chassis is having critical condition when comparing to the concept 4. Chassis with concept 5 is slightly lighter compared to concept 4 which means it can have a better performance on racing but bot the protection when comparing the safety factor. Hence, it can be concluded that even though the concept 4 might be over-designed, it shows the result of providing the better protection for the driver when the chassis is having a frontal or side impact.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.0 Conclusion

In conclusion, the objective of the project is achieved. A space frame chassis is chose as the final design of chassis that provide better protection after the comparison and evaluation among different concepts of design. A total of seven concepts have been generated based on the morphological chart where the main components to form a chassis are stated as well. After that, three best concept of designs are selected based on the important criteria for a racing car chassis using the method of weighted matrix decision. After the evaluation, the chosen concepts are proceeded to 3D modelling using CATIA V5R19 where the design criteria and dimension of the chassis are predicated to the FSAE rule 2019. To analyze the chassis, the velocity of the chassis, impulse time, load estimation and boundary condition are determined based on some past researches and journals. Before analyzing the drawn chassis, the boundary condition is validated by repeating the crash test simulation from journal (Sood, 2015). As the percentage of error of the von mises stress applied on the chassis for the frontal and side impact test are small to 3.33 % and 1.89 % only, the boundary condition used to analyze the designed concepts is reliable. All three concepts are then analyzed using CATIA V5R19 Generative Structural Analysis. The frontal and side impact test are simulated with the applying of the validated boundary condition. The resulted von mises stress is then used to calculate the safety factor for each concept of design. At last, the best concept design of the chassis is chose after the comparison and evaluation between the calculated safety factors. Chassis concept 4 which weighed 33.88 kg with the factor of safety of 2.46 and 1.51 on the frontal and side impact respectively is decided to be the best concept of chassis.

5.2 Recommendation

The 3D modelling of the chassis is recommended for further study on the analysis other than crash test such as torsional test, bump test, lateral bending test, vertical bending test and acceleration test. These test are often used to study the factor of safety of the different chassis components. Beside the von mises stress and displacement of beam that included in this study, the stiffness and bending moment are also the important criteria to consider and study when designing a chassis. In addition, the study of the used material, optimization of the chassis design or triangulation will help to improve by reducing the weight, strength, manufacturability and manufacturing cost of the chassis. A low weight chassis will ultimately improve the efficiency and speed of the racing car. A better design concept and triangulation of chassis may improve the safety factor of the particular part of chassis.

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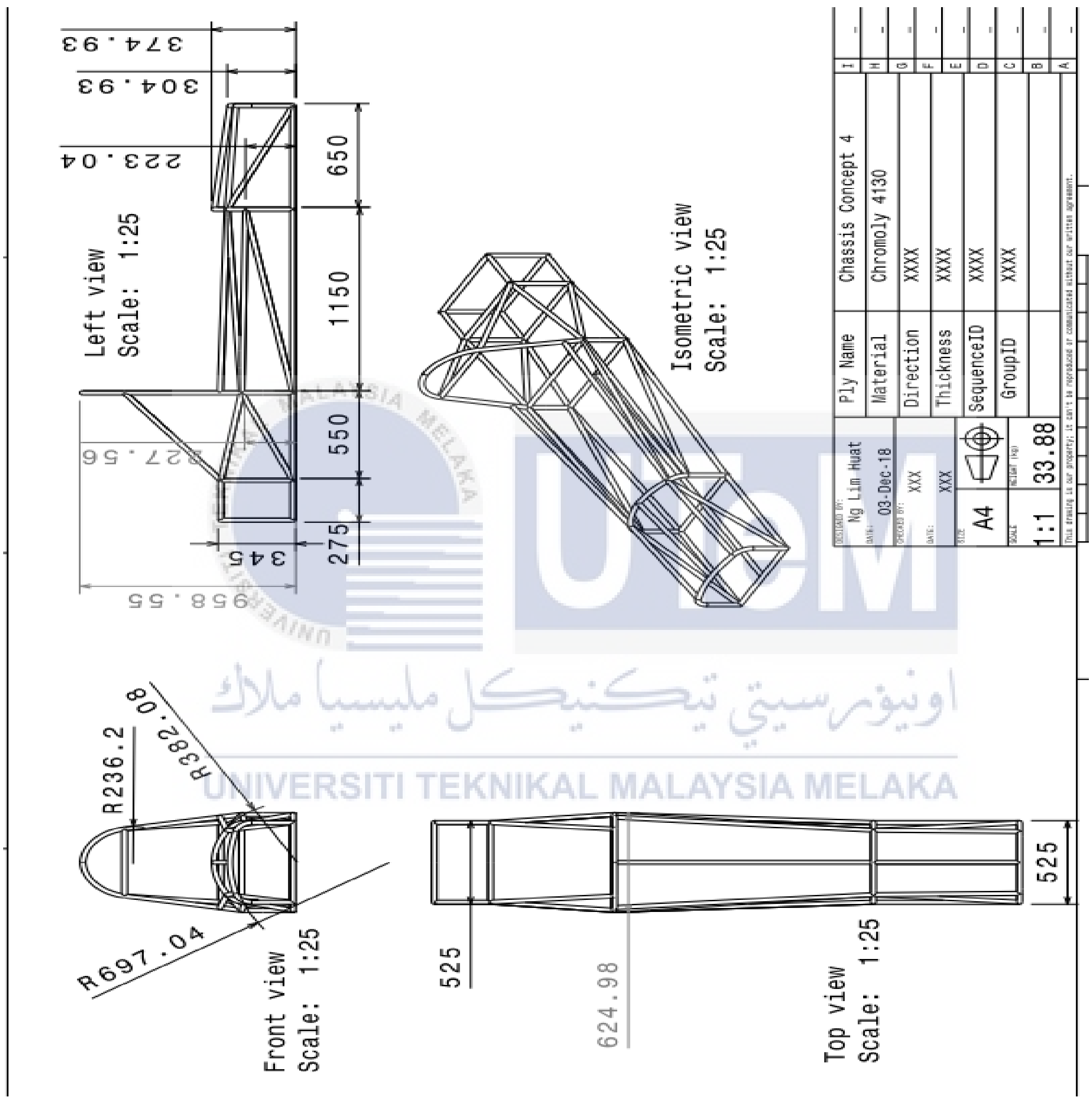
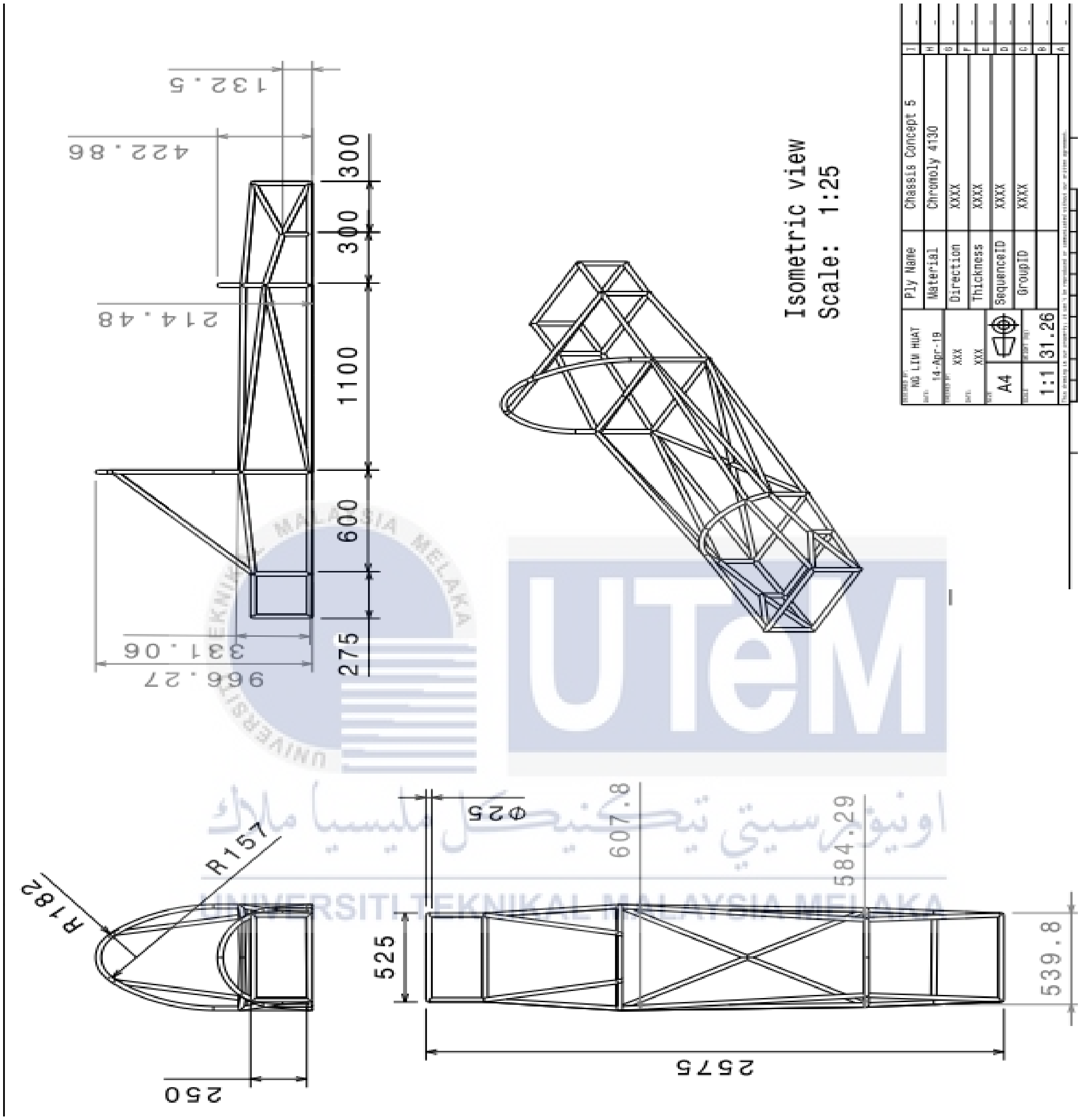
APPENDICES

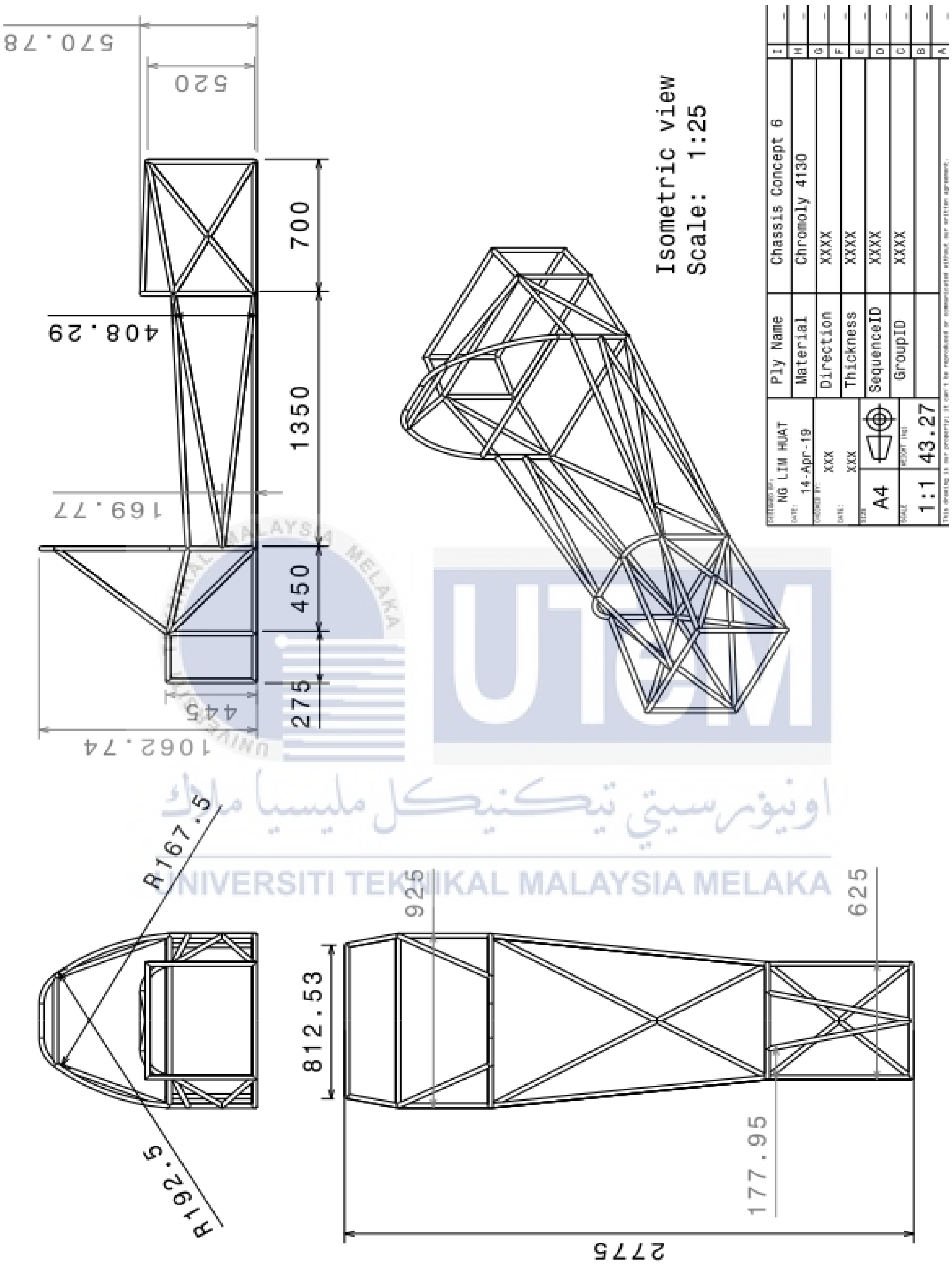
Appendix – A1 Concept 4 2D Drafting



Appendix – A2 Concept 5 2D Drafting



Appendix – A3 Concept 6 2D Drafting



570.78
520
700
408.29
1350
169.77
450
275
445
1062.74
Isometric view
Scale: 1:25
Ply Name
Chassis Concept 6
Material
Chromoly 4130
Direction
XXXX
Thickness
XXXX
SequenceID
XXXX
GroupID
XXXX
NG LIM HUAT
14-Apr-19
XXX
XXX
A4
1:1
43.27
R167.5
R192.5
925
625
812.53
177.95
2775

Appendix- B FSAE Rule 2019

GR - GENERAL REGULATIONS

GR.1 FORMULA SAE COMPETITION OBJECTIVE

GR.1.1 Formula SAE Concept

The Formula SAE® competitions challenge teams of university undergraduate and graduate students to conceive, design, fabricate, develop and compete with small, formula style vehicles.

GR.1.2 Engineering Competition

Formula SAE® is an engineering education competition that requires performance demonstration of vehicles in a series of events, both off track and on track against the clock. Each competition gives teams the chance to demonstrate their creativity and engineering skills in comparison to teams from other universities around the world.

GR.1.3 Vehicle Design Objectives

GR.1.3.1 Teams are to assume that they work for an engineering firm that is designing, fabricating, testing and demonstrating a prototype vehicle.

GR.1.3.2 The vehicle should have high performance and be sufficiently durable to successfully complete all the events at the Formula SAE competitions.

GR.1.3.3 Additional design factors include: aesthetics, cost, ergonomics, maintainability, and manufacturability.

GR.1.3.4 Each design will be judged and evaluated against other competing designs in a series of Static and Dynamic events to determine the vehicle that best meets the design goals and may be profitably built and marketed.

GR.1.4 Good Engineering Practices

Vehicles entered into Formula SAE competitions should be designed and fabricated in accordance with good engineering practices.

GR.1.5 Restriction on Vehicle Use

SAE International and competition organizer(s) are not responsible for use of vehicles designed in compliance with these Formula SAE Rules outside of the official Formula SAE competitions.

T - TECHNICAL REQUIREMENTS

T.1 GENERAL DESIGN

T.1.1 Vehicle Configuration

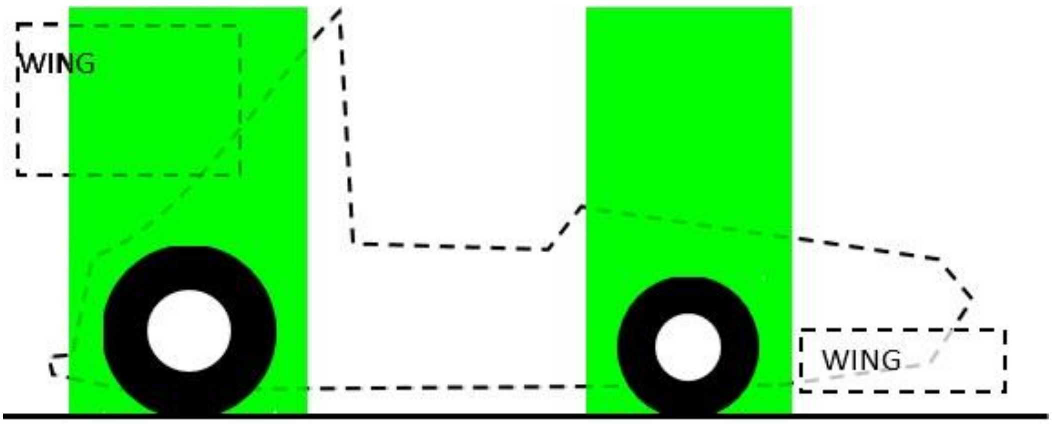
T.1.1.1 The vehicle must be open wheeled and open cockpit (a formula style body) with four wheels that are not in a straight line.

T.1.1.2 Open Wheel vehicles must satisfy all of the following criteria:

a. The top 180° of the wheels/tires must be unobstructed when viewed from vertically above the wheel.

b. The wheels/tires must be unobstructed when viewed from the side.

c. No part of the vehicle may enter a keep out zone defined by two lines extending vertically from positions 75 mm in front of and 75 mm behind, the outer diameter of the front and rear tires in the side view elevation of the vehicle, with tires steered straight ahead. This keep out zone will extend laterally from the outside plane of the wheel/tire to the inboard plane of the wheel/tire.



T.1.2 Wheelbase

T.1.2.1 The vehicle must have a wheelbase of at least 1525 mm. The wheelbase is measured from the center of ground contact of the front and rear tires with the wheels pointed straight ahead.

T.1.3 Vehicle Track

T.1.3.1 The track and center of gravity must combine to provide adequate rollover stability. See **IN.9.2**

T.1.3.2 The smaller track of the vehicle (front or rear) must be no less than 75% of the larger track.

T.1.4 Wheels

T.1.4.1 Wheels must be 203.2 mm (8.0 inches) or more in diameter.

T.1.4.2 Any wheel mounting system that uses a single retaining nut must incorporate a device to retain the nut and the wheel in the event that the nut loosens.

A second nut (jam nut) does not meet this requirement

T.1.4.3 Teams using modified lug bolts or custom designs must provide proof that good engineering practices have been followed in their design.

T.1.4.4 If used, aluminum wheel nuts must be hard anodized and in pristine condition.

T.1.5 Driver

The vehicle must be able to accommodate drivers of sizes ranging from 5th percentile female up to 95th percentile male.

- Accommodation includes driver position, driver controls, and driver equipment.
- Anthropometric data may be found on the FSAE Online Website.

T.2 CHASSIS

T.2.1 Definitions

T.2.1.1 Chassis - The fabricated structural assembly that supports all functional vehicle systems. This assembly may be a single fabricated structure, multiple fabricated structures or a combination of composite and welded structures.

T.2.1.2 Frame Member - A minimum representative single piece of uncut, continuous tubing.

T.2.1.3 Monocoque – A type of Chassis where loads are supported by the external panels

T.2.1.4 Main Hoop - A roll bar located alongside or just behind the driver's torso.

T.2.1.5 Front Hoop - A roll bar located above the driver's legs, in proximity to the steering wheel.

T.2.1.6 Roll Hoops – Referring to both the Front Hoop AND the Main Hoop

T.2.1.7 Roll Hoop Bracing Supports – The structure from the lower end of the Roll Hoop Bracing back to the Roll Hoop(s).

T.2.1.8 Front Bulkhead – A planar structure that provides protection for the driver's feet.

T.2.1.9 Impact Attenuator – A deformable, energy absorbing device located forward of the Front Bulkhead.

T.2.1.10 Side Impact Zone – The area of the side of the vehicle extending from the top of the floor to 350 mm above the ground and from the Front Hoop back to the Main Hoop.

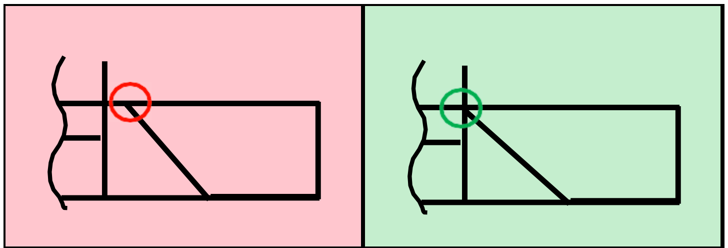
T.2.1.11 Primary Structure – The combination of the following components:

- Main Hoop
- Front Hoop
- Roll Hoop Braces and Supports
- Side Impact Structure
- Front Bulkhead
- Front Bulkhead Support
- Any Frame Members, guides, or supports that transfer load from the Driver Restraint System

T.2.1.12 Primary Structure Envelope – A volume enclosed by multiple planes, each of which are tangent to the outermost surface of all the Primary Structure frame members.

T.2.1.13 Major Structure– The portion of the Chassis that lies within the Primary Structure Envelope, excluding the Main Hoop Bracing and the portion of the Main Hoop above a horizontal plane located at the top of the upper side impact bar.

T.2.1.14 Triangulation – An arrangement of frame members projected onto a plane, where a coplanar load applied in any direction, at any node, results in only tensile or compressive forces in the frame members. This is also what is meant by "properly triangulated".



Not OK	Properly Triangulated

T.2.2 General Chassis

T.2.2.1 The driver’s head and hands must not contact the ground in any rollover attitude.

T.2.2.2 The driver’s feet and legs must be completely contained within the Major Structure of the Chassis. While the driver’s feet are touching the pedals, in side and front views, any part of the driver’s feet or legs must not extend above or outside of the Major Structure of the Chassis.

T.2.3 General Structural

T.2.3.1 The Primary Structure must be constructed from one or a combination of the following:

- Baseline Tubing and Material
- Alternate Steel Tubing
- Alternative Tubing Materials
- Composite Material

T.2.3.2 Any chassis design that is a hybrid of the Frame, Monocoque, tubing and/or composite types must meet all relevant requirements. For example, a sandwich panel Side Impact Structure in a tube frame chassis

T.2.4 Structural Documentation

T.2.4.1 All teams must submit a Structural Equivalency Spreadsheet (SES) as described in section **DR - Document Requirements**.

T.2.4.2 Any equivalency calculations must prove equivalency relative to Baseline Steel Material

T.2.4.3 The properties of tubes and laminates may be combined to prove equivalence.

For example, in a Side Impact Structure consisting of one tube as per **T.2.5** and a laminate panel, the panel only needs to be equivalent to two side impact tubes.

T.2.4.4 Any holes drilled in any regulated tubing (other than inspection holes) must be addressed on the SES.

T.2.4.5 Vehicles completed under an approved SES must be fabricated in accordance with the materials and processes described in the SES.

T.2.5 Baseline Tubing and Material

T.2.5.1 Minimum Dimensions – Steel Tubing

Application	Outside Diameter and Wall Thickness Options
Main Hoop, Front Hoop, Shoulder Harness Mounting Bar	Round 1.0 inch x 0.095 inch, Round 25.0 mm x 2.50 mm
Side Impact Structure, Front Bulkhead, Roll Hoop Bracing, Driver Restraint Harness Attachment (other than Shoulder Harness Mounting Bar), (EV) Accumulator Protection Structure	Round 1.0 inch x 0.065 inch, Round 25.0 mm x 1.75 mm, Square 1.0 inch x 1.0 inch x 0.047 inch, Square 25.0 mm x 25.0 mm x 1.20 mm
Front Bulkhead Support, Main Hoop Bracing Supports, Shoulder Harness Mounting Bar Bracing, (EV) Tractive System Component Protection	Round 1.0 inch x 0.047 inch, Round 25.0 mm x 1.5 mm
Bent Upper Side Impact Member	Round 1.375 inch x 0.047 inch Round 35.0 mm x 1.2 mm

T.2.5.2 Tubing that differs from the above minimum dimensions may be used without additional approval when:

- Tubing of the specified outside diameter but with greater wall thickness
- Tubing of the specified wall thickness and a greater outside diameter
- Replacing round tubing with square tubing of the same or larger outside diameter and wall thickness

T.2.5.3 Properties for ANY steel material for calculations submitted in an SES must be:

a. Non Welded Properties for continuous material calculations:

Young's Modulus (E) = 200 GPa (29.0 ksi)

Yield Strength (Sy) = 305 MPa (44.2 ksi)

Ultimate Strength (Su) = 365 MPa (52.9 ksi)

b. Welded Properties for discontinuous material such as joint calculations:

Yield Strength (Sy) = 180 MPa (26 ksi)

Ultimate Strength (Su) = 300 MPa (43.5 ksi)

T.2.5.4 Any tubing with Outside Diameter less than 25.0 mm or wall thickness less than 1.2 mm (0.047 inch) is not considered structural and will be ignored when assessing compliance to any rule

T.2.5.5 Where welded tubing reinforcements are required (such as inserts for bolt holes or material to support suspension cutouts), the tubing must retain the Non Welded Properties while using the Welded Properties for the additional reinforcement material.

T.2.6 Alternate Steel Tubing

T.2.6.1 Alternate Steel Tubing geometry may be used.

T.2.6.2 If Alternate Steel Tubing geometry is used, the SES must include calculations demonstrating equivalent to or better than the minimum requirements found in **T.2.5** for yield and ultimate strengths in bending, buckling and tension, for buckling modulus and for energy dissipation.

The Buckling Modulus is defined as EI, where, E = modulus of Elasticity, and I = area moment of inertia about the weakest axis.

T.2.6.3 Minimum Wall Thickness - Steel Tubing

Application	Minimum Wall Thickness
Main Hoop, Front Hoop, Shoulder Harness Mounting Bar	2.0 mm (0.079 inch)
Roll Hoop Bracing, Main Hoop Bracing Supports, Side Impact Structure, Front Bulkhead, Front Bulkhead Support, Driver Restraint Harness Attachment (other than Shoulder Harness Mounting Bar), Shoulder Harness Mounting Bar Bracing, (EV) Accumulator Protection Structure, (EV) Tractive System Component Protection	1.2 mm (0.047 inch)

To maintain EI with a thinner wall thickness, the outside diameter MUST be increased.

To maintain the equivalent yield and ultimate tensile strength the same cross sectional area of steel as the Baseline Tubing MUST be maintained.

T.2.6.4 Properties for ANY steel material for calculations submitted in an SES must be per **T.2.5.3 above**

T.2.6.5 Any tubing with wall thickness less than 1.2 mm (0.047 inch) is not considered structural and will be ignored when assessing compliance to any rule

T.2.7 Alternative Tubing Materials

T.2.7.1 Alternative Materials may be used for areas other than the Main Hoop and Main Hoop Bracing.

T.2.7.2 If any Alternative Materials are used, the SES must include calculations demonstrating equivalent to or better than the minimum requirements found in **T.2.5** for yield and ultimate strengths in bending, buckling and tension, for buckling modulus and for energy dissipation.

The Buckling Modulus is defined as EI, where, E = modulus of Elasticity, and I = area moment of inertia about the weakest axis.

T.2.8 Roll Hoops

T.2.8.1 The Frame must include both a Main Hoop and a Front Hoop.

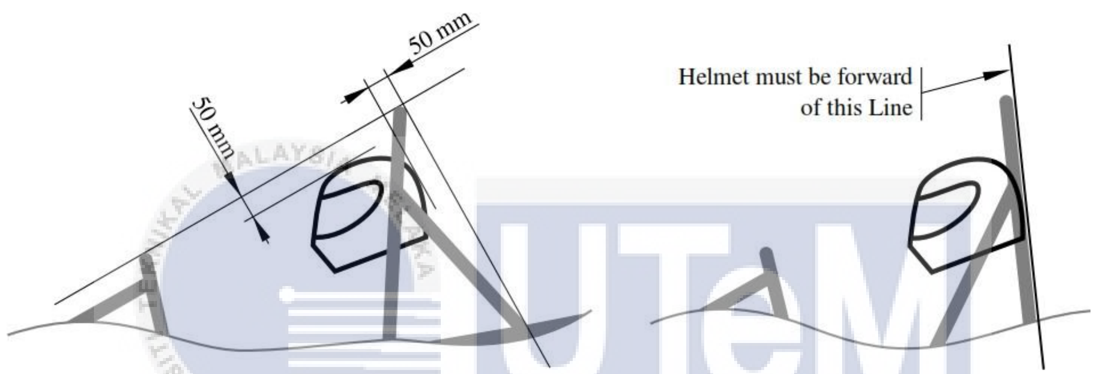
T.2.8.2 The Main Hoop and Front Hoop must be securely integrated into the Primary Structure using proper Triangulation.

T.2.8.3 When seated normally and restrained by the Driver Restraint System, the helmet of a 95th percentile male (anthropometrical data) and all of the team's drivers must:

a. Be a minimum of 50 mm from the straight line drawn from the top of the Main Hoop to the top of the Front Hoop.

b. Be a minimum of 50 mm from the straight line drawn from the top of the Main Hoop to the lower end of the Main Hoop Bracing if the bracing extends rearwards.

c. Be no further rearwards than the rear surface of the Main Hoop if the Main Hoop Bracing extends forwards.



T.2.8.4 Driver Template

A two dimensional template used to represent the 95th percentile male is made to the following dimensions (see figure in next step):

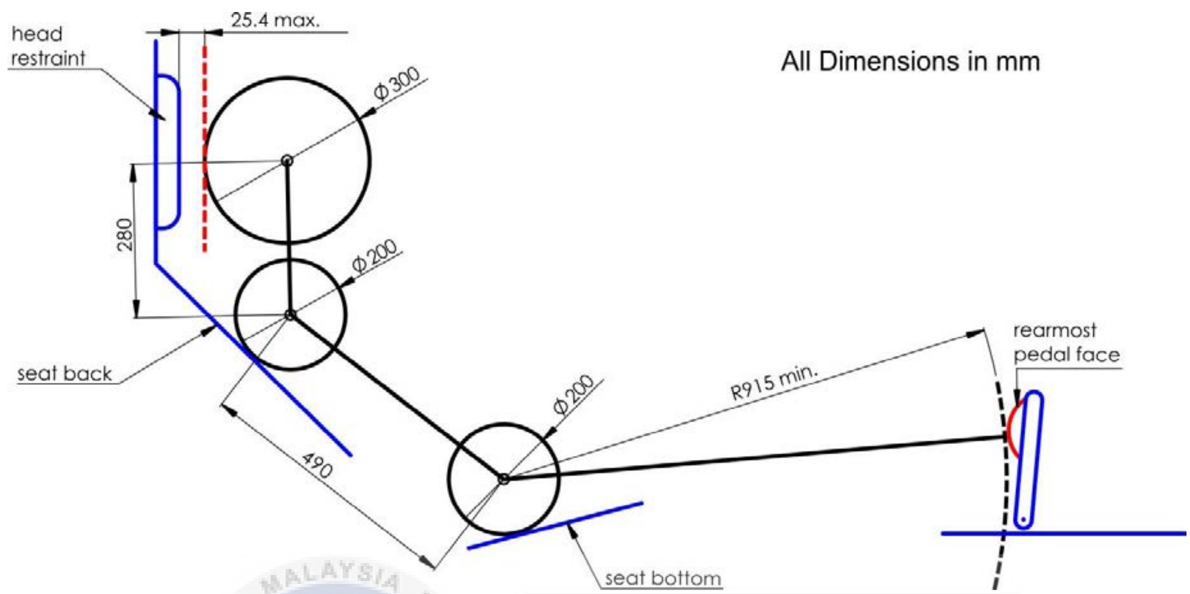
- A circle of diameter 200 mm will represent the hips and buttocks.
- A circle of diameter 200 mm will represent the shoulder/cervical region.
- A circle of diameter 300 mm will represent the head (with helmet).
- A straight line measuring 490 mm will connect the centers of the two 200 mm circles.
- A straight line measuring 280 mm will connect the centers of the upper 200 mm circle and the 300 mm head circle.

T.2.8.5 Driver Template Position

The Driver Template will be positioned as follows:

- The seat will be adjusted to the rearmost position
- The pedals will be placed in the most forward position
- The bottom 200 mm circle will be placed on the seat bottom such that the distance between the center of this circle and the rearmost face of the pedals is no less than 915 mm
- The middle 200 mm circle, representing the shoulders, will be positioned on the seat back
- The upper 300 mm circle will be positioned no more than 25 mm away from the head restraint (where the driver's helmet would normally be located while driving)

Figure - Driver Template and Position



T.2.9 Main Hoop

T.2.9.1 The Main Hoop must be constructed of a single piece of uncut, continuous, closed section steel tubing per **T.2.5 Baseline Tubing** OR **T.2.6 Alternate Steel Tubing**

T.2.9.2 The Main Hoop must extend from the lowest Frame Member on one side of the Frame, up, over and down the lowest Frame Member on the other side of the Frame.

T.2.9.3 In the side view of the vehicle,

a. The portion of the Main Hoop that lies above its attachment point to the upper Side Impact Tube must be within 10° of the vertical.

b. Any bends in the Main Hoop above its attachment point to the Major Structure of the Frame must be braced to a node of the Main Hoop Bracing Support structure with tubing meeting the requirements of Roll Hoop Bracing per **T.2.5 Baseline Tubing** OR **T.2.6 Alternate Steel Tubing**

c. The portion of the Main Hoop that lies below the upper side impact member attachment point may be inclined at any angle to the vertical in the forward direction but, it must be inclined rearward no more than 10° of the vertical.

T.2.9.4 In the front view of the vehicle, the vertical members of the Main Hoop must be at least 380 mm apart (inside dimension) at the location where the Main Hoop is attached to the bottom tubes of the Major Structure of the Frame.

T.2.10 Front Hoop

T.2.10.1 The Front Hoop must be constructed of closed section metal tubing per **T.2.5 Baseline Tubing** OR **T.2.6 Alternate Steel Tubing** OR **T.2.7 Alternative Tubing Materials**

T.2.10.2 The Front Hoop must extend from the lowest Frame Member on one side of the Frame, up, over and down to the lowest Frame Member on the other side of the Frame.

T.2.10.3 With proper triangulation, the Front Hoop may be fabricated from more than one piece of tubing.

T.2.10.4 The top-most surface of the Front Hoop must be no lower than the top of the steering wheel in any angular position. See figure in **T.2.13.4 below**

T.2.10.5 The Front Hoop must be no more than 250 mm forward of the steering wheel.

This distance is measured horizontally, on the vehicle centerline, from the rear surface of the Front Hoop to the forward most surface of the steering wheel rim with the steering in the straight ahead position.

T.2.10.6 In side view, the Front Hoop or any part of it must be inclined no more than 20° from the vertical.

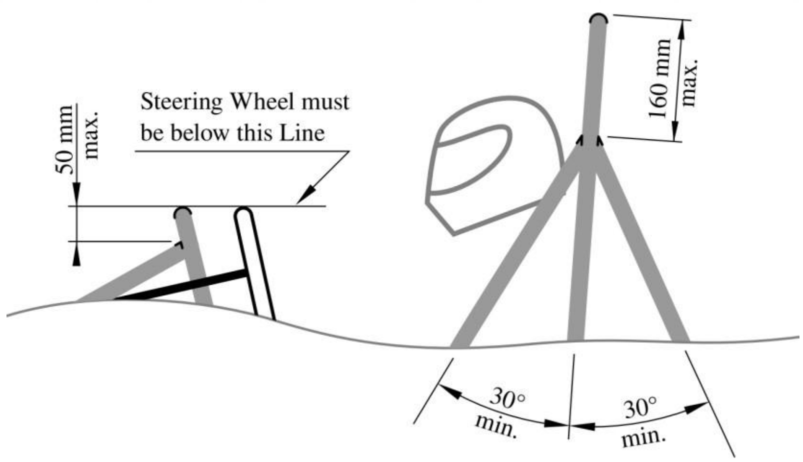
T.2.11 Main Hoop Bracing

T.2.11.1 Main Hoop braces must be constructed of closed section steel tubing per **T.2.5 Baseline Tubing** OR **T.2.6 Alternate Steel Tubing**

T.2.11.2 The Main Hoop must be supported by two braces extending in the forward or rearward direction, one on each of the left and right sides of the Main Hoop.

T.2.11.3 In the side view of the Frame, the Main Hoop and the Main Hoop braces must not lie on the same side of the vertical line through the top of the Main Hoop. (If the Main Hoop leans forward, the braces must be forward of the Main Hoop, and if the Main Hoop leans rearward, the braces must be rearward of the Main Hoop)

T.2.11.4 The Main Hoop braces must be attached as near as possible to the top of the Main Hoop but not more than 160 mm below the top-most surface of the Main Hoop. The included angle formed by the Main Hoop and the Main Hoop braces must be at least 30°.



T.2.11.5 The Main Hoop braces must be straight, without any bends.

T.2.11.6 The Main Hoop Braces must be securely integrated into the Frame and be capable of transmitting all loads from the Main Hoop into the Major Structure of the Frame without failing.

T.2.11.7 The lower end of the Main Hoop Braces must be supported back to the Main Hoop by a minimum of two Frame Members on each side of the vehicle: an upper member and a lower member in a properly Triangulated configuration.

a. The upper support member must attach to the node where the upper Side Impact Member attaches to the Main Hoop.

b. The lower support member must attach to the node where the lower Side Impact Member attaches to the Main Hoop.

c. Each of the above members may be multiple or bent tubes provided the requirements of **T.2.8** are met.

d. Examples of acceptable configurations of members may be found on the FSAE Online Website.

T.2.11.8 All the Frame Members of the Main Hoop Bracing Support system listed above must be constructed of closed section tubing per **T.2.5 Baseline Tubing** OR **T.2.6 Alternate Steel Tubing**

T.2.11.9 If any item which is outside the envelope of the Primary Structure is attached to the Main Hoop braces, then additional bracing must be added to prevent bending loads in the braces in any rollover attitude

T.2.12 Front Hoop Bracing

T.2.12.1 Front Hoop braces must be constructed of material per **T.2.5 Baseline Tubing** OR **T.2.6 Alternate Steel Tubing** OR **T.2.7 Alternative Tubing Materials**

T.2.12.2 The Front Hoop must be supported by two braces extending in the forward direction, one on each of the left and right sides of the Front Hoop.

T.2.12.3 The Front Hoop braces must be constructed such that they protect the driver's legs and should extend to the structure in front of the driver's feet.

T.2.12.4 The Front Hoop braces must be attached as near as possible to the top of the Front Hoop but not more than 50 mm below the top-most surface of the Front Hoop. See Figure in **T.2.13.4**

T.2.12.5 If the Front Hoop leans rearwards by more than 10° from the vertical, it must be supported by additional Front Hoop braces to the rear.

T.2.12.6 The Front Hoop braces must be straight, without any bends

T.2.13 Other Bracing Requirements

T.2.13.1 Where the braces are not welded to steel Frame Members, the braces must be securely attached to the Frame using 8 mm or 5/16" minimum diameter **Critical Fasteners**, see **T.10.2** and **T.10.3**.

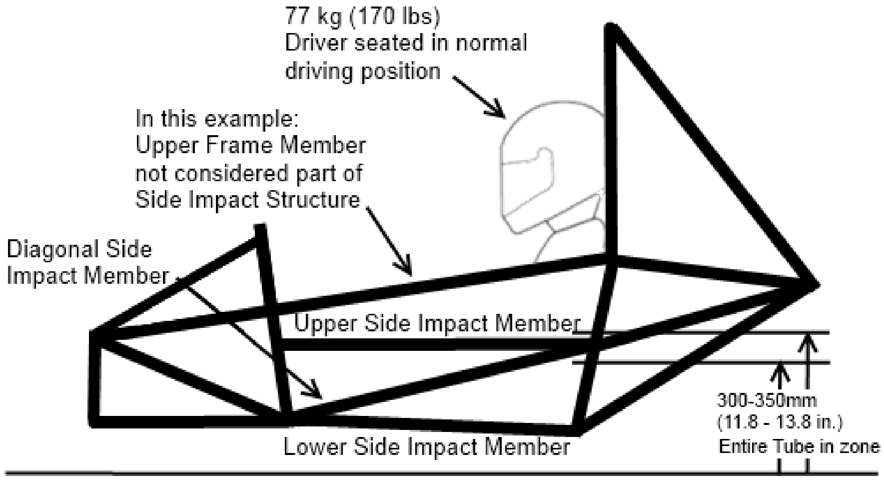
T.2.13.2 Mounting plates welded to the Roll Hoop braces must be 2.0 mm (0.080 in) minimum thickness steel.

T.2.14 Side Impact Structure for Tube Frame Designs

T.2.14.1 The Side Impact Structure must be comprised of at least three tubular members located on each side of the driver while seated in the normal driving position

T.2.14.2 The required tubular members must be constructed of material per **T.2.5** OR **T.2.6** OR **T.2.7**

T.2.14.3 With proper Triangulation, Side Impact Structure members may be fabricated from more than one piece of tubing.



T.2.14.4 The Upper Side Impact Structure member must:

a. Connect the Main Hoop and the Front Hoop.

b. Be located so that all of the member must be at a height between 300 mm and 350 mm above the ground with a 77 kg driver seated in the normal driving position.

The upper frame rail may be used as this member if it meets the height, diameter and thickness requirements.

T.2.14.5 The Lower Side Impact Structure member must connect the bottom of the Main Hoop and the bottom of the Front Hoop.

The lower frame rail/frame member may be this member if it meets the diameter and wall thickness requirements.

T.2.14.6 The Diagonal Side Impact Member must:

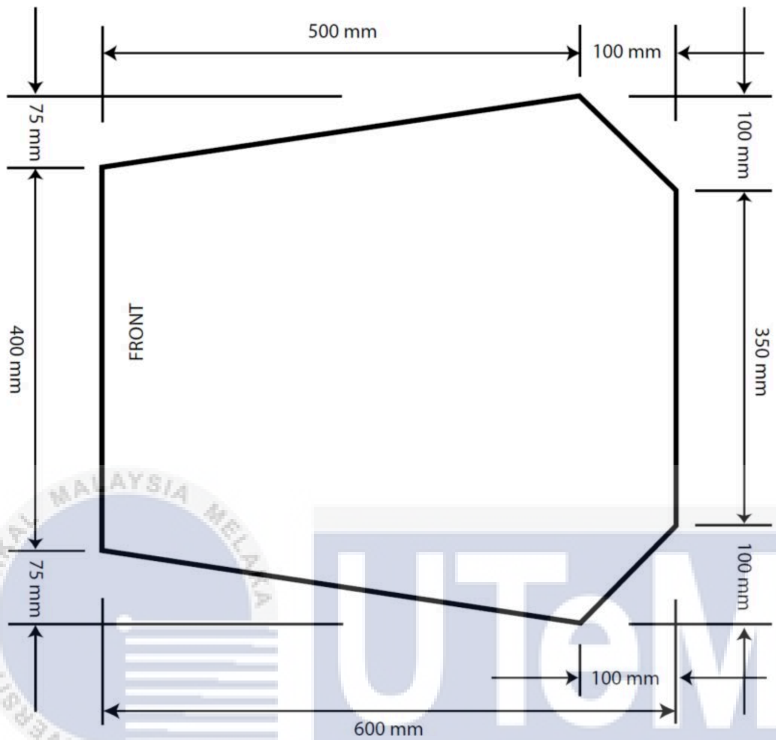
a. Connect the Upper Side Impact Member and Lower Side Impact Member forward of the Main Hoop and rearward of the Front Hoop

b. Completely triangulate the bays created by the Upper and Lower Side Impact Members.

T.3 COCKPIT

T.3.1 Cockpit Opening

T.3.1.1 The template shown below must fit into the cockpit opening



T.3.1.2 The template will be held horizontally, parallel to the ground, and inserted vertically from a height above any Primary Structure or bodywork that is between the Front Hoop and the Main Hoop until it:

a. Has passed below the top bar of the Side Impact Structure

b. Is 350 mm above the ground for monocoque designs

T.3.1.3 Fore and aft translation of the template is permitted during insertion.

T.3.1.4 During this test:

a. The steering wheel, steering column, seat and all padding may be removed.

b. The shifter or shift mechanism may not be removed unless it is integral with the steering wheel and is removed with the steering wheel.

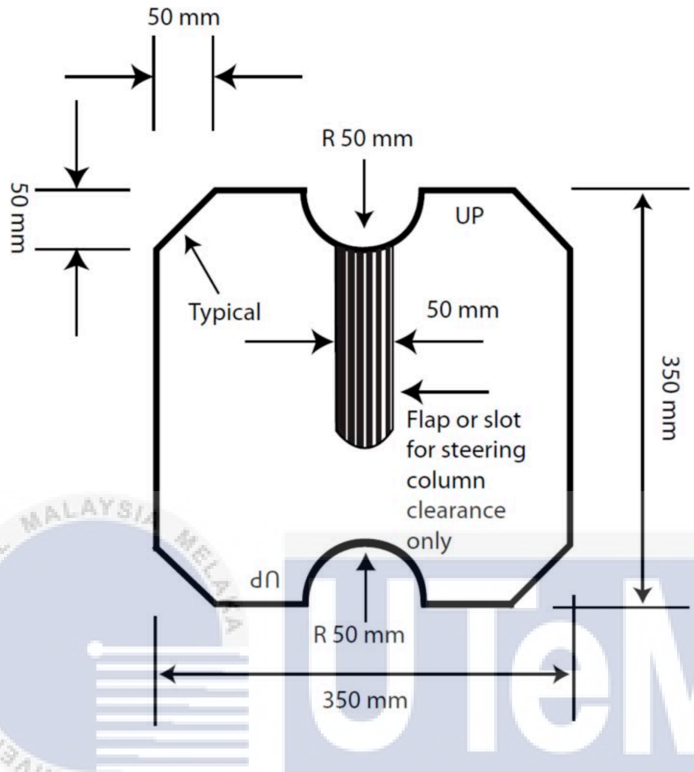
c. The firewall must not be moved or removed.

d. Cables, wires, hoses, tubes, etc. must not impede the template

During inspection, the steering column, for practical purposes, will not be removed. The template may be maneuvered around the steering column shaft, but not the steering column supports.

T.3.2 Internal Cross Section

T.3.2.1 A free internal cross section to allow the template shown below to pass through must be maintained through the cockpit.



Template maximum thickness: 7 mm

T.5.1 Front Mounted

T.5.1.1 In plan view, any part of any aerodynamic device must be:

a. No more than 700 mm forward of the fronts of the front tires

b. Within a vertical plane parallel to the centerline of the chassis touching the outside of the front tires at the height of the hubs.

T.5.1.2 When viewed from the front of the vehicle, the part of the front wheels/tires that are more than 250 mm above ground level must be unobstructed when measured without a driver in the vehicle.

T.5.2 Rear Mounted

T.5.2.1 In plan view, any part of any aerodynamic device must be:

a. No more than 250 mm rearward of the rear of the rear tires

b. No further forward than a vertical plane through the rearmost portion of the front face of the driver head restraint support, excluding any padding, set (if adjustable) in its fully rearward position (excluding undertrays).

c. Inboard of two vertical planes parallel to the centerline of the chassis touching the inside of the rear tires at the height of the hub centerline.

T.5.2.2 In side elevation, any part of an aerodynamic device must be no higher than 1.2 meters above the ground when measured without a driver in the vehicle

T.5.3 Between Wheels

T.5.3.1 Between the centerlines of the front and rear wheel axles, an aerodynamic device may extend outboard in plan view to a line drawn connecting the outer surfaces of the front and rear tires at the height of the wheel centers

T.5.3.2 Except as permitted under **T.9.4.1 above**, any aerodynamic devices, or other bodywork, located between the transverse vertical planes positioned at the front and rear axle centerlines must not exceed a height of 500 mm above the ground when measured without a driver in the vehicle.

Bodywork within vertical fore and aft planes set at 400 mm outboard from the centerline on each side of the vehicle is excluded from this requirement.

IC - INTERNAL COMBUSTION ENGINE VEHICLES

IC.1 GENERAL REQUIREMENTS

IC.1.1 Engine Limitations

IC.1.1.1 The engine(s) used to power the vehicle must:

a. Be a piston engine(s) using a four stroke primary heat cycle

b. Have a total combined displacement less than or equal to **710 cc** per cycle.

IC.1.1.2 Hybrid powertrains, such as those using electric motors running off stored energy, are prohibited.

IC.1.1.3 All waste/rejected heat from the primary heat cycle may be used. The method of conversion is not limited to the four stroke cycle.

IC.1.1.4 The engine may be modified within the restrictions of the rules.

Appendix – C KTM 690 Duke Specification

2017 KTM 690 Duke

Engine Configuration	Single, 4-Stroke
Engine Displacement	692.7cc
Engine Cooling System	Liquid
Compression Ratio	12.7:1
Combustion Chamber Design	Pentroof
Valves Per Cylinder	4
Intake Valves Per Cylinder	2 (Steel)
Exhaust Valves Per Cylinder	2 (Steel)
Bore x Stroke	105.0mm x 80.0mm
Measured Peak Horsepower	70.56 bhp @ 8,350 rpm
Measured Peak Torque	50.93 lbs-ft @6,600 rpm
Measured Horsepower To Weight Ratio	5.2 pounds per horsepower
Engine Redline	10,000 rpm

Combustion Chamber Volume	59 cc
Valve Train Type	SOHC, Link-plate Chain Drive, Bucket Tappers (Intake) and Forked Roller Rocker Arm (Exhaust)
Valve Adjustment Interval	6,200 miles (10,000km)
Intake Valve Diameter	42.0 mm
Exhaust Valve Diameter	36.0 mm
Intake Valve Stem Diameter	5.9 mm
Exhaust Valve Stem Diameter	5.9 mm
Fuel Delivery System	Keihin Fuel Injection
Throttle Body Venturi Size	50 mm
Air Filter Type	Pleated Paper Element
Exhaust System Type	1-1, Stainless Steel
Ignition System	Digital
Lubrication System	Semi-Dry Sump
Oil Capacity	1.8quarts (1.7 liters)
Fuel Capacity	3.7 gallons (14.0 liters)
Transmission Type	6-speed, Constant mesh
Clutch Type	Multi-plate, Wet, APTC Back-Torque-Limiting
Clutch Actuation System	Hydraulic
Clutch Spring Type	Coil
Number Of Clutch Springs	4
Number of Clutch Plates	15
Drive Plates	8
Driven Plates	7
Primary Drive	Gear (Straight-cut)
Primary Drive Gear Teeth (Ratio)	79/36 (2.194:1)
Final Drive Sprocket Teeth (Ratio)	40/16 (2.500:1)

Transmission Gear Teeth (Ratios)	
6th	20/23 (0.870:1)
5th	22/23 (0.957:1)
4th	23/21 (1.095:1)
3rd	28/21 (1.333:1)
2nd	28/16 (1.750:1)
1st	35/14 (2.500:1)
Transmission Overall Ratios	
6th	4.772: 1
5th	5.249: 1
4th	6.006: 1
3rd	7.312: 1
2nd	9.599: 1
1st	13.713:1
Theoretical Speed in Gears at Redline	
6th	139 mph
5th	126 mph
4th	110 mph
3rd	91 mph
2nd	69 mph
1st	48 mph