University of Warwick

School of Engineering

Chassis Design Analysis for Formula Student Car

by

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Report Reference Code: ES327

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Author's Self Assessment

What is the engineering contribution of this project?

This project focuses on gaining primary data on the strength and stiffness of the proposed chassis for the 2009 Warwick formula student car. This data has been analysed to identify any areas that lack the necessary stiffness and also areas that could have the stiffness reduced in order to lower the total weight of the chassis.

Why should this contribution be considered either relevant or important to engineering?

This project can be considered relevant to engineering as it demonstrates ways in which finite element analysis techniques can be adopted and used for basic analysis of space frame style chassis' designs in order to allow an optimal design to be achieved. The project also provides an example of how finite element analysis can be applied to many different situations and serves as an illustration of the wide umbrella of areas that it is suitable for.

How can others make use of the work in this project?

Other people who may find this report useful include future teams on Warwick Formula Student projects. This report can serve as a base upon which there designs can be built. The report shows areas on the chassis that are prone to high forces under certain conditions and so future teams can develop their vehicles appropriately in order to reduce the effect of these forces.

Why should this project be considered an achievement?

This project can be considered an achievement because it has shown that the proposed chassis design suitably meets the needs of the vehicle and will provide confirmation to the 2009 Warwick Formula Student team that their design is suitable for the purpose intended and will allow them to know with confidence that their design will function to the full extent that it was designed for.

What are the weaknesses of this project?

The weaknesses of this project are that although it can be used as a basis for future teams to design optimal chassis for future cars it is tied in to the 2009 rule specifications and is only useful for fully steel constructed chassis'. This means that although teams can base designs on the outcome of this report any future rule changes or use of different materials will have to be taken into account and may result in the chassis having to be designed in a slightly different way.

Summary

This project focuses on the proposed chassis design for the 2009 Warwick Formula Student team.

Formula Student is a competition in which teams of students design and build single-seater racing vehicles and enter them in an annual competition where they are awarded points for a number of different key areas.

The chassis of a vehicle is arguably the most important part as it serves as the framework onto which all other components are attached. Chassis's can be of many different types including ladder frames, monocoque, space frame and backbone style.

The proposed chassis is of the space frame style design and using computer aided design (CAD) has been created in a virtual environment. Using finite element analysis (FEA) techniques different loading conditions where simulated in order to ascertain how the chassis would react.

The chassis was subjected to braking loads, cornering loads, asymmetric loads and torsional loads.

It was found that under these different loads the chassis performed well and was easily able to carry the stresses that were created under these conditions.

Optimisation of the chassis proved to be beyond the scope of the report as the chassis had been design to maximum effect using the smallest tubing sizes available under the current rules.

Further work that could be carried out would require more time in order to create a more accurate model with the additional components added in order to represent real conditions more precisely.

Acknowledgements

I would like to thank Dr Ken Mao for his continued support and supervision during the course of this project.

I would like to thank James Brown for his help and support in the computer simulations and FEA processes.

I would like to thank Dr Steve Maggs and Mr Howard Neal for their help in providing information that has proved valuable in completing the project.

I would like to thank the 2009 Warwick Formula Student team for their help in providing the necessary information about the chassis design to allow me to complete the project.

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1.0 Introduction

1.1 Introduction to Formula Student

Formula Student is a design and manufacture competition run by the Institution of Mechanical Engineers (IMechE) in partnership with the Society for Automotive Engineers (SAE). The competition requires teams of students to design and build a fully functioning single-seater racing car by assuming roles in an engineering company. Attracting teams of students from all over the world, Formula Student is the biggest competition of its type in Europe.

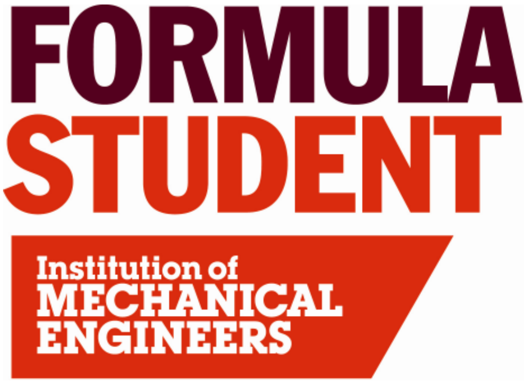

Image 1 – Formula Student logo

An annual competition is held in which the completed cars are entered. Points are then awarded on a variety of different events by a group of experienced engineers with the team gaining the most points winning the competition.

1.2 The Formula Student Competition

1.2.1 Classes

Formula Student comprises of five different classes into which cars can be entered.

- Class 1 – A fully constructed and running vehicle
- Class 1(A) – Low carbon race vehicles will be judged on the amount of carbon emission and can be powered by any fuel, first introduced in 2008
- Class 1 (200 Series) – Further development of Class 1 cars from previous years
- Class 2 – For teams that have progressed beyond initial design concepts into manufacture, minimum entry requirement is a complete chassis
- Class 3 – This is for teams new to Formula Student and is only marked on design, presentation and cost.[*]

1.2.2 Static Events

The static events are split into three parts; design, cost and presentation. For the engineering design section the team are awarded points by a panel of judges for how well their design meets the design goals and the needs of the intended market. The cost section sees teams awarded points for how well they have spent money on the project and the amount of value that has been added. The teams are finally awarded points for

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[*] See appendix B for more details

presentation; high points are awarded for strong teamwork, good communication and the ability to sell their ideas. These events make up 325 points of the total 1000 available.

1.2.3 Dynamic Events

The dynamic events are split into four parts. The cars are tested and awarded points during an acceleration test, an autocross test, a skid pad test and an endurance test. These tests are used to assess the speed and handling of the cars. During each event the fuel economy of the cars is also measured. These points make up the final 675 points on offer for each vehicle.

Table 1 shows how points are split between the two events.

Static Events		**Dynamic Events**	
Event	**Weighting**	**Event**	**Weighting**
Cost	100	Acceleration	75
Presentation	75	Skidpan	50
Engineering Design	150	Autocross	150
		Fuel Economy	100
		Endurance	300
Sub Total	**325**	**Sub Total**	**675**
Total 1000			

Table 1 – Formula Student scoring system

1.3 Warwick Formula Student team

The University of Warwick has been entering a team into the Formula Student competition since 2000.

Initially the teams used large engines in order to gain maximum power however after the W6 proved to be vastly heavier than predicted the teams recently have chosen to use much smaller engines and so have been able to reduce the weight dramatically. The W7 car (image 2) which was entered in the 2008 competition used a 525cc single cylinder engine and weighed a total of 215kg.

Image 2 – Warwick Formula Student W7 car

The teams previously have managed to secure budgets of around £20,000 and so while having a lot less than some other university teams; they have still managed to build racing cars that have been competitive.

So far the cars produced have struggled to advance further than the mid field with the W7 team finishing 45th with a total of 179.96 points. The car performed particularly poorly in the acceleration and sprint test and failed to compete in the endurance economy test due to technical difficulties.

The W8 team hopes to significantly improve on this result and gain a top 10 finish. The main method for this will be to finish the design early to allow maximum testing and optimisation of the vehicle.

2.0 Final Project Specification

2.1 Project Brief

This project will focus on the analysis of the proposed chassis design for the W8 racing car and suggest ways in which it could be improved. In addition to the desired weight reduction the optimised design must fulfil the following conditions. The suspension geometry must be able to attach to the frame at intersections of the frame tubes to ensure good connections without having to compromise the stiffness. The revised chassis must also meet all the Formula Student rules so as not to disqualify it from the competition.

The main tools for this project will be computer aided design (CAD) and finite element analysis (FEA). These will be used to create a 3D model of the chassis and then analyse the model during stress and displacement simulations.

2.2 Project Objectives

- Research and investigate different types of chassis design
- Calculate boundary conditions and loading forces and apply them to the computer models
- Analyse the W8 chassis using FEA techniques
- Using the results from the FEA analysis, determine areas of high stress and suggest ways they can be optimised

3.0 Literature Review

3.1 What is a racing vehicle

A racing vehicle is describe as -

"a system by which artificial forces are generated in order to accelerate the driver's body while he attempts to use the vehicle control system to maintain the highest possible acceleration level, in the appropriate direction, at all times."[†]

Racing vehicles are usually required to be as light as possible but must be able to survive the immense forces that could be created in the unlikely event of a crash. The pinnacle of racing vehicle design is generally considered to be the Formula 1 motor racing series (image 3). These cars are built with the highest budgets and can achieve the fastest speeds of up to 220 mph yet are strong and safe enough to survive crashes above speeds of 100 mph.

Image 3 – Ferrari F60

[†] Taken from Formula 1 Technology, page 1

3.2 The chassis

The chassis is possibly the most important part of any vehicle. Its main role is to provide the vehicle with a main structure which all other components can be fixed to. The chassis must be rigid in both torsion and bending and must be able to resist twisting and sagging. The chassis must be able to accommodate and support all the components of the vehicle and any occupants and must absorb all loads without excessive deflection.

The chassis is also required to be light weight to allow maximum power to be gained from the engine and be rigid enough so that the handling of the vehicle is not compromised in any way.

3.3 Types of chassis design

3.3.1 Ladder Frame Chassis

The ladder frame chassis was the earliest type of chassis used. It was widely used for the earliest cars until the early 60s. The design is, as the name suggest, similar to a ladder. There are two longitudinal rails running the length of the vehicle which are connected together by several lateral and cross braces. The longitudinal members act as the main stress members in this type of chassis and deal with the load as well as the longitudinal forces caused by accelerating or braking. Torsional rigidity is further increased by the lateral and cross braces which also deal with any lateral forces. The ladder frame type chassis is not used for the majority of modern cars as it has low torsional rigidity especially when encountering asymmetric loads; however it is still used for some pick-up trucks and SUVs.

Image 4 shows a ladder frame still used today in the construction of the Dodge Ram.

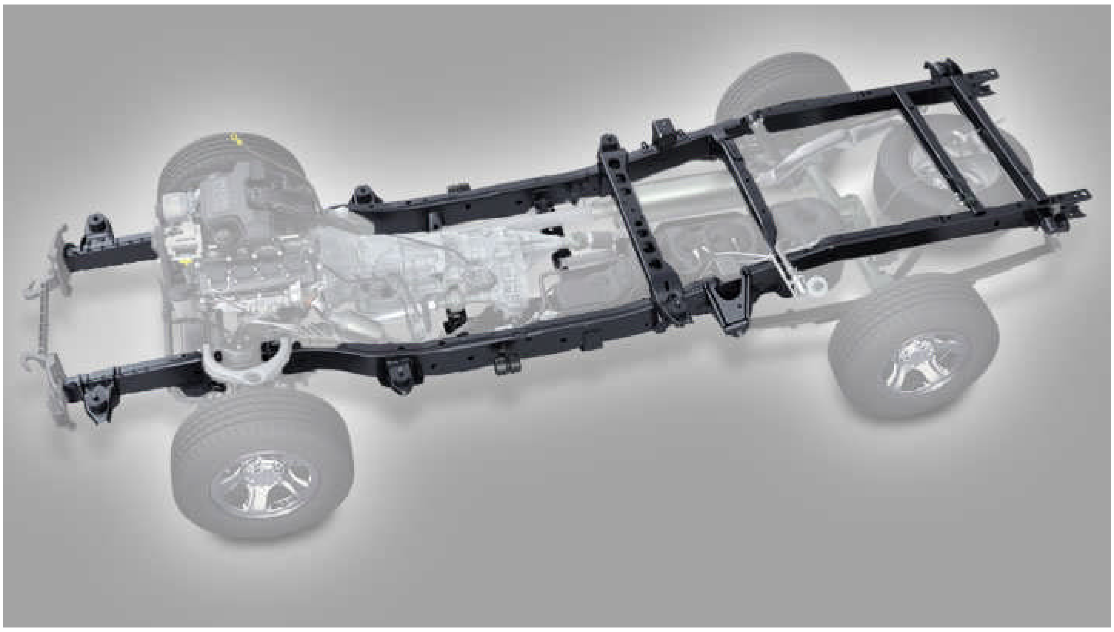

Image 4 – Ladder frame chassis from a Dodge Ram

3.3.2 Space Frame Chassis

The space frame was the next logical step up from the ladder frame. A space frame has a number of features that distinguish it from a ladder frame and add massive advantages. A perfectly designed space frame would have the tubular sections arrange so that the only forces on them are either tension or compression. This is a massive advantage as materials have much better resistance to tensile and compressive loads than they do to bending loads.

One of the earliest examples of the use of a space frame was the Maserati Tipo 61 "Birdcage" racing car (image 5) built between 1959 and 1961. Since then many high end sports cars have been designed with a space frame due to the major advantages it gives in weight reduction while maintaining its rigidity. Space frames have some disadvantages however, they can be enormously time consuming and costly to build, due to the fact they can be very complex. Also, production cannot currently be done using robotic arms due to the complexity of the structure and so large scale production is impossible.

Image 5 – A space frame from a Maserati Tipo 61

3.3.3 Monocoque Chassis

The monocoque style of chassis is used by almost all car manufacturers today. A monocoque is a one-piece structure that defines the overall shape of the vehicle. This type of chassis is very attractive to mass production as the process can be automated very easily. The structure also has very good crash protection as crumple zones can be built into the structure itself. A monocoque chassis has a few disadvantages however that make it unsuitable for use by the Warwick Formula Student team. The main one of these is that a monocoque chassis is much heavy than other types of chassis due to the amount of metal used. It is also very expensive to produce on a small scale as the tooling costs to produce the chassis are very high. Image 6 shows an example of an early monocoque from Chrysler and how the safety aspect was used to market the cars. Image 7 shows a modern example of a monocoque built by Jaguar.

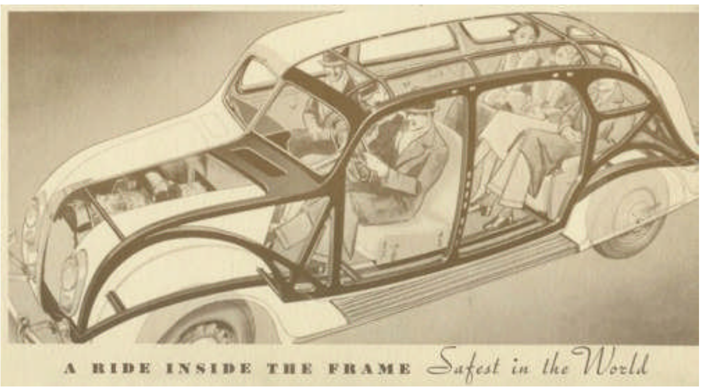

Image 6 – An early example of a monocoque chassis from a Chrysler Airflow

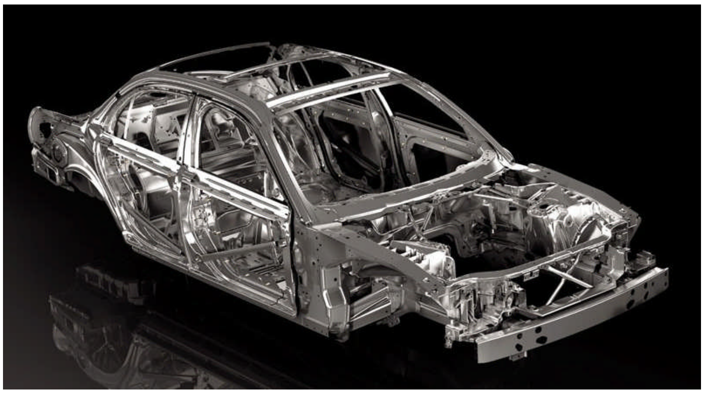

Image 7 – A modern example of the monocoque chassis from a Jaguar XJ

3.3.4 Backbone Chassis

A backbone chassis is a simple style of frame that uses a central backbone running the length of the chassis that connects to the front and rear suspension attachment areas. The backbone usually has a rectangular cross section. The body of the vehicle is then placed onto of the structure. This type of chassis is used sometimes for small sports cars however it provides little or no protection against a side impact and so requires the body to be designed to accommodate this. This can often lead to heavy reinforcing beams being needed in the body frame adding extra weight to the vehicle.

One of the most well known uses of the backbone chassis was for the De Lorean DMC-12 (image 8).

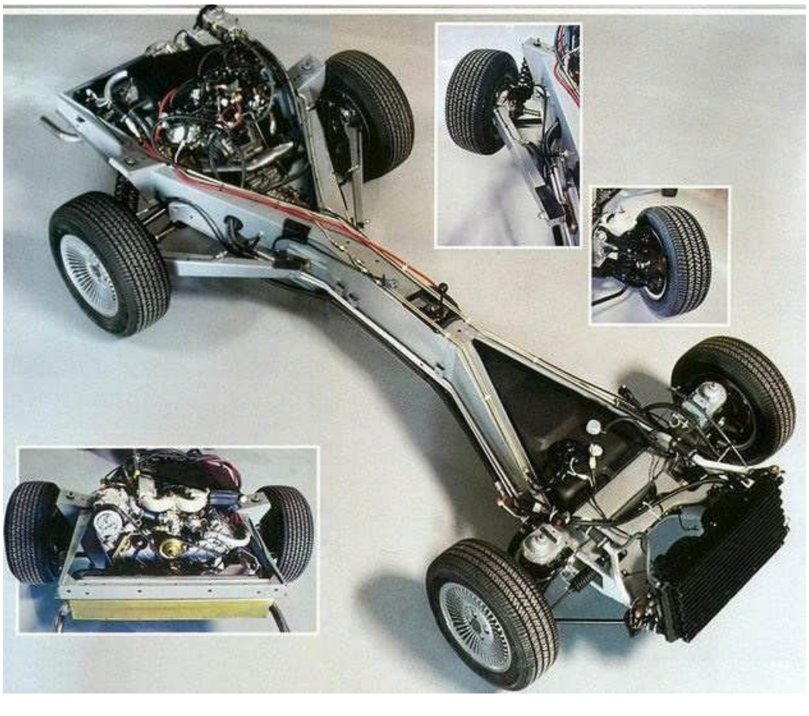

Image 8 – The backbone chassis from a De Lorean DMC-12

3.4 Understanding the basic need of a vehicle chassis

For a racing car to achieve its goal of winning races it must have a structurally rigid frame with adequate stiffness. This will allow it to have effective handling capabilities and resist any twisting or bending forces it will encounter. Designing a rigid frame requires the knowledge and application of a few simple design elements, the types of shapes and arrangements that add rigidity to a structure are vital.

There is one basic shape above all that is perfect for this purpose, the triangle. A triangle will approximately retain is shape and dimensions unless one of its members is broken or damaged. In comparison to this a rectangular shape is very poor at resisting diagonal loads as it must rely solely on the strength of the joints to resist these forces.

A rectangle can, however, be used by adding cross bracing. This effectively splits the rectangle into two triangles, a process known as triangulation (image 9), and turns the weak rectangular section into a much more rigid structure. In image 5 the triangulation is clearly visible on the frame behind the windscreen. Further triangulation can be applied with a second cross bracing beam being added to create four triangles, however this is only necessary for cases were very large loads are applied or if the area of the triangular sections is particularly large.

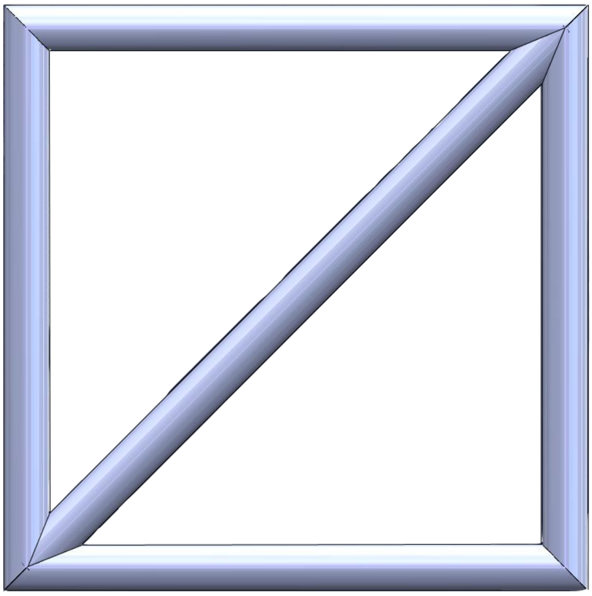
Image 9 - Triangulation

Designing a rigid frame is firmly based in having a good understanding of structural basics and being able to apply them to the application. As the majority of the loads will be applied to the chassis through the connections with the suspension it is important that these areas receive particular attention.

3.5 Problems with previous designs

The W7 had a number of design flaws that came to light during the competition.

The first of these was a poorly designed rear beam that prevented the drive chain being position. Due to this the chain was forced to slide over the top of the beam which caused unnecessary friction and heating on the chain which in turn caused it to stretch. This problem will be resolved by altering the position of this bar on the W8 chassis.

A further problem was brought to light through the concern of the judges. It was pointed out that the lack of cross-bracing on the rear of the car could cause it to twist. This would push the rear axle out of line which could cause the drive chain to become dislodged and the car would lose drive. Figure 1 shows a plan view of the rear of the car and how the twist would look.

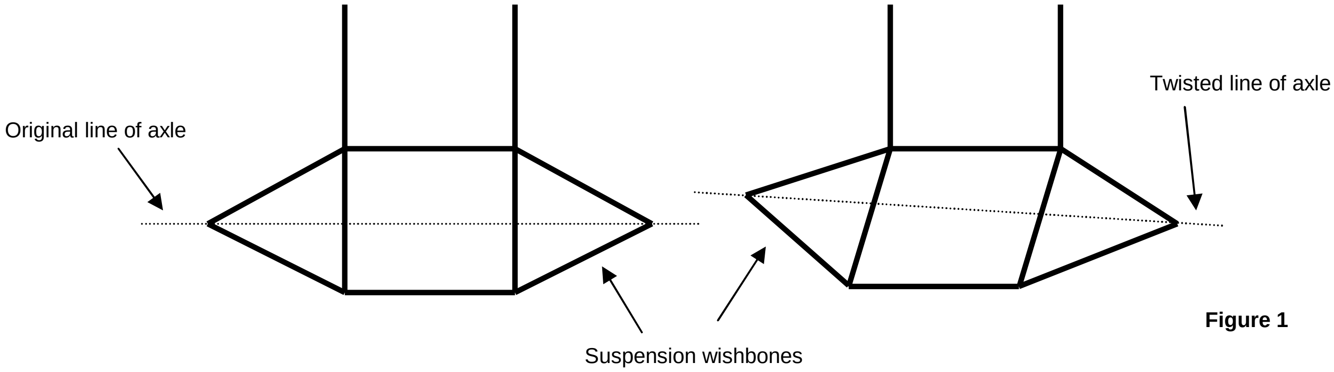

Figure 1

A similar problem was found by the judges on the roll-bar supports. The lack of bracing meant that should the car roll over the roll-bar would be quite likely to simply fold backwards again due to the lack of cross-bracing.

While this project is not focused at finding these effects specifically the results will be analysed to see if there is any indication that the W8 could suffer from similar problems.

4.0 Research Methodology

4.1 Computer software

4.1.1 Computer Aided Design (CAD)

Computer aided design is the process of using computer technology to assist in the design of a component or model. A CAD software package will allow an engineer to create a digital 2 or 3 dimensional model that can then be used for further analysis without the need of making costly physical models. Warwick Formula Student team is using SolidWorks for the modelling of its car and so it was therefore necessary to become familiar with this package so that any manipulations of the model could be done quickly and accurately.

4.1.2 Finite Element Analysis (FEA)

Finite element analysis is computer software that uses numerical methods to analyse the behaviour of components and structures under certain loading conditions predetermined by the engineer.

To ensure the structural integrity of the chassis, areas of high stress must be located and if necessary redesign to ensure there will be no failure during use. While hand calculations could be used to determine the forces in the chassis using the stiffness matrix method, the complexity of the structure would make the equations incredibly complex and time consuming to solve. Using a computer software package allows engineers to identify areas of stress much faster and doesn't require a physical prototype model to be manufactured.

The University of Warwick has two FEA packages available to use. Abaqus is a standalone FEA program while COSMOSworks is an add-in module of SolidWorks. While both these programs are fully capable of running the necessary simulations, Abaqus has been chosen as the preferred program to run the simulations due to its ability to deal with wireframe models which COSMOSworks cannot.

4.2 Chassis loading analysis

As with previous cars, the W8 will be made with a space frame chassis. This will allow the frame to be as light as possible while still having the necessary structural strength and rigidity to withstand all the forces it is likely to see. Another factor is the familiarity that the team can gain in regards to a space frame design by inspecting older designs to see how they can be improved upon.

The chassis will be subjected to four different types of loads that will show how it would react under different conditions, these are bending, braking, cornering and asymmetric loads and will all be experienced by the chassis at some point.

4.2.1 Bending loads

Bending loads are caused by the weight of the components on the chassis. Bending loads are loads applied normal to an axis that produce a bending moment. To simulate these loads, forces will be applied in the vertical plane to simulate the bending force cause by the weights of the various components and the driver. Using the theory of bending the maximum bending moment can be derived.

4.2.2 Braking loads

Braking loads are those experienced by the car during deceleration. The loads originate at the surface of the road where the tyres are in contact with the tarmac. The forces are transferred through the suspension struts onto the chassis of the vehicle through the mounting points.

4.2.3 Cornering loads

Cornering loads are creating as the car travels around a bend. Cornering loads originate from the contact patch between the tyre and the road surface. During cornering manoeuvres loads act on the wheels mainly on the outside of the corner depending on the roll of the car.

4.2.4 Asymmetric loads

Asymmetric loads, or torsional loads, occur when the car encounters a bump or pothole while moving. While on a race track it is unlikely there will be any significant bumps the same effect would be generated should the driver direct the car over the inside kerbs when navigating a corner. These loads cause the chassis to twist however they can largely be absorbed by the suspension of the car.

4.3 Triangulation analysis

Triangulation, as explained earlier, is the process of splitting a rectangular section into two triangular sections using cross bracing in order to increase the torsional rigidity of the section. In order to fully understand the process it was necessary to perform a simple test to see the effects. Two models were created on SolidWorks. The first is a simple square section and the second is the same square section with a cross brace added. The same force was applied to each section in the upper left corner to see how the stress patterns and the displacement of the sections would be affected by the added bracing.

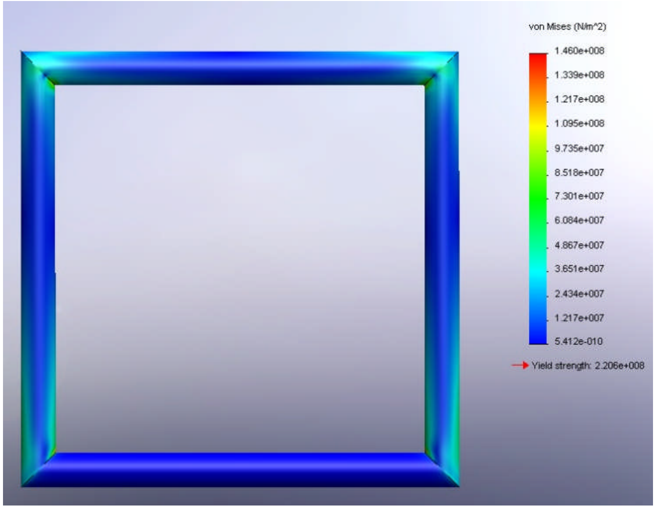

Figure 2 – von Mises stress, Non-triangulated

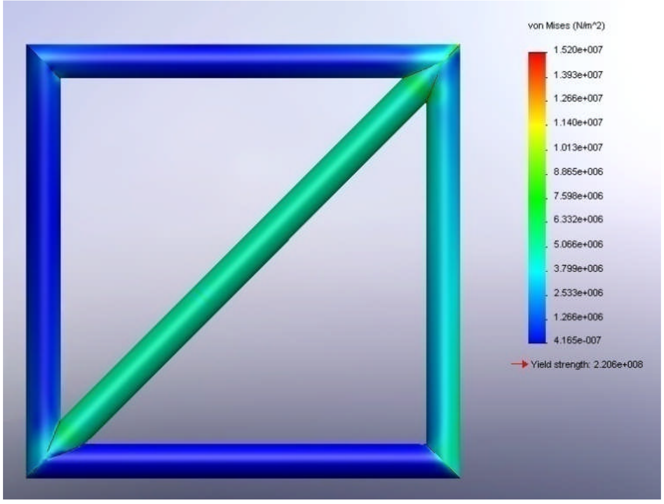

Figure 3 – von Mises stress, Triangulated

Figure 2 shows the stress pattern on the non-braced member while figure 3 shows the stress pattern on the braced member. It is clear from the results that the stress in the triangulated section is greatly less than that of the non-triangulated section, with the triangulated section only showing 10% of that in the non-triangulated section.

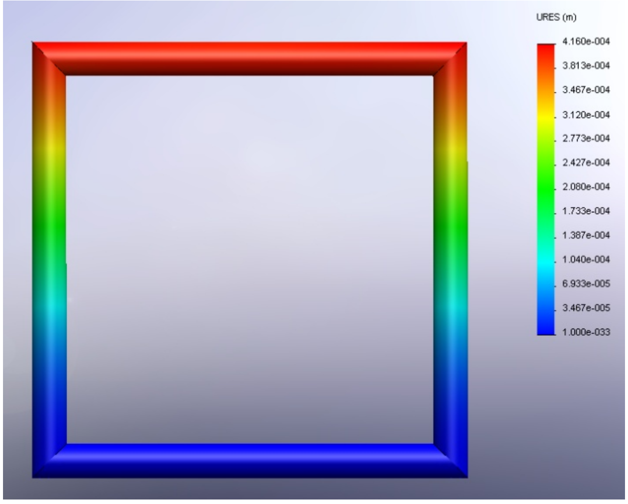

Figure 4 – Displacement, Non-triangulated

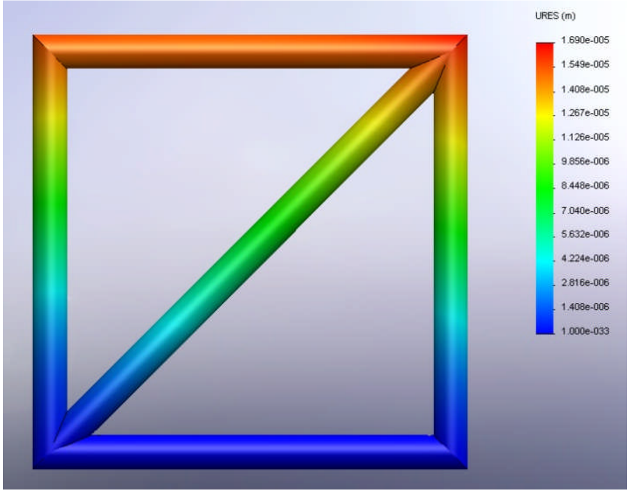

Figure 5 - Displacement, Non-triangulated

Figure 4 shows the displacement on the non-triangulated section to be 0.41mm, while figure 5 shows the displacement on the triangulated section to be only 0.017mm. this is a 96% reduction.

Overall it can clearly be seen from these tests that triangulation creates a 90% reduction in stress and a 96% reduction in displacement with only a 32% increase in weight proving that triangulation is a very effective method for increasing the torsional rigidity of a section.

The FEA analysis was run using COSMOSworks for this simulation due to the simple nature of the framework being analysed.

4.4 Calculating boundary conditions

4.4.1 Static bending loads

In a space frame chassis the individual members support those around them in 3 dimensions, this is complex to model and so for this section the space frame can be simplified into a simple cantilever beam with the axle points acting as the supports. The major components will be treated as dead loads acting through their centre of gravities which have been established using a SolidWorks model of the completed car.

Component	Distance from front (mm)	Weight (kg)
Crash Structure	0	1.5
Steering system	325	3.0
Front Axle	435	-
Pedal Box	563	2.5
Springs	724	2.0
Bodywork	1011	7.0
Driver controls	1020	2.0
Driver/Harness	1326	80.0
Fuel tank	1474	5.0
Radiators	1708	2.2
Engine/Gearbox	1924	30.0
Air intake/Exhaust	2096	4.0
Springs	2118	2.0
Rear Axle	2220	-
Differential	2220	8.0

Table 2 – Component list for weight calculations

Assuming gravity to be 10m s^{-2} the bending moments can be calculated as follows:

$$\begin{aligned}(1785)R_{rear} = {} & (15 * -435) + (30 * -110) + (25 * 128) + (20 * 289) \\ & + (70 * 576) + (20 * 585) + (800 * 891) + (50 * 1039) \\ & + (22 * 1273) + (300 * 1489) + (40 * 1661) + (20 * 1683) \\ & + (80 * 1785)\end{aligned}$$

R_{rear}=859.1N and R_{total}=1492N ∴ R_{front}=632.9

This gives a weight distribution of 42.4% and 57.6% to the front and back respectively.

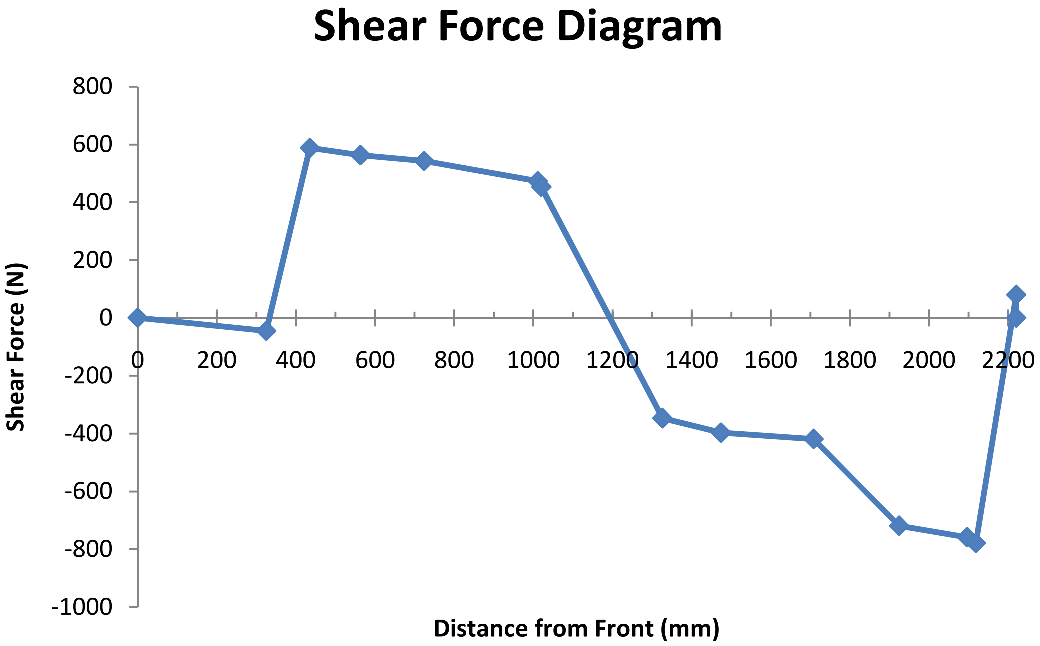

Figure 6 – Weight distribution

4.4.2 Linear braking

The forces need to slow a car act through the contact area between the tyres of the car and the road surface it is travelling over. However, the inertia of the car is translated though its centre of gravity. As the centre of gravity is above the road level a moment effect is created during breaking that tries to rotate the car about this point. This effect causes more of the weight to be translated to the front of the car.

Assuming the vehicle brakes going into a corner from 50mph to 20mph the g-forces experienced can be calculated.

$$30\text{mph} = 30 * \frac{1600}{3600} = 13.33\text{m s}^{-2}$$

This is equal to 1.36g.

Using equation 1 the load transfer can be calculated.

$$\text{Load transfer} = \frac{\text{longitudinal deceleration (g)} * \text{mass (kg)} * \text{CoG (m)}}{\text{Wheel base length (m)}}$$

Equation 1 – Longitudinal load transfer

$$\text{Load transfer} = \frac{1.36 * 300 * 0.3}{1.786}$$

Load transfer = 68.5kg transfers to the front of the car due to braking.

Weight transfer under braking

W = Weight of car (N)

W_f = Weight over front (N)

W_r = Weight over rear (N)

L = Wheelbase (m)

h = Centre of gravity height (m)

a = Deceleration (ms^{-2})

$$F_{BF} = W_f + \left(W * a * \frac{h}{L}\right)$$

$$F_{BF} = 1885 \text{ N}$$

Equation 2 – Front forces under braking

$$R_{BF} = W_r + \left(W * a * \frac{h}{L}\right)$$

$$R_{BF} = 1115 \text{ N}$$

Equation 3 – Rear Forces under braking

This can be used to calculate the brake distribution that could result in a lock-up.

$$\frac{1885}{3000} = 0.628 \text{ or } 62.8\% \text{ on the front}$$

$$\frac{1115}{3000} = 0.372 \text{ or } 37.2\% \text{ on the rear}$$

In order to avoid locking the rear wheels a distribution of 35% on the rear and 65% on the front would be the best way as if the rear tyres reach the limit first the car has a tendency to over steer which in certain conditions can lead to complete loss of directional control and so the car spins.

Longitudinal forces under braking

$$F = M * A$$

$$F = 300 * 9.81 * 1.36$$

$$F = 4002.5\ N$$

$$F_{BF} = 4002.5 * 0.63$$

$$F_{BF} = 2521.6\ N$$

Equation 4 – Front braking forces

$$R_{BF} = 4002.5 * 0.37$$

$$R_{BF} = 1480.9\ N$$

Equation 5 – Rear braking forces

4.4.3 Lateral cornering Loads

During a cornering manoeuvre the car chassis is subject to lateral forces. These originate from the area known as the contact patch. This is the area of the tyre that is in contact with the road surface.

$$\text{Load transfer} = \frac{\text{Lateral acceleration (g)} * \text{mass (kg)} * \text{CoG (m)}}{\text{Wheel base width (m)}}$$

Equation 6 – Lateral load transfer

$$\text{Load transfer} = \frac{1.3 * 300 * 0.3}{1.18}$$

$$\text{Load transfer} = 99.15\text{kg}$$

It can be seen from these calculations that as the car enters a 1.3g corner, 100kg of the car mass is transferred to the outside edge. The result of this is a load of 250kg on the outside tyres and 50kg on the inside tyres.

Lateral force on the outside tyres

Lateral force on outside tyres = 250 * 9.81 * 1.3

Lateral force on each tyre = 3188.2 / 2

Lateral force on each tyre = 1594.1 N

Equation 7 – Lateral force on outside tyres

Vertical force on outside tyres = 250 * 9.81

Vertical force on each tyre = 2452.5 / 2

Vertical force on each tyre = 1226.2 N

Equation 8 – Vertical force on outside tyres

Lateral force on inside tyres = 50 * 9.81 * 1.3

Lateral force on each tyre = 637.6 / 2

Lateral force on each tyre = 318.8 N

Equation 9 – Lateral force on inside tyres

Vertical force on inside tyres = 50 * 9.81

Vertical force on each tyre = 490.5 / 2

Vertical force on each tyre = 245.25 N

Equation 10 – Vertical force on inside tyres

4.4.4 Asymmetric loads

Asymmetric loads are created when the car travels over a bump or pothole in the road surface. The force is transferred into the chassis through the suspension mounting points and causes the chassis to twist.

The front suspension shock absorber must be design for a maximum travel of 50.8mm under the rules. During the bump loading test the suspension will be subject to a force that causes the suspension to fully contract to simulate the effects of the car hitting a kerb on the track. This results in the force translating from the contact patch, overcoming the damping force in the shock absorber, and into the chassis through the pushrod. The chassis is required to be able to resist any forces that occur this way.

For this loading condition the front left wheel will be subject to the load. This means that only half the car's mass will be included diagonally through the wheel centres. It will be assumed that the other wheels are fixed to the road. The result of this is a load of 1471.5N being exerted onto the front wheel. The recommended stiffness for a small racing car is 4068Nm/deg[‡].

Equation 11 shows the formula for torsional stiffness

$$\text{Torsional stiffness} = \frac{\text{Torque}}{57.3\ \text{deg}} * \frac{\text{Spread distance}}{\text{Deflection}}$$

Equation 11 – Torsional stiffness

Rearranging the equation allows for the calculation for the deflection that would occur were a load of 1500N to be applied to the front wheel if the chassis had a stiffness of around 4000Nm/deg.

[‡] http://www.fisita.com/students/congress/sc08papers/f2008sc005.pdf

Spread distance = 0.3m

Torque = 450Nm

Torsional stiffness = 4068Nm/deg

Deflection = δ

$$4068\,\text{Nm}\quad \text{deg} = \frac{450\ \text{Nm}}{57.3\ \text{deg}} * \frac{0.3\ \text{m}}{\delta}$$

$$\delta = \frac{0.3}{4068 * \frac{57.3}{450}}$$

$$\delta = 0.579\text{mm}$$

This calculation shows that when a load of 1500N is applied to the front left-hand side of the chassis it cannot have a deflection of more than 0.579mm in order for it to meet the requirements of a stiffness of 4068Nm/deg.

4.5 The current design in conjunction with the rules

2009 SAE rules

The definitions below are taken from Formula SAE rules 2009.

"General requirements

Among other requirements, the vehicle's structure must include two roll hoops that are braced, a front bulkhead with support system and Impact Attenuator, and side impact structures.

- *Main Hoop – A roll bar located alongside or just behind the driver's torso*
- *Front Hoop – A roll bar located above the driver's legs, in proximity to the steering wheel*
- *Roll Hoops – Both Front Hoop and the Main Hoop are classified as 'Roll Hoops'*
- *Frame Member – A minimum representative single piece of uncut, continuous tubing*
- *Frame – The 'Frame' is the fabricated structural assembly that supports all functional structures or a combination of composite and welded structures*
- *Primary Structure – The Primary Structure is comprised of the following Frame components*
    1) *Main Hoop*
    2) *Front Hoop*
    3) *Roll Hoop Braces*
    4) *Side Impact Structure*
    5) *Front Bulkhead*

6) *Front Bulkhead Support System*
7) *All Frame Member, guides and supports that transfer load from the Driver's Restraint System into items 1) through 6)*

- *Major Structure of the Frame – The portion of the Frame that lies within the envelope defined by the Primary Structure. The upper portion of the Main Hoop and the Main Hoop braces are not included in defining this envelope*
- *Front Bulkhead – A planar structure that defines the forward plane of the Major Structure of the Frame and functions to provide protection for the driver's feet*
- *Impact Attenuator – A deformable, energy absorbing device located forward of the Front Bulkhead*

SAE also provides rules on material requirements for the Frame components.

- *Baseline Steel Material – The Primary Structure of the car must be constructed of:*
    - *Either: Round, mild or alloy, steel tubing (minimum 0.1% carbon) of the minimum dimensions specified in the following table,*
    - *Or: Approved alternatives"*

ITEM or APPLICATION	*OUTSIDE DIAMETER X WALL THICKNESS*
Main & Front Hoops, Shoulder Harness Mounting Bar	*1.0 inch (25.4 mm) x 0.095 inch (2.4 mm) or 25.0mm x 2.5 mm metric*
Side Impact Structure, Front Bulkhead, Roll Hoop Bracing, Driver's Restraint Harness Attachment (except as noted above)	*1.0 inch (25.4 mm) x 0.065 inch (1.65 mm) or 25.0 mm x 1.75 mm metric or 25.4 mm x 1.60 mm metric*
Front Bulkhead Support	*1.0 inch (25.4 mm) x 0.049 inch (1.25 mm) or 25.0 mm x 1.5 mm metric or 26.0 mm x 1.2 mm metric*

Table 3 – Minimum frame size specification

Further rules and regulations are provide for the use of alternatives to steel (e.g. aluminium, titanium) however due to the costs associated with these alternatives they are not currently used by Warwick Formula Student team. See appendix B for further details.

The W8 car has been designed so that it meets these specifications but does not exceed them. This should allow the chassis to be created with the minimum possible weight.

Image 10 below shows the 3 different tube sizes being used in the chassis

Members in blue are 25.4 mm x 2.4 mm.

Members in red are 25.4 mm x 1.65 mm.

Members in green are 25.4 mm x 1.25 mm.

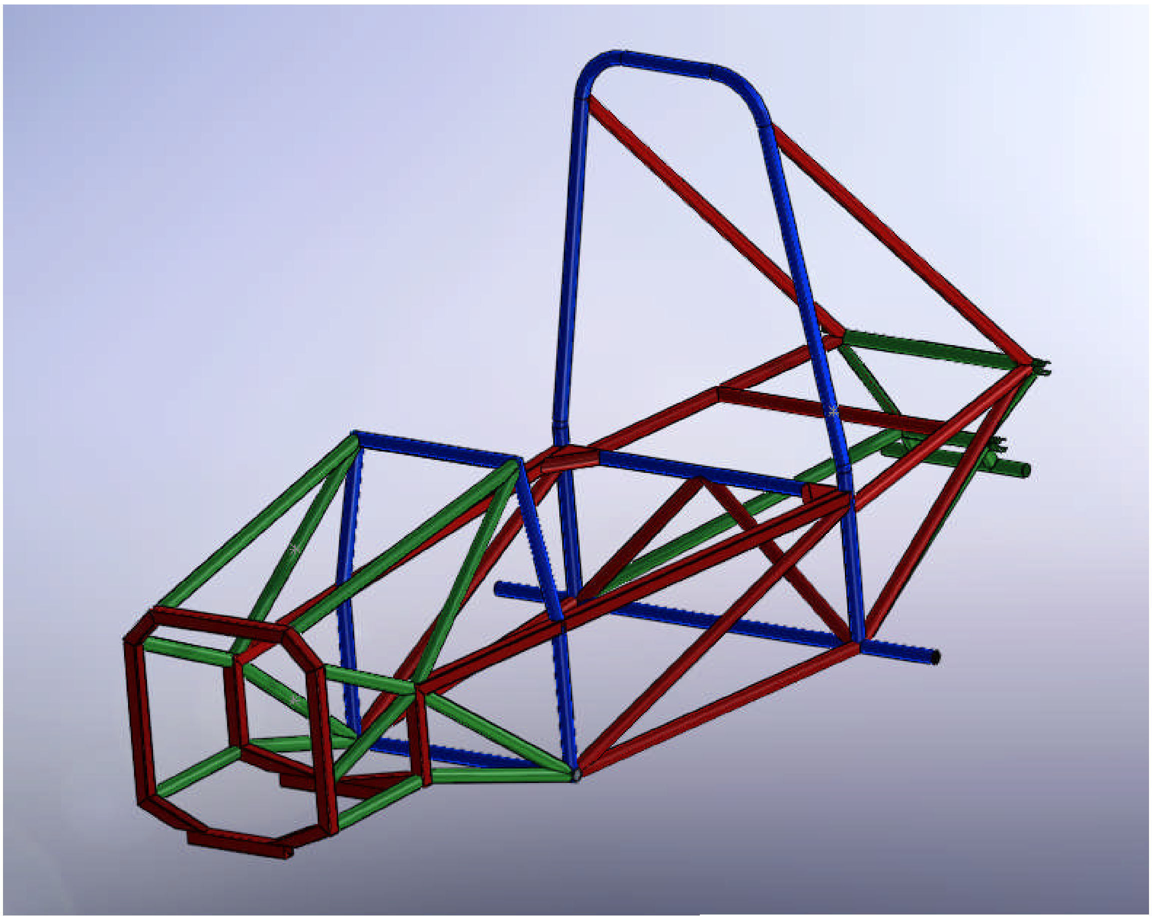

Image 10 – Member profiles on chassis

5.0 Finite Element Method

For this section of the report data calculated in the previous section will be used to simulate loads encountered by the car during asymmetric, braking and cornering forces using the finite element method. Using this data large displacements and areas of high stress can be found and subsequently optimised in order to try and reduce the stress concentrations and if possible reduce the amount of tubing in the frame and in doing so reducing the overall weight of the car.

For each of the simulations boundary conditions were added to appropriate points in order to make the simulations as accurate as possible to what the car would experience during actual racing conditions.

The forces have been added to points on the chassis that reflect the points where the suspension wishbones would attach. This was done as it allows the chassis to take all the force which allows for a worst case scenario to be analysed.

The forces were also added to these points in order to simplify the model to a reasonable degree without compromising the integrity of the results.

5.1 Linear braking simulation

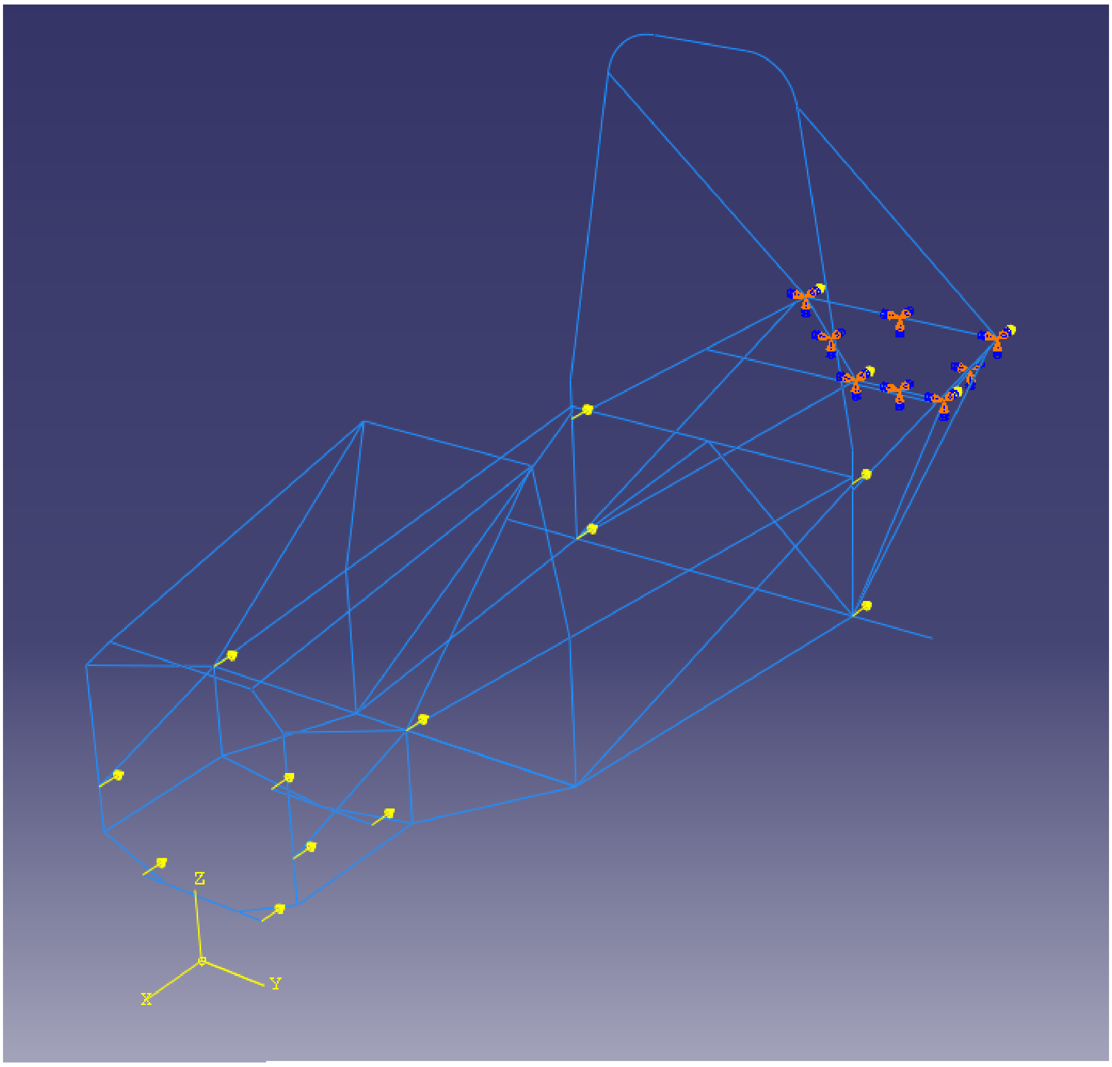

Figure 7 –Boundary and loading conditions applied during braking simulation

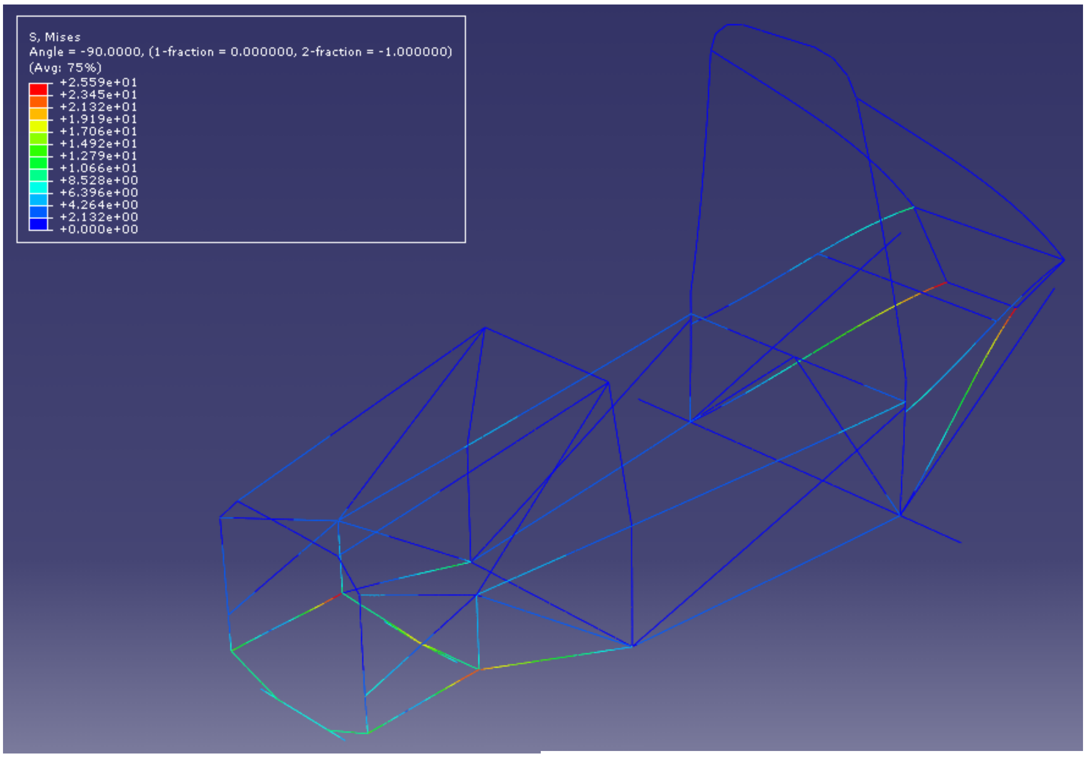

Figure 8 - Von Mises stress for braking simulation

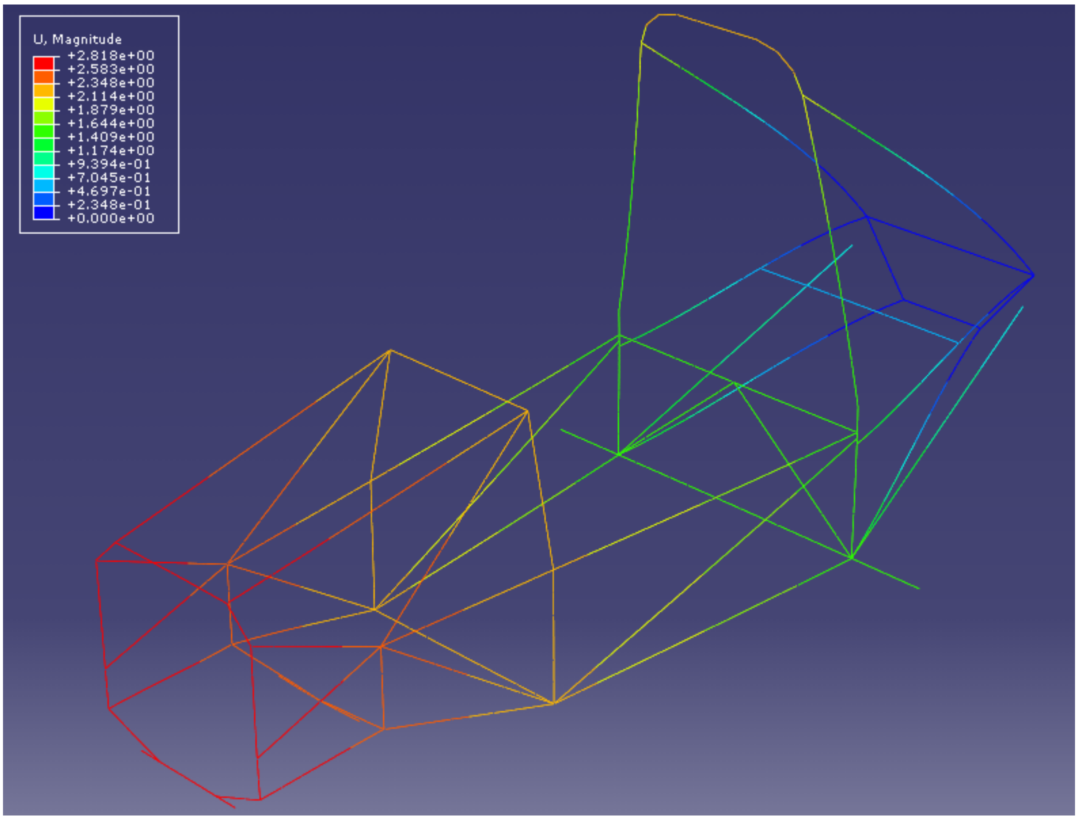

Figure 9 – Displacement plot for braking simulation

5.2 Lateral cornering simulation

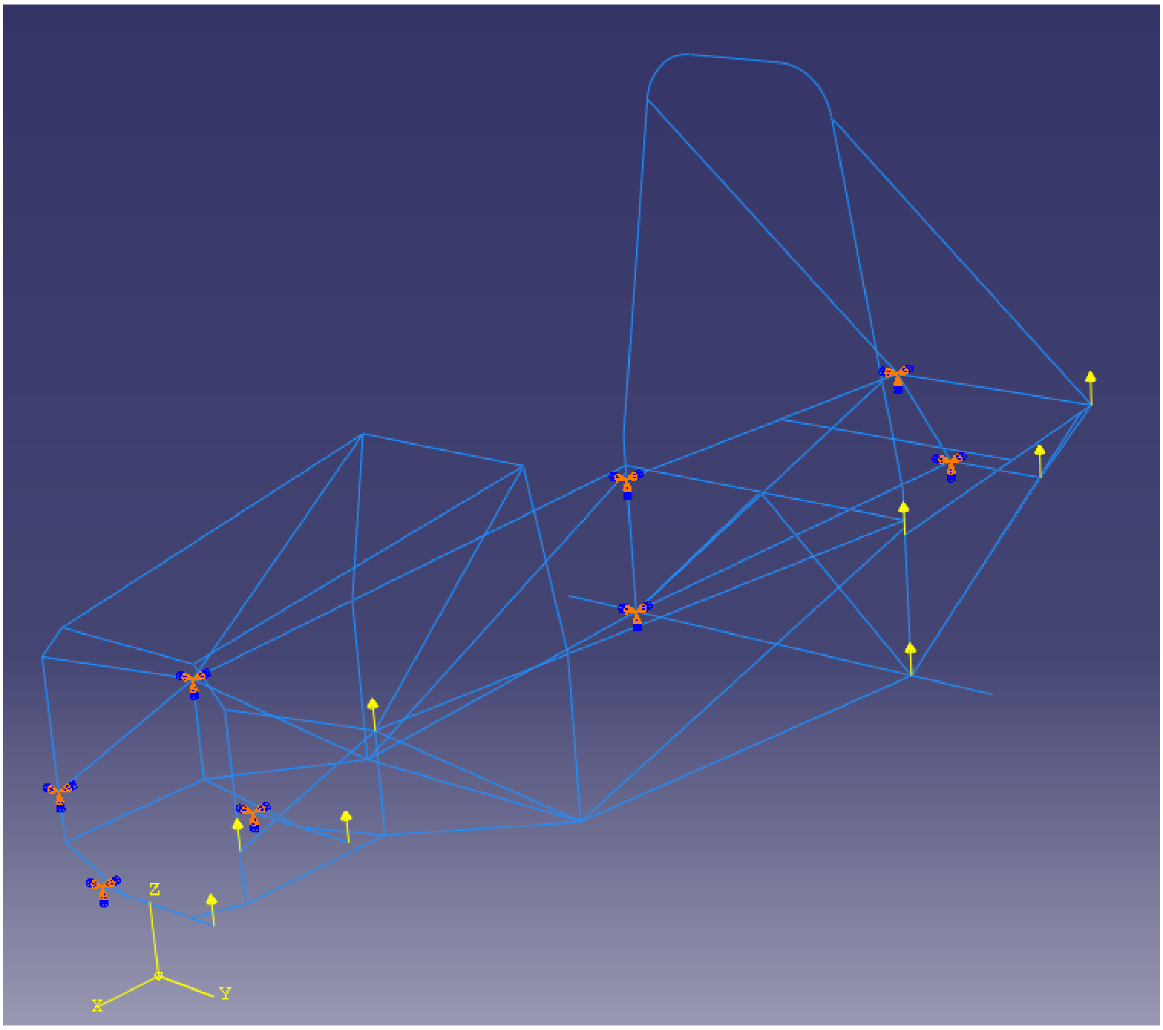

Figure 10 – Boundary and loading conditions applied during cornering simulation

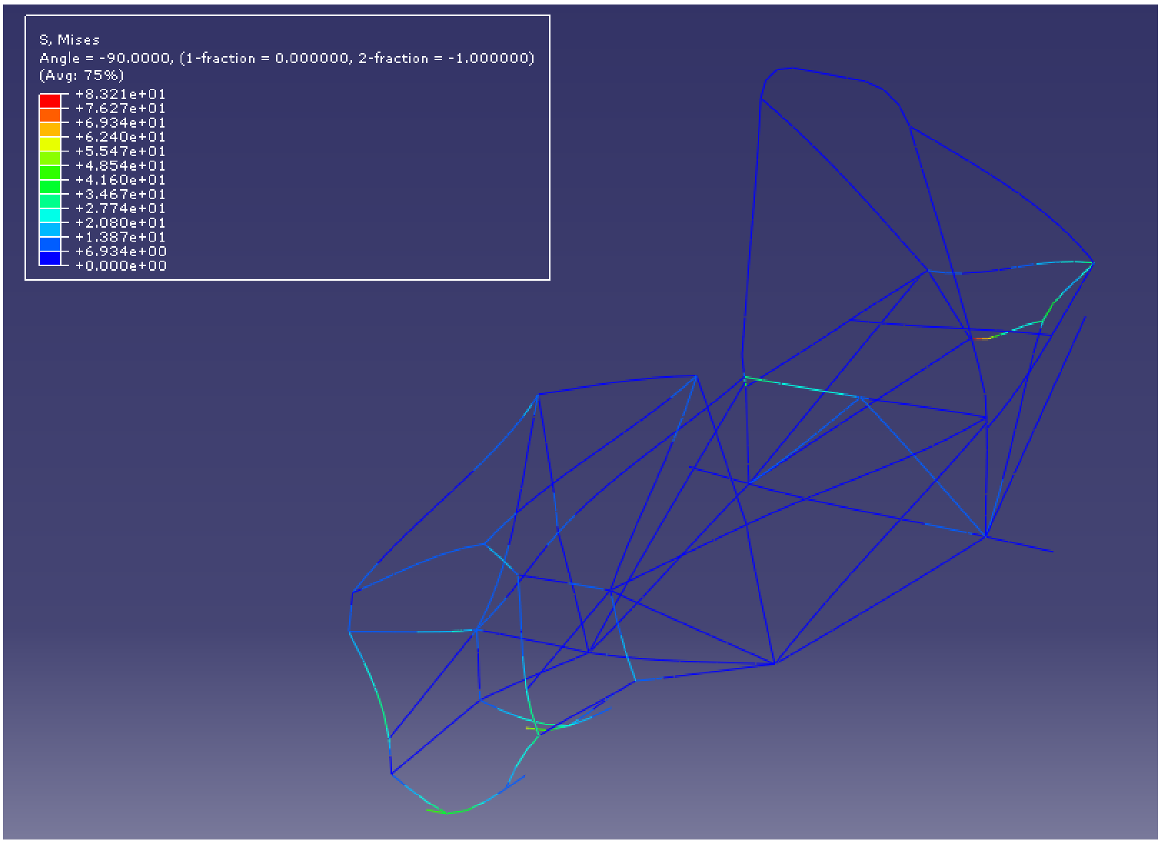

Figure 11 – Von Mises stress for cornering simulation

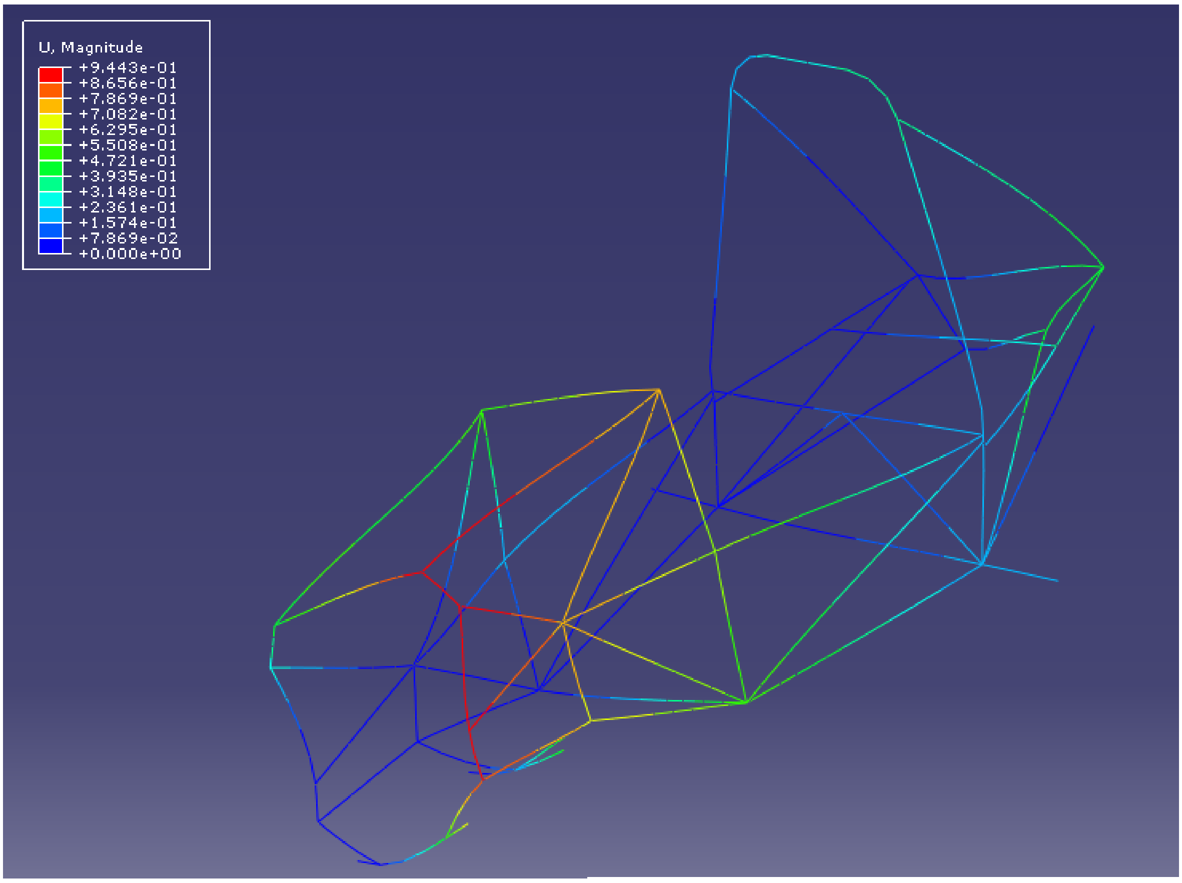

Figure 12 – Displacement plot for cornering simulation

5.3 Asymmetric loading simulation

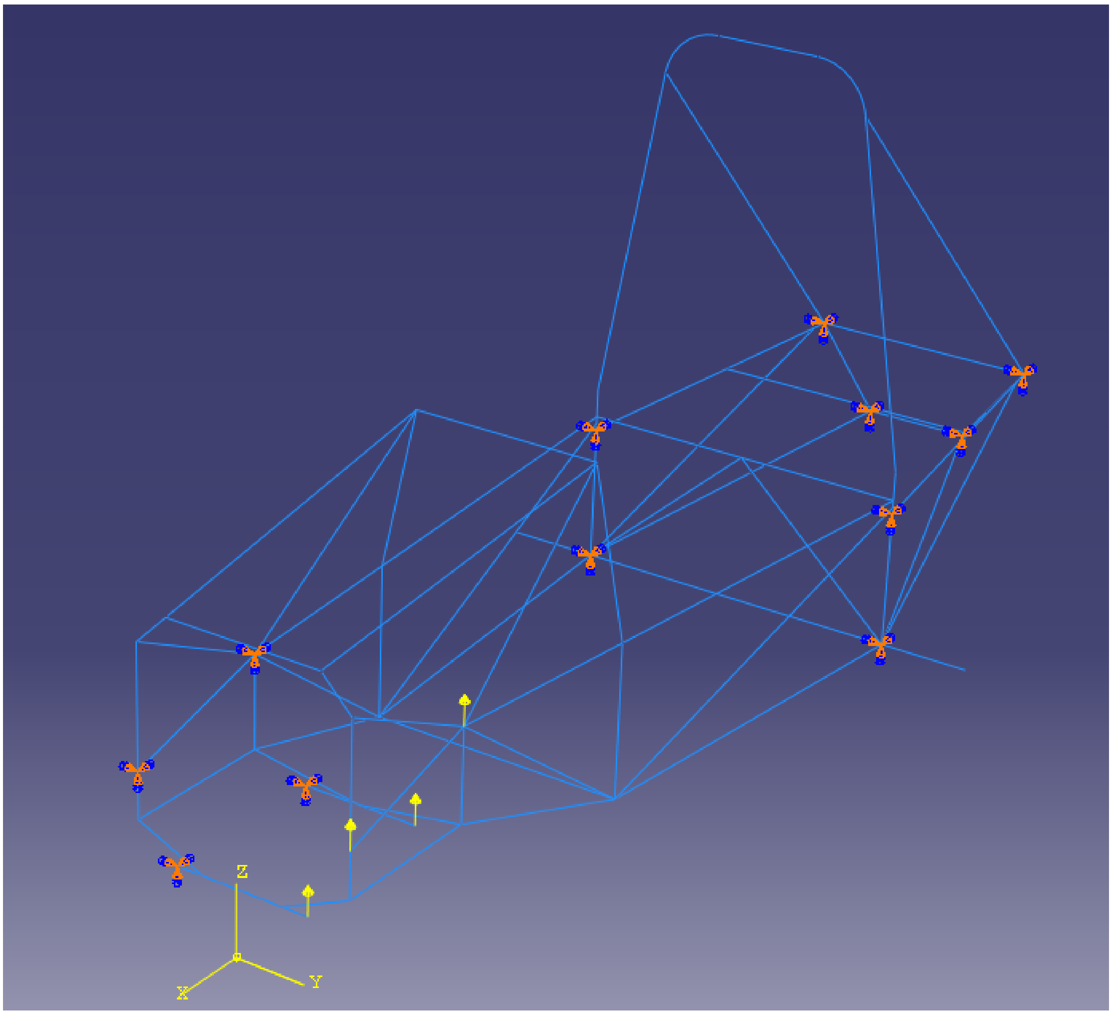

Figure 13 – Boundary and loading conditions applied during asymmetric loading simulation

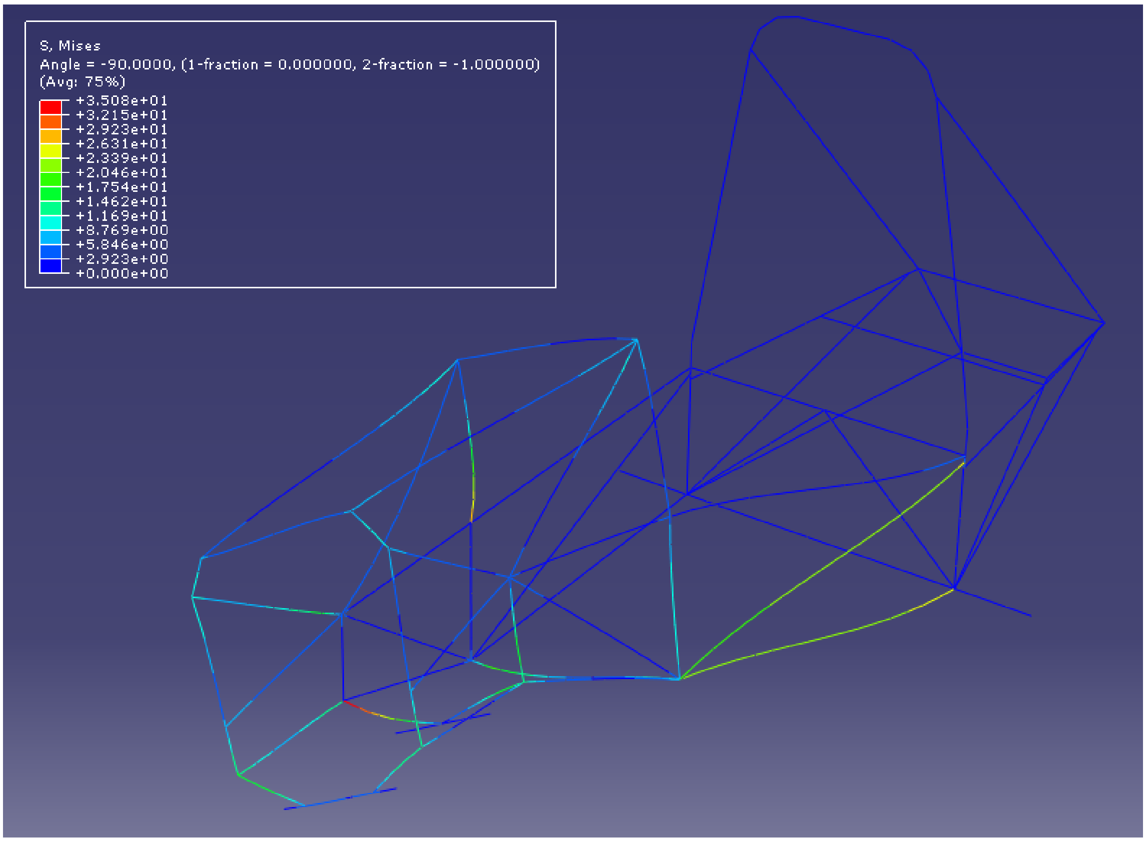

Figure 14 – Von Mises stress for asymmetric loading simulation

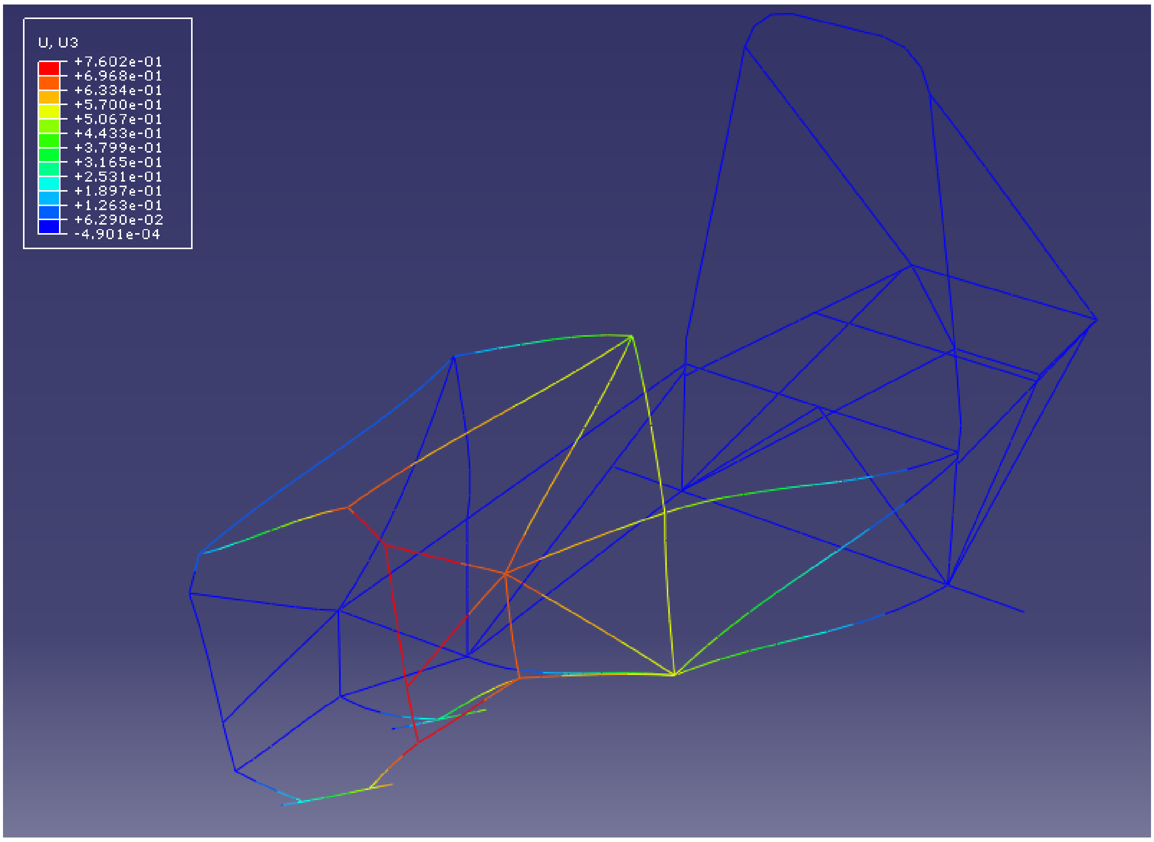

Figure 15 – Displacement plot for asymmetric loading simulation

5.4 Torsional loading simulation

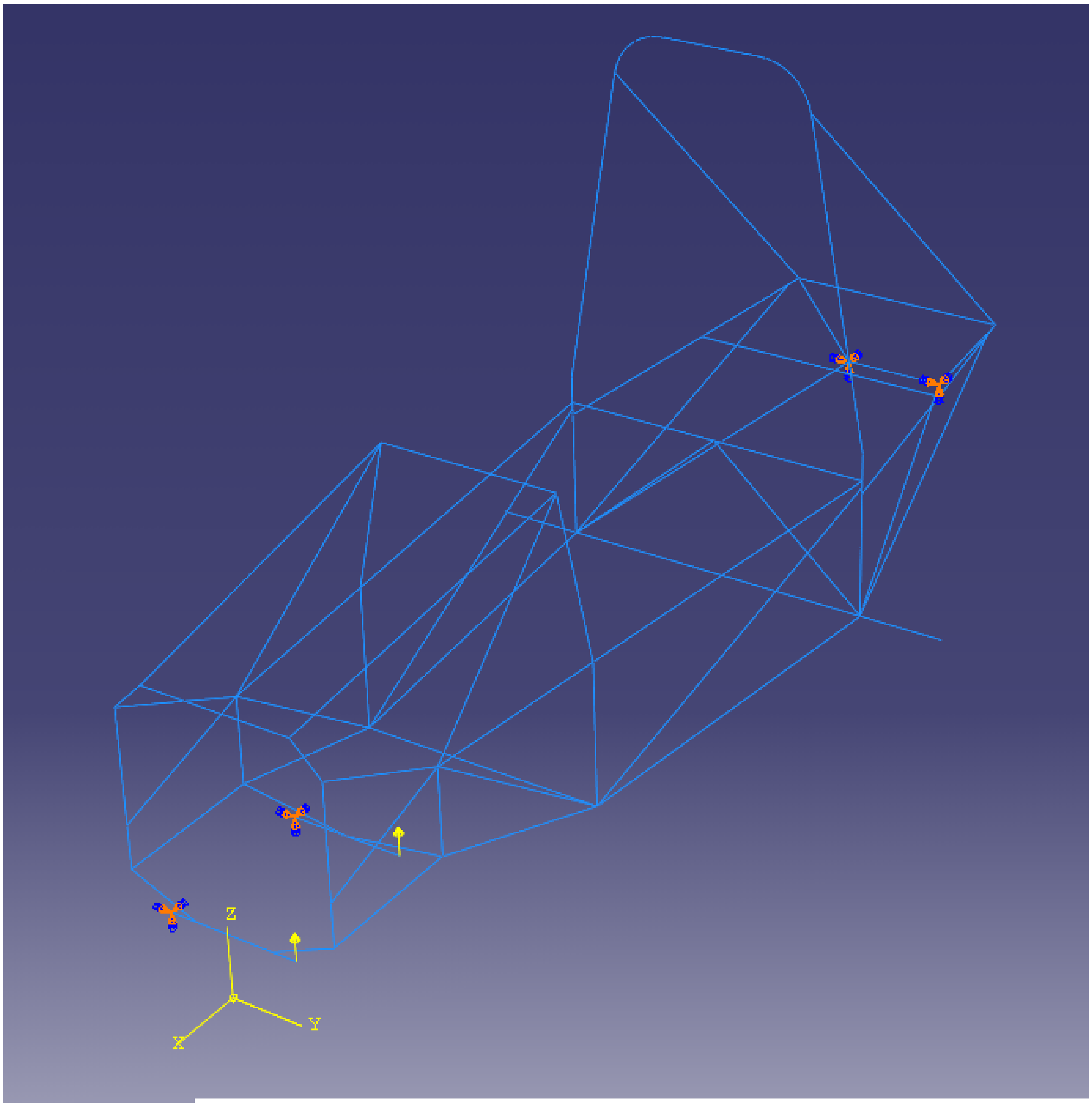

Figure 16 – Boundary and loading conditions applied during torsional loading simulation

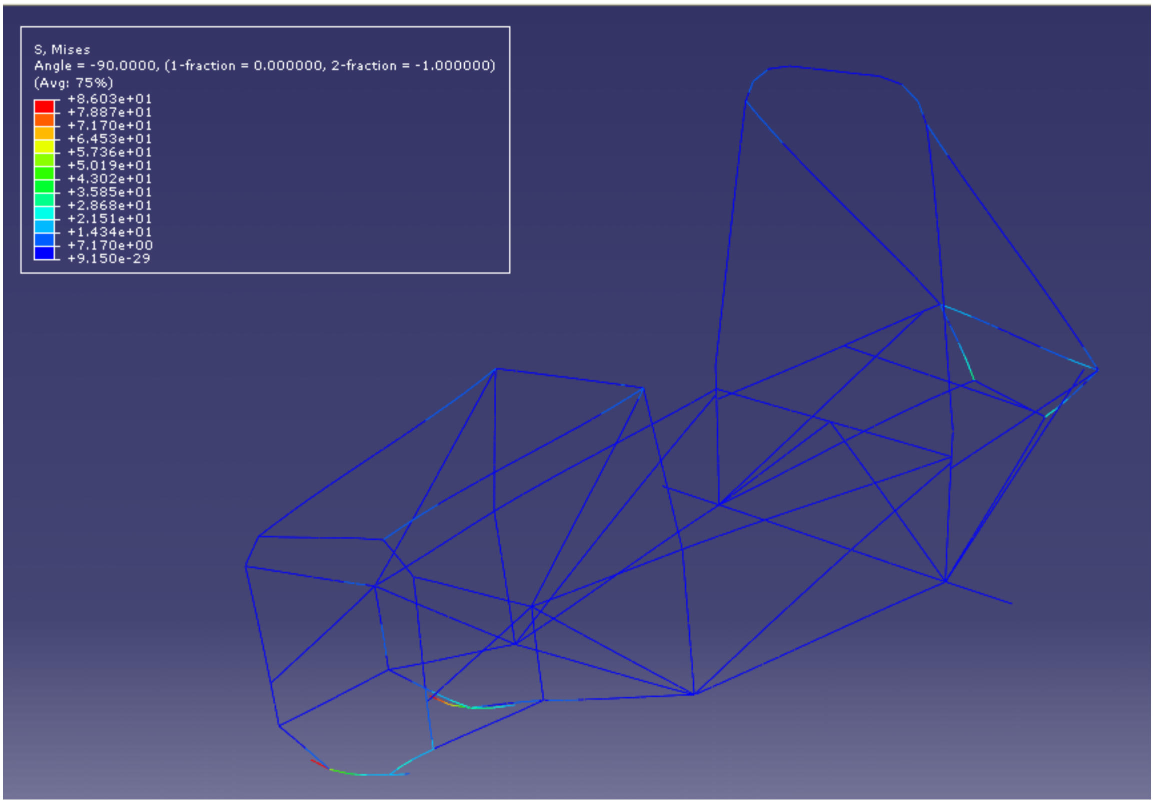

Figure 17 – Von Mises stress for torsional loading simulation

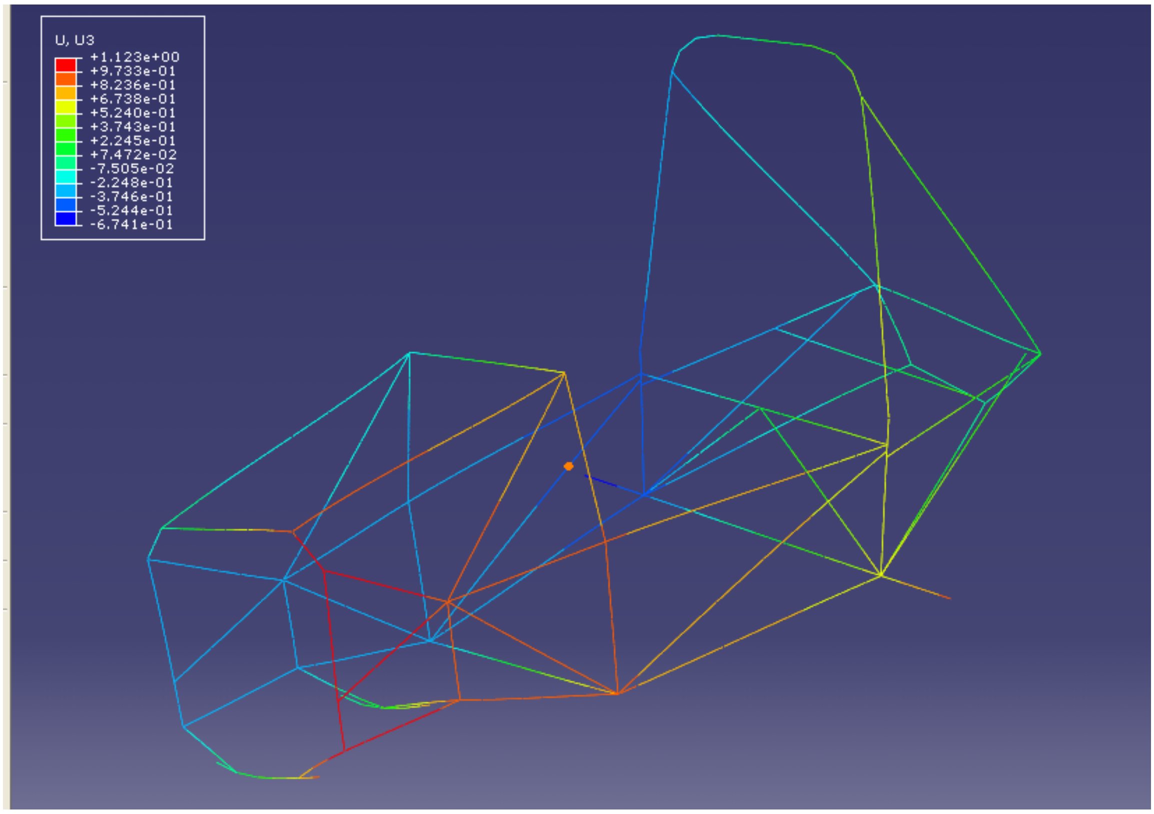

Figure 18 – Displacement plot for torsional loading simulation

6.0 Analysis and Discussion

6.1 Linear braking simulation

For the linear braking scenario the chassis model was restrained at the rear edge. Forces were then applied to the front and rear suspension mounts. The front had a total force of 2550N applied to each side while the rear had a force of 750N applied on each side. This is to simulate the greater braking at the front of the chassis due to the weight transfer it would undergo. This is reflected in the outcome of the results as greater displacement occurs at the front of the chassis as can be seen in figure 9.

It can be seen in figure 8 that approximately 40 – 50% of the members in the frame carry some stress during braking. The load paths taken are sufficient to limit the von Mises stress at any one point to only 26 MPa. With the yield strength of the steel used being 460 MPa this allows a large safety factor of about 15.

The large safety factor present suggests that optimisation could be done however as a large number of the members carry some stress it would be unwise to remove any from the framework. This leaves the option of reducing the profile of some of the members. This is not possible as the members used are already the smallest allowed by the Formula Student rules and so the options available for optimisation of the chassis become greatly reduced. Also the stiffness of the chassis has meant the displacement is limit to a maximum of only 2.8mm. This should allow for good handling as the chassis is less likely to move about during braking.

The best way to reduce the weight would be a complete redesign of the chassis however this is not feasible in the time left before the competition deadline as it would involve not only a redesign of the chassis but also a redesign of other components that have been created and design to integrate with the chassis in its current format.

6.2 Lateral cornering simulation

The chassis also shows good performance during cornering manoeuvres. For this simulation a force of 1600N was applied to each of the outside wheels while constraining the inside wheels.

Figure 11 shows the peak von Mises stress of 83 MPa occurring towards the rear of the chassis. This is well within the yield strength of the steel used (460 MPa) and allows for a safety factor of about 5.

Figure 12 shows a deflection of about 1mm towards the front of the chassis. This is small enough that any driver would not notice the effect during racing conditions and the handling of the car will not be affected to any noticeable degree.

Optimisation would prove difficult under these situations as removing any members could produce increased deflections that could start to interfere with the vehicle dynamics. Figure 11 suggests that it would be possible to reduce the profile of some members around the front roll hoop however the Formula Student rules only allow a change from 24.5mm x 1.65mm down to 24.5mm x 1.60mm. This would not make much difference to the overall weight of the vehicle and so any potential performance gain is vastly overshadowed by the cost of changing the design at this stage.

6.3 Asymmetric loading simulation

The asymmetric loading condition was created by applying a force of 1500N to the front left-hand wheel while the front right-hand wheel and the two rear wheels were fixed at the chassis.

Figure 14 shows the von Mises stress under asymmetric loading conditions. It can be seen that the peak stress is only 35 MPa. This is very low and shows that again, the chassis is more than capable of withstanding the forces from such an event.

Again it would be unwise to remove any members form the area around the front wheels as they are all directly or indirectly carrying some of the load from the applied force. This suggests that as the stress is very low around the affected area the chassis has been designed very well and would not benefit from optimisation in this area.

6.4 Torsional loading simulation

The torsional loading condition was created by adding constraints to the rear and front right-hand side of the chassis while adding a force of 1500N to the front left-hand side.

It can be seen from figure 18 that the maximum deflection of the chassis is 1.1mm. Using this value in equation 11 the effective torsional stiffness of the chassis can be calculated.

$$\text{Torsional stiffness} = \frac{\text{Torque}}{57.3\ \text{deg}} * \frac{\text{Spread distance}}{\text{Deflection}}$$

$$\text{Torsional Stiffness} = \frac{450}{57.3} * \frac{0.3}{0.0011}$$

$$\text{Torsional Stiffness} = 2142\ \text{Nm/deg}$$

While this value is much lower than the recommended stiffness for small racing cars of 4068 Nm/deg it is more than adequate for a Formula Student racing vehicle and should perform well during racing conditions.

In order to simplify the project to allow for the analysis to be carried out the chassis was modelled without any panels attached or any of the components added. As a result the stiffness calculated will be below the actual stiffness when the whole vehicle is assembled. The addition of components such as the engine block and body panels will greatly increase the stiffness of the chassis and provide further protection against the chassis twisting reducing the amount of displacement.

Figure 17 shows a peak von Mises stress of 86 MPa. This is easily within the yield strength of the steel tubing and provides a safety factor of 5.

The lower than expected torsional stiffness of the chassis suggests that optimisation cannot be carried out without first finding out how much extra resistance would be created from adding the other components. The relatively low stress towards the rear of the chassis suggest this would be a good area for further study as the addition of the engine block would further stiffen this area and so reducing the profiles of some of the tubing may be an option.

7.0 Conclusions

In conclusion the processes and steps followed in this report have proven to be vital in understanding how a good chassis should be designed and have provided the necessary techniques in order to analyse the space frame chassis in order to indentify how it will react during racing conditions and to identify any areas that could benefit from optimisation.

The proposed chassis design analysed in this report has proven to be more than capable of withstanding any loads it is likely to experience during racing conditions which suggests that any optimisation that would be needed is minimal.

The chassis has been designed to be very close to the rules and so any optimisation would be limited as many of the members cannot be changed due to them being the smallest allowed in the competition. It is possible to reduce the thickness of some of the members however this will only reduce the thickness from 1.65mm to 1.60mm which would provide very little benefits for the level of work that would be involved.

In order to truly optimise the chassis it would be necessary to begin a complete redesign from scratch. This would allow the lessons learnt from this report to be incorporated into the new design and so provide a basis for creating the most efficient chassis design possible with the resources available to the team.

7.1 Costing

The costing for this project can be calculated mainly based on the amount of human resources spent on the project in the form of time. A value of £50 per hour has been assigned to academic and research staff while a value of £15 per hour has been assigned to the time spent by myself on the project.

This results in a value of £500 for academic and research staff. This can be further dissected into 5 hours with Dr Ken Mao, 2 hours with James Brown, ½ hour with Dr Steve Maggs, ½ hour with Howard Neal and 2 hours of help from the Formula Student team.

At around 300 hours spent by myself on the project a cost of £4500 can be added.

With £45 spent on printer credit a total cost of £5045 can be attributed to the project. This may seem quite high as the Formula Student team is trying to create the car on a minimal budget however as the project can serve as a basis for other teams it can be seen as an investment and a one-off cost that will allow future teams to produce cars that already meet the required standards of the team.

8.0 Recommendations for further work

Due to the time constraints imposed by this project there are a number of areas that could benefit from the furthering of this project.

As the project relied on a chassis deign being submitted by the 2009 Warwick Formula Student team there was a large period when it was not possible to perform any analysis as there was not model on which to do this. If a model was present from the beginning of the project it would have been possible to complete a much more thorough study and complete many cycles of optimisation. This would have allowed for a revised model to be submitted that could then have been considered for manufacture and possibly use in the Formula Student competition. However as the team were working towards their own deadlines the chassis was produced to late for this to take place and so only a basic analysis was able to be carried out.

Given more time it would also be possible to learn some of the more complex features of the Abaqus program that would have allowed for greater detail to be acquired. As Abaqus was new to me, a reliance on help from others was necessary in order to complete the basic analysis for this report as there was not sufficient time to learn all the features from scratch.

Extra time would also allow for the panels and other major components to be attached to the model that would have provided a more accurate result for the torsional loading simulation.

It would have been beneficial to create a small scale model of the chassis also. This could have been a very effective way of identifying key areas quickly that performed well and others that were not as good.

As the vehicle was created and designed very closely with the Formula Student rules optimisation proved to be very difficult as the only optimisation that is possible is reducing the profile of some of the members. This would give only very small benefits in comparison to the amount of time and effort that would be required in submitting the new design. Therefore the best course would be a complete redesign of the existing chassis in order to create a more efficient design based on the lessons learnt from this report in respect to chassis design.

A. Glossary

Triangulation –	The process of adding cross bracing in order to create a structure out of triangles
CAD –	Computer Aided Design
FEA –	Finite Element Analysis
Contact patch -	The area of the tyre in contact with the road surface
Torsional Rigidity –	The ability of a framework to resist twisting caused by asymmetric loading

B. References

2009 Formula Student Class definitions

- http://www.formulastudent.com/universities/Rules.htm

Wright, Peter. Formula 1 Technology. Warrendale: Society of Automotive Engineers, Inc, 2001.

2009 Formula SAE Rules

- http://www.formulastudent.com/universities/Rules.htm

Image 1 - http://www.formulastudent.com/universities/Use+of+logos.htm
Image 2 - http://formulastudent.smugmug.com/gallery/5504382_fd49j#336808110_sRUJr
Image 3 - http://www.itv-f1.com/photo.aspx?im_id=51960
Image 4 - http://www.dodge.com/shared/2008/ram_trucks/durability/images/lowb/lb_dur_ladder_frame.jpg
Image 5 - http://en.wikipedia.org/wiki/File:Maserati_T61_engine_bay_Donington.jpg
Image 6 - http://www.jalopyjournal.com/?p=560
Image 7 - http://www.cadillacforums.com/forums/cadillac-xlr-v-series-forum/35170-price-2006-xlr-v.html
Image 8 - http://antholonet.com/EngineersCars/DeLorean/delorean.html

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Appendix A

2009 Formula Student class definitions

Appendix B

FSAE Rules 2009